

NON-DESTRUCTIVE EXAMINATIONS OF IRRADIATED FUEL RODS AT THE ITU HOT CELLS

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ABSTRACT

A specialised set of facilities for Non-Destructive Examinations (NDE) is operating since more than four decades in the β -, γ -reception hot cell of the Institute for Transuranium Elements (ITU), where the irradiated fuel rods are delivered. The inspection techniques, including multi-isotope γ -spectrometry, defect detection and corrosion examination with eddy-current, dimensional measurements, visual control and gas analysis of the plenum region are performed with devices updated according to the state of the art. The NDE system has proven to be a powerful tool providing key information on the state and physical condition of several hundred irradiated fuel rods over the past decades. The fuel's burn up level is determined through evaluation of the γ -spectra; the shadow corrosion of BWR rods is detected by means of the eddy-current measurements. Fuel swelling, measurable through profilometry and fuel stack elongation is also part of the NDE deliverables. The data collected by NDE provide the basis for an effective planning of the subsequent rod sectioning and destructive examination. Locations where intense external corrosion is measured represent potential clad failure spots or regions where other anomalies may have occurred. Such locations are natural candidate positions for sampling and further detailed analysis. In this paper we present the configuration and current status of the NDE equipment and demonstrate the system's performance with some representative results.

1. Introduction

The non-destructive examinations (NDE) are performed on irradiated fuel rods as part of the post irradiation examinations (PIE) to assess fuel rod safety and performance during reactor irradiation. This type of investigation allows controlling the cladding integrity, searching for cracks, deformations or other defects that could permit the release of volatile fission products and therefore cause risks of contamination [1]. They also allow verifying that the safety operation limits in-pile set by the licensing authorities are fulfilled. At ITU, the NDE equipment is operated in a non-alpha contaminated hot cell, where the whole spent fuel rods are received and studied.

2. Overview of the NDE hot cell at ITU

The layout of the NDE hot cell is shown schematically in Fig. 1, whereas Fig. 2 shows a photo of a cell's model illustrating the operator stations and the outer working configuration. The biologic shielding consists of a 1.1 m thick concrete wall made of heavy cement (3.5 t/m^3). The cell is operated by means of 3 pairs of manipulators on the longest side installed in front of lead glass windows. The left side of the cell, as shown in Fig.1, is occupied by a stainless steel caisson for rod sectioning and re-encapsulation of the segments (practically a separate hot cell), which is also operated with a pair of manipulators in front of a lead glass protective window. The maximum load that can be handled by the normal operation manipulators is 7-8

kg. For heavier objects than, the NDE cell is equipped with a heavy duty automatic manipulator capable of lifting up to 80 kg. A ceiling crane movable along the cell is also available for heavy objects.

