# NONDESTRUCTIVE EVALUATION OF NUCLEAR FUEL RODS CLADDING

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**Abstract** Nuclear fuel rods used in commercial Nuclear Power Plants are submitted to several damage induction agents, such as high temperature, high radiation levels, corrosive environment and high stresses levels that can promote the fuel rods cladding failure. Eddy current is a nondestructive testing method used to verify the fuel rod cladding integrity, allowing the detection and evaluation of discontinuities such as cracks, corrosion pits and reduction in the cladding thickness. In this paper, a study about the sensibility of this test method to detect and evaluate small discontinuities in Zircaloy-4 tubes, used as nuclear fuels cladding is presented, including the development of eddy current probes as well as an analysis of the capabilities and limitations of this test method for this application.

***Keywords***: *eddy current, nondestructive testing, nuclear fuel cladding*

## 1. INTRODUCTION

Nuclear fuel cladding must attend to several purposes, such as avoid the fuel corrosion by the coolant medium, act as a shield to contain the products resulting from the fission process, allows the free volume changes occurring in the fuel during its use and promote an adequate heat transference rate between the fuel and the coolant medium. Moreover, materials used for these purposes must be able to support the high neutron fluxes present into reactor core that produce changes in its mechanical properties. Thus, these materials must have special characteristics such as adequate mechanical properties to support the operational conditions of the nuclear fuel rod (internal pressure, temperature, mechanical vibration), chemical compatibility with the fuel and the coolant medium, good thermal conductivity and good resistance to neutron embrittlement. Cladding of nuclear fuel rods used in PWR Nuclear Power Plants generally consists of a sealed Zircaloy-4 tube, which acts as the first barrier to prevent the contact of the fuel with the external environment.

During the operational life of the fuel element, the cladding of nuclear fuel rods must be periodically inspected, in order to detect structural discontinuities which can promote its premature failure. Usually, these inspections are performed using nondestructive testing methods such as ultrasound and eddy current. Eddy current testing allows the detection of discontinuities in the wall cladding, to determine if a specific discontinuity started at the external or internal side of cladding and to evaluate its depth.

For tube inspection, it is necessary the use of specific probes, normally supplied by manufactures of eddy current testing equipment. The probe design (mechanical and electrical design) depends on the characteristics of the material to be tested, such as the tube diameter and its wall thickness, its magnetic permeability and electrical conductivity, the type, size and shape of the discontinuities that can be occur in the cladding. A specific eddy current probe was developed at CDTN Nondestructive Testing Laboratory, as part of a program to develop electromagnetic probes and sensors for nondestructive testing purposes, in order to make available this kind of technology in Brazil. Good results were obtained from the initial experiments performed with test specimens of Zircaly-4 tubes.

## 2. METHODOLOGY

Eddy current testing allows the detection and sizing of discontinuities located in the tube wall, such as cracks, inclusions, corrosion pits and gradual wall thickness loss along the tube. During the inspection, a signal referent to a specific discontinuity is showed at the eddy current instrument screen. With the probe used in this study, this signal presents a characteristic aspect, as can be seen in Fig. 1. The amplitude of this signal is related with the discontinuity size and the angle formed between the straight part of the signal and the horizontal axis in the instrument screen, called phase angle, is related with the depth of the discontinuity. After a careful calibration of the test system, using a convenient set of calibration standards, a curve relating the changes in the phase angle and the depth of the corresponding discontinuities is obtained. This curve will be used during the evaluation stage of the discontinuities detected in the inspected component. So, a successful inspection depends on the adequate design of the reference and calibration standards, the correct design, manufacture and adjust of the test probes and adequate calibration procedures.