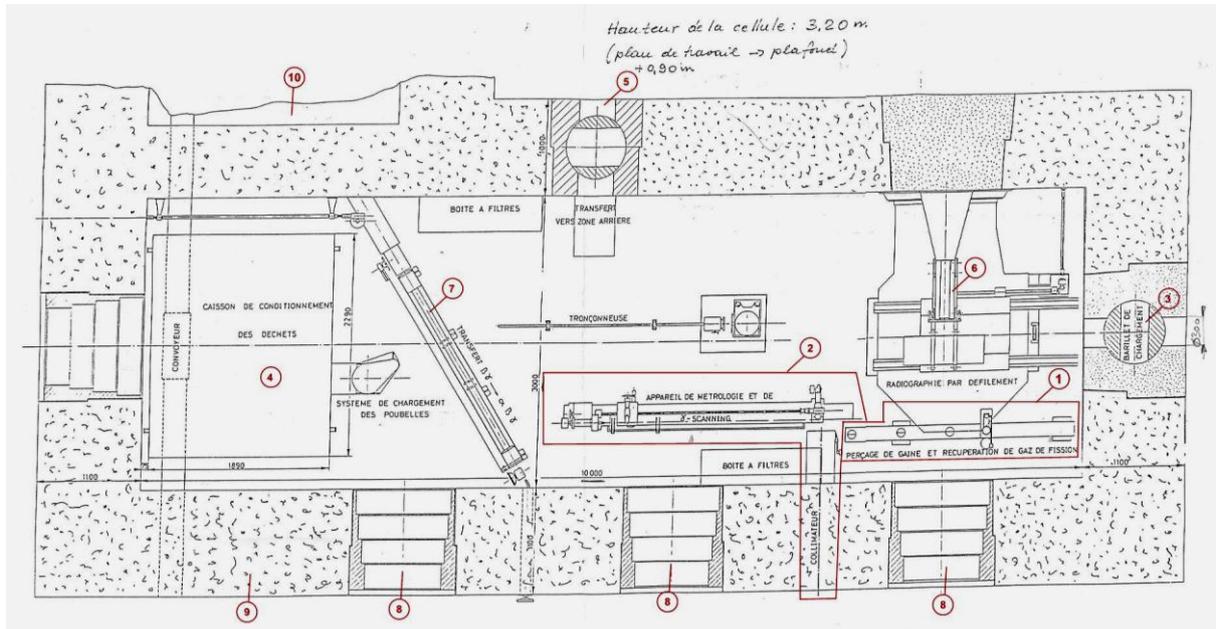


Fig. 1. Schematic layout of the NDE cell at ITU. (1) gas puncturing system, (2) metrology bench and γ -scanning, (3) docking system for transport containers, (4) stainless steel caisson for sectioning and re-encapsulation, (5) connection for removal of waste containers, (6) x-ray radiography, (7) tube connection to another hot cell, (8) lead glass windows, (9) concrete wall, (10) adjacent hot cell.



Fig. 2. Photo illustrating the working configuration of the NDE cell (model with scale 1:25)

The inner cell dimensions are 10 m x 3 m x 4.1 m (length x width x height). Through the special connecting system (Nr. 3 in Fig.1) the transport containers are connected to the cell, allowing irradiated fuel rods to be introduced in the cell. Through the same connection, encapsulated fuel rods or rod segments are loaded into the transport container. The NDE equipment consists of the metrology bench, the gas analysis unit and the x-ray radiography system (Nr. 1, 2 and 6 in Fig. 1). The radiography system is currently under renewal and is not described in this paper. The other systems are presented in the followings paragraphs.

3. Examinations on the metrology bench

The main component of the metrology bench is the so-called cassette, a sort of magazine/housing device fixed at the end of the bench, where all sensors and measuring transducers are placed. The fuel rod is horizontally placed on the bench and inserted into the fixing mandrel centring of an axially sliding motor, which is pulling and (if wished) simultaneously rotating the fuel rod through the cassette. Except for the rod's length measurement, all examinations described below are performed in this way.

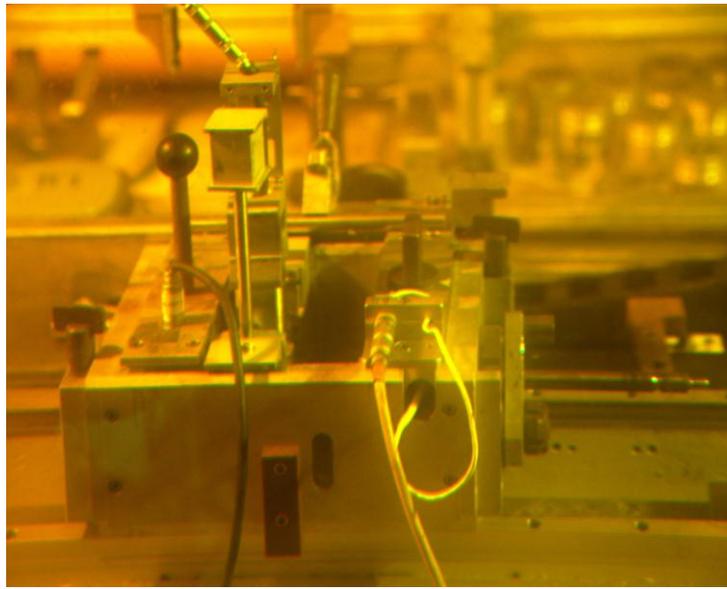


Fig. 3. The magazine (cassette) of the metrology bench with all attached measuring sensors and transducers

3.1 Visual inspection

Visual inspection primarily determines the mechanical integrity and surface appearance of the fuel rod. The outcome of these measurements is compared with the as-built condition of the rod to identify deviations and anomalies. The NDE cell is equipped with a magnifying periscope for close-up and detailed viewing of the fuel rod, while digital photographs can be obtained via high resolution cameras. With a known speed (2.5 mm/s) the fuel rod is translated in front of a CCD digital video camera at a focal length of ca. 20 cm. A digital video film of the complete length of the fuel rod is recorded and characteristic zones of normal or abnormal states are recorded in the examination report indicating the corresponding axial position. This procedure is repeated along 3 axes at 120° to each other.

3.2 Dimensional measurements

a) Length measurements

The length measurements can give valuable information on the axial fuel swelling (fuel stack elongation). The fuel rod is placed horizontally on the metrology bench and pushed up to the fixed stop-end. A sliding stop-plug whose axial position is measured by a digital scale is brought in touch with the free fuel rod end. The axial length coordinate of the fuel rod corresponds to the axial position of the sliding stop-plug. The measurement is carried out with a precision ± 0.01 mm / meter and reproducibility ± 0.05 mm. The measurement is repeated twice and the average is calculated.

b) Diameter measurements

The diameter measurements (profilometry) constitute a very important examination with respect to fuel rod performance, radial fuel swelling, cladding creep, ovalisation and other geometrical anomalies. Local diameter variations can be caused for instance by hydride blis-

ters, extreme clad ridging due to fuel swelling, etc. The measurement technique is based on LVDT (linear variable differential transformers). The fuel rod is simultaneously translated and rotated during the measurement and crossed through the knife edge contacts of the LVDT gauge. The following parameters are typically used:

Spiral rotation:	2 mm advance/ rotation
Translation speed:	1000 mm / hour
Measurement precision:	$\pm 3 \mu\text{m}$

The outputs of the LVDT gauge (diameter measurement) are recorded continuously via data logger on the connected computer and stored electronically. The scanning rate of the data logger is one value every 0.25 s. Reference standards with diameter similar to the nominal value ($10.5 \div 10.85 \text{ mm}$) are used for the calibration of the LVDT gauge.

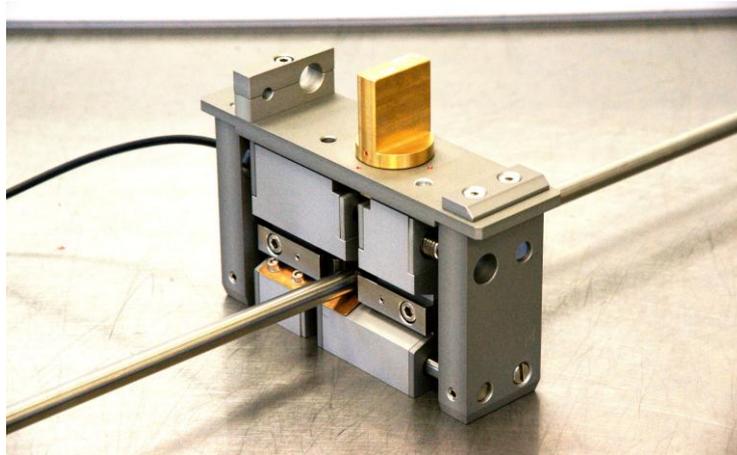


Fig. 4. The LVDT gauge before placing on the metrology magazine

3.3 Gamma scanning

The recording of the γ -ray emission spectrum along a fuel rod allows the fission products to be qualitatively and quantitatively analysed. This technique enables:

- observation of mobile/volatile fission product migration (for instance Cs);
- estimation of the fuel's average burn up;
- estimation of the power experienced by the fuel rod during a power transient.

The fuel rod is translated during the measurement in front a collimator and a Ge-detector (Fig. 5); the collimator aperture is 1.2 mm. Analyses of a fixed energy channel corresponding to a particular energy are associated with a nuclide (for example the 661.6 keV line for ^{137}Cs) for its qualitative and quantitative determination. The impulses provided by the Ge-counter are analysed simultaneously by a multi channel spectrometer and by a rate meter provided with an analogue output proportional to the counting rate of the detector.