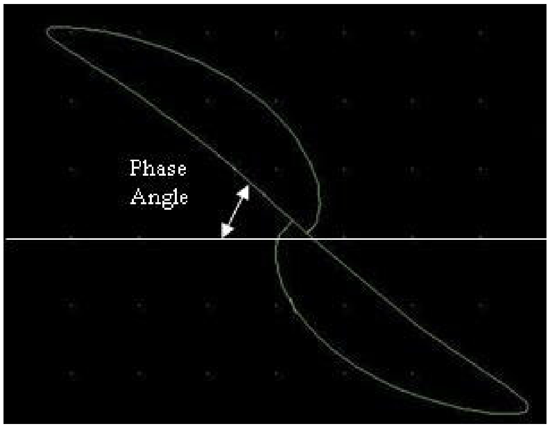


Figure 1. Signal referent to the through wall hole.

### 2.1. Materials

The experiments were performed in test specimens obtained from a Zircaloy-4 tube with the following characteristics:

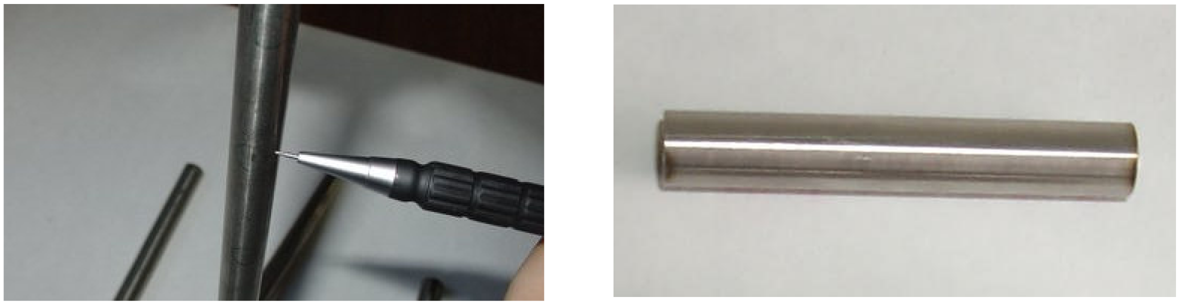
- external diameter - 10.75 mm
- wall thickness - 0.65 mm
- electrical conductivity - $7.4 \times 10^{-7}$ Ω.m (ECT, 2000)

### 2.2. Calibration Standards and Test Specimens

Reference and calibration standards are used for the test system calibration procedures and to characterize the discontinuities detected during the inspections. For the purposes of this study, reference standards containing different kinds of artificial discontinuities were prepared, in order to verify the sensibility of the test system to detect small discontinuities and to allow the test system calibration, as follows:

- 01 test specimen containing 04 holes of different depths, at the external surface of the tube, identified as test specimen 1;
- 01 calibration standard containing a through wall hole;
- 01 calibration standard containing a internal flat bottom hole with depth of 80% of the tube wall thickness;
- 01 calibration standard containing a internal flat bottom hole with depth of 60% of the tube wall thickness;
- 01 calibration standard containing a internal flat bottom hole with depth of 40% of the tube wall thickness;
- 01 calibration standard containing a internal flat bottom hole with depth of 20% of the tube wall thickness.

The diameter of all holes is equal to 0.5 mm. A detail of the test specimen containing slits can be observed in Fig. 2(a). In Fig. 2(b) can be observed one of the five calibration standards used in the experiments. The dimensions of this calibration standard are similar to the one showed in Fig 3.


(a)

(b)

Figure 2. Detail of the reference standard containing flat bottom holes (a). Calibration standard used in this study (b).

## 2.3. Eddy Current Probes and Equipment

Probes used in eddy current examination must be designed considering the characteristics of the component to be tested. For nuclear fuel rods cladding inspection, encircling probes (Cecco, 1983) are used. During the inspection, the fuel rod is dislocated inside the probe and the data referent to the material condition are acquired and analyzed. An experimental probe developed at CDTN Nondestructive Testing Laboratory can be observed in Fig. 3.

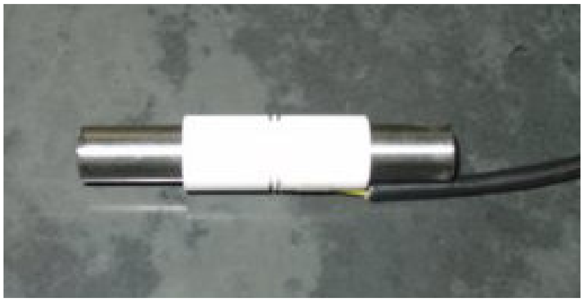


Figure 3. External involving eddy current probe developed at CDTN NDT Laboratory.