Before or after each specific measurement, and keeping exactly the same conditions, it the background spectrum is obtained and the total γ -ray intensity counted. The background values are subtracted from the primary spectrum to calculate the real (net) pin data. The γ -spectroscopy system is calibrated using ^{137}Cs and ^{152}Eu sources at the beginning of each measurement series or when a measurement parameter is changed (e.g. amplification gain, displacement of the detector, use of other collimator aperture). Three known energy lines (for instance the ^{152}Eu lines at 344, 778 and 1408 keV) covering the whole range are measured and put on the peak positions of the graph "measured vs. reference". If the standard deviation of the linear regression does not exceed 2 keV, the calibration is accepted. Otherwise the calibration is repeated. The efficiency calibration is carried out using a known, certified

^{137}Cs source with homogeneous surface activity distribution, with same form, geometry and similar chemical composition (to guarantee identical absorption effects) as the fuel pin. The quantitative determination of the selected isotopes is performed in any case after subtracting the background signal.

Before the measurement of a fuel rod, it is necessary to control the following measuring conditions:

- i) Reproducibility of the data acquisition system using a calibrated ^{137}Cs -source with activity of 1.113×10^9 Bq.
- ii) Preliminary identification of the spectrum peaks and expected intensity, so that no overflow of the detection system takes place during the measurement.

The γ -counting rate should not exceed 15000 counts/s. If necessary, the counting rate can be attenuated. The measurements cover the energy range 50 to 2200 keV. The impulses generated by the detector's Ge crystal are treated simultaneously by:

- a multi-channel spectrometer for nuclide identification. The γ -spectrum is obtained for 150 s time intervals and corresponds to a pin length of 5 mm.
- a rate meter. Here the total γ -ray intensity for the complete wavelength range is measured to determine the axial distribution of γ -emitters. The length-relevant resolution of the measurement depends on of the collimator aperture. The analogue output of the rate meter is measured continuously with a multi meter; an analogue to digital converter (ADC) changes this output to digital. The output is also recorded on the hard disk of a computer. The scanning rate of the digital signal is one value per second and the translation speed of the fuel rod 2 mm/min. The modifying factor of the rate meter is 3000 with an analogue output range from 0–5 V. During the measurement no changes in the cell environment that could affect the γ -background level are permitted.

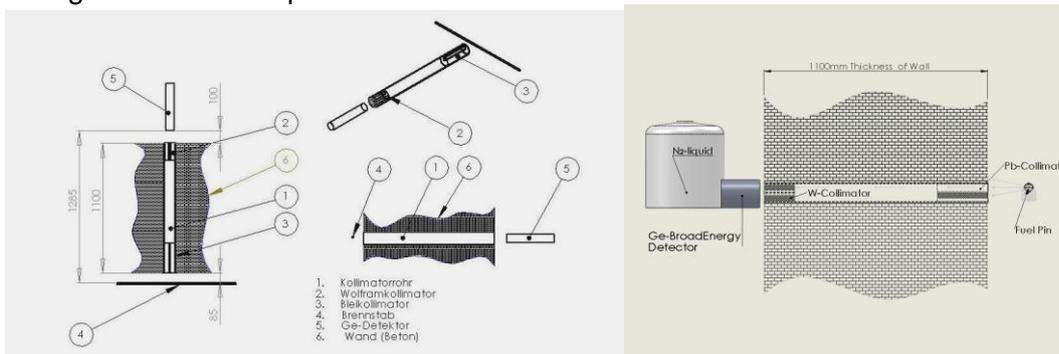


Fig. 5. Schematic drawings of the collimating and detector system for the γ -scanning spectroscopy

3.4 Eddy current examinations

The objective of these examinations is to detect eventual fuel rod cladding failures, cracks, thickness variations, as well as to quantify the thickness of the outer corrosion layer produced in the reactor by the attack of water. The technique is based on the assessment of eddy current variations generated in the examined part by the alternating field of a coil. Geometrical or structural heterogeneities in the cladding (crack, corrosion, etc.) modify the eddy current path.

a) Outer corrosion

The fuel rod is simultaneously translated and rotated during the measurement, which is carried out by means of eddy current using a punctual coil unit touching the outer surface of the cladding.

Spiral rotation: 5 mm advance per rotation

Translation speed: 20 mm per minute

Scanning rate of the data logging: one value per second.

The measuring system is calibrated using standards consisting of oxidized rods of the same material under examination. The thickness of the standard's oxide layer is certified by the manufacturer. Calibration control is carried out before each fuel rod examination. The precision of the translation is ± 0.05 mm/metre and $\pm 5^\circ$ for the rotation. The precision of the oxide layer thickness measurement is ± 2 μm . The outputs of the eddy current coil (oxide layer thickness) and the axial position are continuously acquired and logged by a PC.

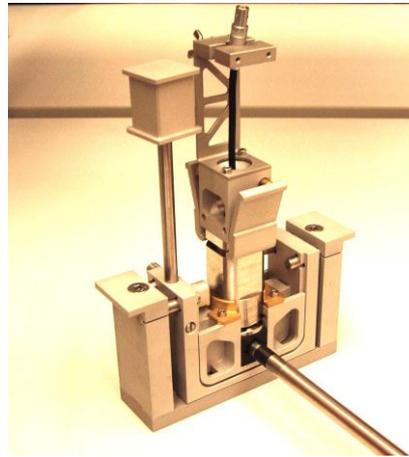


Fig. 6. The coil unit for eddy current measurements before placing on the metrology magazine.

b) Clad defect detection

The fuel rod is translated during the measurement at a speed of 100 mm/min and moved through an encircling coil. The standard coil frequency of 300 kHz can be preferably adjusted depending on the depth of the detected defect. The measurement is calibrated using standards of the same material under examination with following preset defects:

- 1, 2, 4 holes of 1 mm diameter
- internal groove 0.1 mm thick
- outer groove 0.1 mm thick
- swelling 0.1 mm

A calibration is made before each measurement.

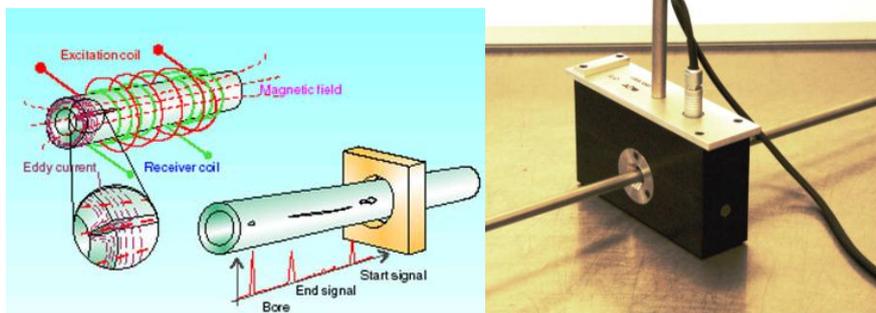


Fig. 7. The through-type coil unit of the defect detection system before placing on the metrology magazine

4. Puncturing and gas analysis

The determination of the fission gas amount released to the plenum, its isotopic composition and the determination of free volume of the fuel rod are of principal importance to evaluate the overall fuel rod performance during irradiation [1, 2]. The puncturing system at ITU establishes the isotopic composition of the fission gases by mass spectrometry while the determi-

nation of the related quantities of the total amount of released gas and the free volume of the pin are measured through a system of standard volumes and calibrated pressure gauges. In this system, the fuel rod is punctured to extract the fission gases released and the free volume is measured through the expansion of an inert gas from a calibrated volume. The fuel rod is introduced with the plenum side into the chamber of a puncturing station, sealed with a flat rubber seal. After puncturing the gas pressure inside the fuel rod forces the fission gas to stream into two storage tanks. Additional pumping completes the gas removal from the rod.

The gas from the storage tank is fed into a quadrupole mass spectrometry in order to determine the isotopic composition of the fission gas. A calibration gas with known composition of Xe, Kr at two concentration levels is used to quantitatively determine specific isotopes and to determine linearity.

Since neon is not present in fission gas it is used to determine the volume of the drilling chamber before and after puncturing. To the evacuated drilling chamber with the punctured rod still inside a chamber with known dimensions is connected. This second chamber is filled with neon gas with a known pressure. The neon will now equilibrate between the two chambers and also filling the free gas volume of the punctured rod. By means of the pressure drop of the chamber the free gas volume of the rod can be calculated using the law of Boyle – Mariott ($P_1V_1=P_2V_2$).