The main characteristics of this probe are presented as follows.

- operation frequency: 800 kHz
- electrical impedance: 100 Ω
- operation mode: differential

The experiments were performed using a MAD 8D Eddy Current Test System with two frequency channels and a software controlled mixer system.

## 2.4. Test System Calibration

The signals referent to the calibration standards containing a through wall hole and flat bottom holes with depths equal to 80%, 60%, 40% and 20% of the tube wall thickness were acquired and a calibration curve (ASME, 2004) relating the signal phase angle and the hole depth was plotted, as can be seen in Fig. 4. The straight part of the calibration curve corresponds to the discontinuities located at the outside surface of the tube. The other one corresponds to the discontinuities located at the inside surface of the tube.

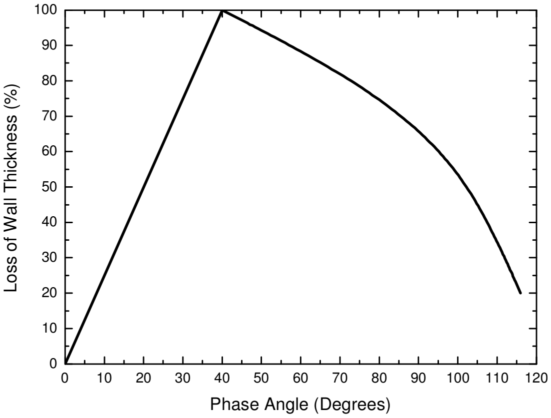
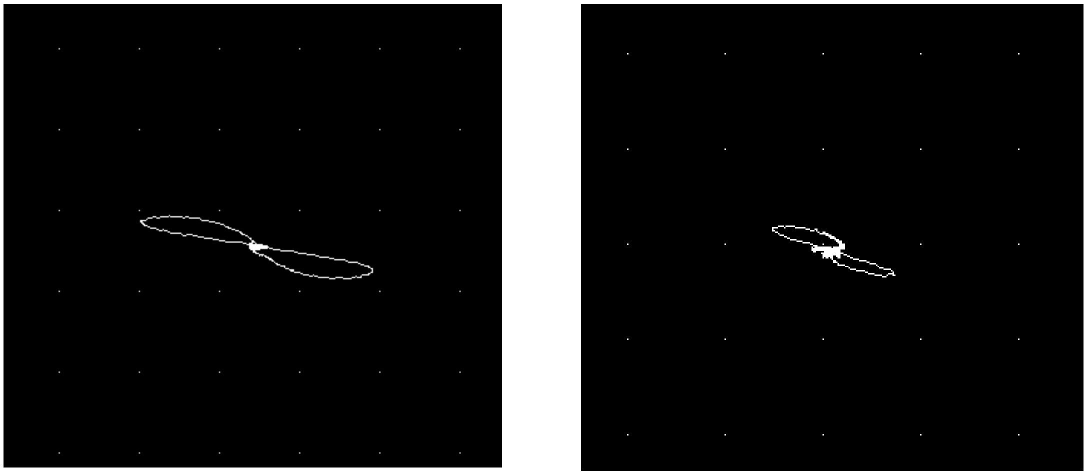


Figure 4. Calibration curve for Zircaloy 4.