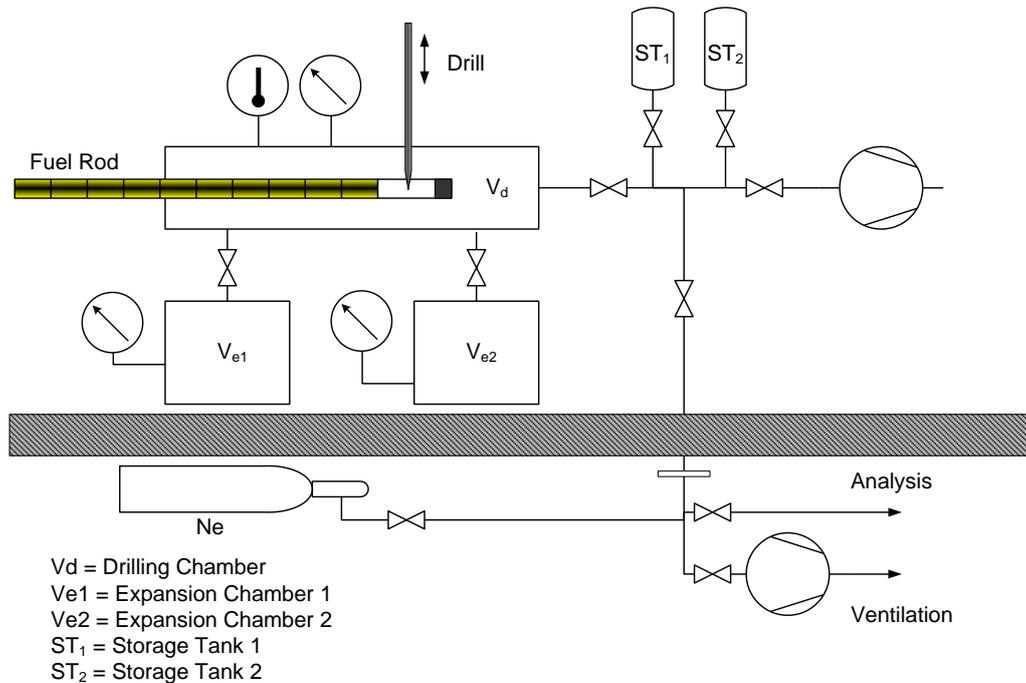


Fig. 8. Scheme of the fuel rod puncturing device.

The time to reach this pressure equilibration depends strongly on the burn up of the fuel since high burn up causes fuel/cladding gap closure due to fuel swelling. This phenomenon is preventing a free gas flow inside the fuel rod and longer equilibrium times are recorded. High burn-up fuel rods are therefore punctured at the plenum side and the bottom side to allow faster pressure equilibrium. Detection limit is set by the leak rate of the drilling chamber. A rapid measurement with fewer drillings gives better accuracy.

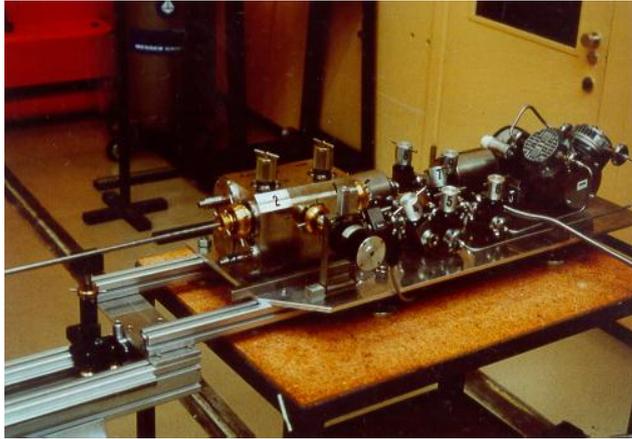


Fig. 9. The puncturing device before installation in the hot cell.

5. Representative results

Several hundred (if not thousand) of fuel rods were examined till today in the NDE hot cell at ITU producing a quite extended range of data. A few typical results are given in this section. In Fig. 10 a sequence of photographs obtained at several axial locations of a BWR fuel rod allow to assess the differences of the outer corrosion, whereas in Fig. 11 the complete oxide layer profiles of a BWR and a PWR fuel rod are compared. In BWR fuel rods the so called shadow corrosion is evident. This is a locally enhanced corrosion (sharp high peaks in Fig 11(a)) on Zircaloy components caused by dissimilar materials in contact. Spacer springs or whole spacers are made of Inconel and are in touch with the Zircaloy cladding of the fuel rod. Shadow corrosion appears during the early stages of irradiation and tends to saturate at higher burn ups.

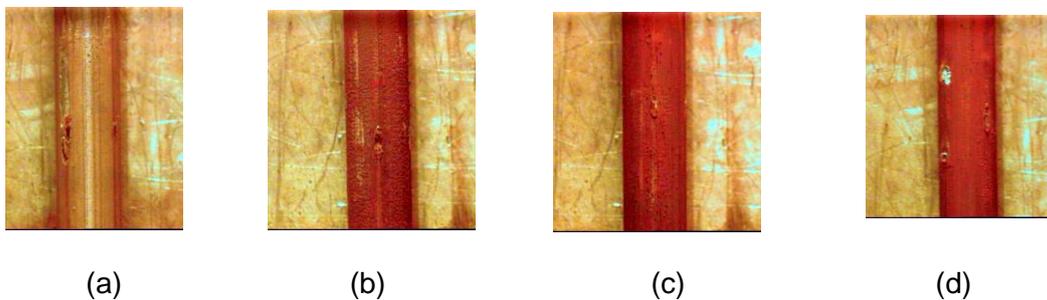


Fig. 10. Visual examination of a BWR fuel rod.

(a) 5 cm; (b) 100 cm; (c) 200 cm and (d) 300 cm from the bottom end.

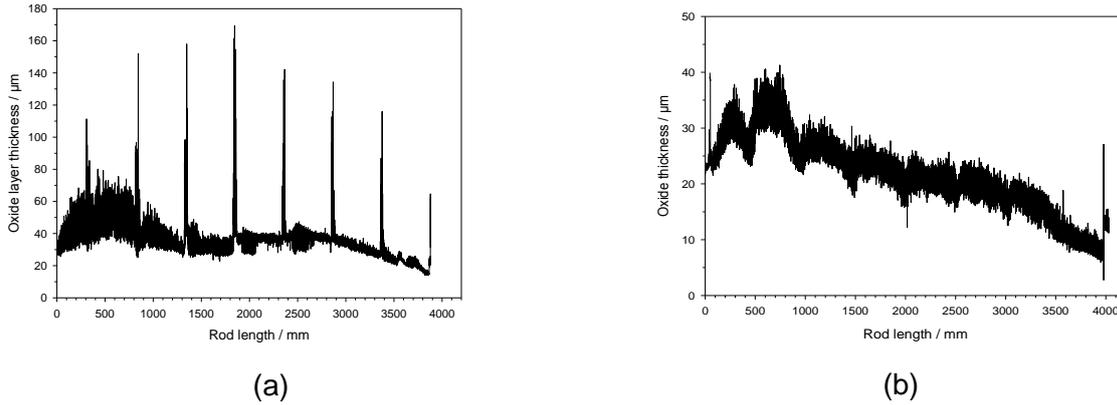


Fig. 11. Typical axial profiles of Zirconia thickness outside irradiated UO₂ fuel rods. (a) BWR and (b) PWR rod.

A nice example of complementary information that can be revealed by combining several NDE techniques is presented in Fig. 12. All three profiles of the short (ca. 500 mm long) fuel rod, namely the outer oxide thickness, γ -scan and diameter measurements clearly allow identifying the rod's plenum, fuel stack length and pellet location.

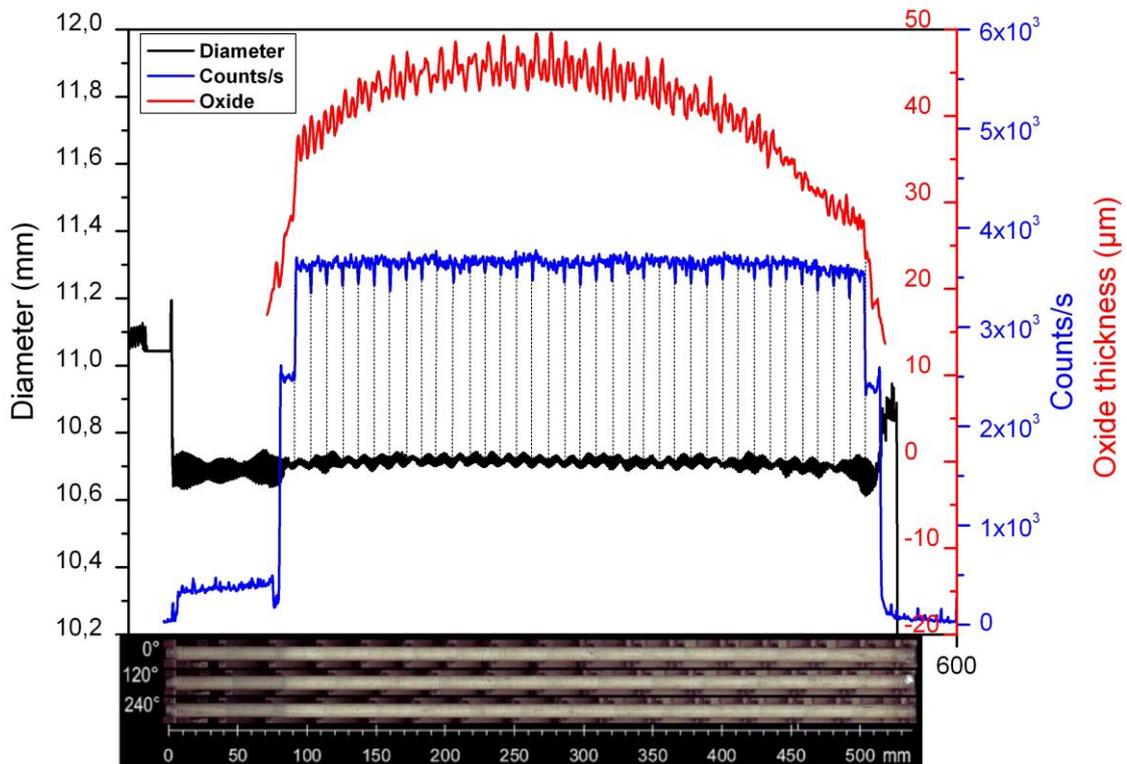


Fig. 12. Visual observation combined with axial outer oxide thickness, γ -scan and diameter measurements

A successful cladding defect detection and subsequent cross section sample preparation for microscopy examination is shown in Fig. 13. The eddy current signal distortion provided the initial indication of the presence and the axial position of a defect; this was the basis for subsequent examinations, which included obtaining high resolution photographs and finally observe and study a cross section of the fuel rod with the optical microscope after rod sectioning.

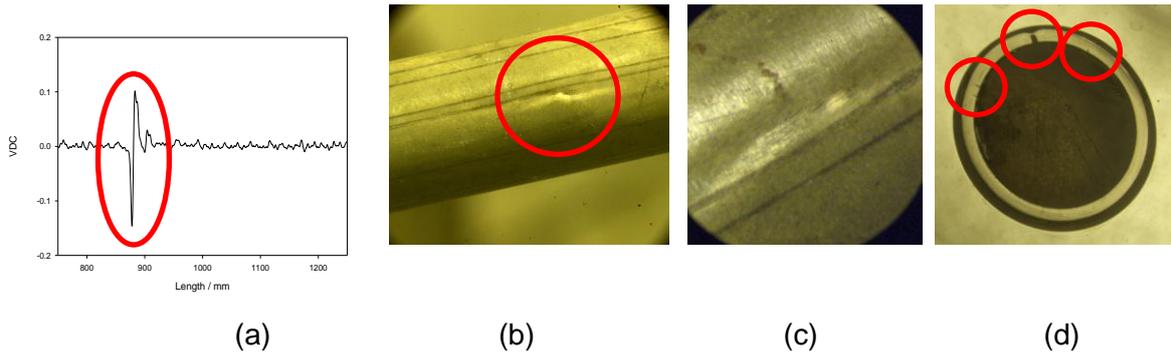


Fig. 13. Successful defect detection and localisation through eddy current measurement, and metallographic sample examination. (a) eddy current spectrum; (b) and (c): visual examination; (d) metallographic examination.

7. Conclusion

The NDE tools, a significant part of the PIE programme, are performed in one of the oldest hot cells in ITU, but still fully functional due to the skilful work of the operators and continuous improvement and update of the equipment. The NDE is an essential set of analysis that allows to consistently acquire reliable data needed for validation of the fuel rod safety and efficient performance in pile and to provide a valuable basis of information to plan and implement successful sampling and destructive PIE.

8. Acknowledgments:

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9. References

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