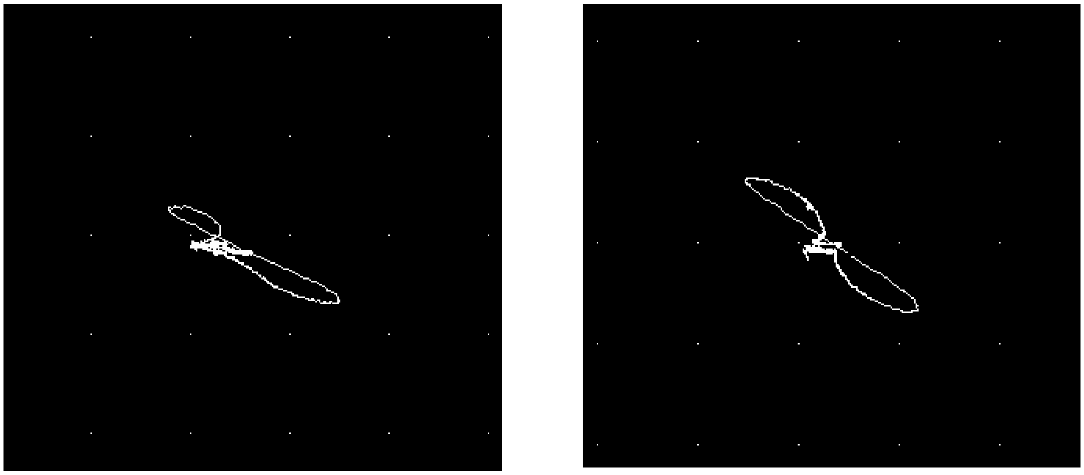
## 2.5 Examination of the test specimen

Test specimens examination was carried out using the same test parameters as the used to obtain the calibration curve. The signals obtained for the test specimen 1 are presented in Fig. 5 and Fig. 6. The signals obtained for the test specimen 2 are presented in Fig. 7 and Fig. 8.After the signal acquisition, measurements of the holes and slits depth were performed using an optical microscope. The results obtained are shown in Tab. 1.



(a) (b)

Figure 5. Signals referent to the hole type discontinuity 1 (a) and 2 (b).



(a) (b)

Figure 6. Signals referent to the hole type discontinuity 3 (a) and 4 (b).

Table 1. Loss of wall thickness obtained from eddy current test method and from measurements performed using optical microscopy in the Test Specimen 1.

| Discontinuity N° | Test Specimen 1 (holes) | |
|---|---|---|
| | Eddy Current Test Results | Optical Microscopy Measurements |
| 1 | 81,5 % | 74% |
| 2 | 62,5% | 58% |
| 3 | 47,5% | 42% |
| 4 | 22,5% | 19,5% |

## 2.6 Discussion of the Results

The probes developed at CDTN NDT Laboratory facilities presented a good sensibility to detect small discontinuities, a good stability, as well as an excellent signal to noise ratio. The discontinuities depth determined from eddy current measurements and optical microscopy measurements show a good correlation, as indicated in Fig. 7. The differences can be related with the shape of the holes machined at the inner surface of the tube (reference standards) and the outer surface of the tube (test specimen 1), due to the influence of the discontinuities morphology in the results obtained from ECT (Silva Jr, 2005).

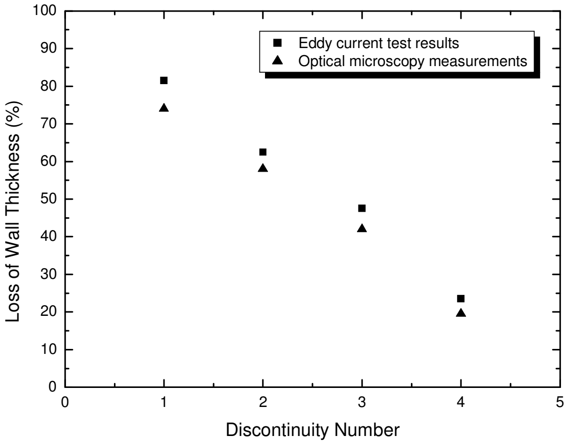


Figure 7. Discontinuities depth determined from eddy current measurements and optical microscopy measurements.

## 3. REFERENCES

ASME, 2004, “American Society of Mechanichal Engineers. Section V, Article 8, Appendix I”. ASME, New York, USA, pp. 127-130.

Ceeco, V.S., Van Drunen, G., Sharp, F. L., 1983, “Eddy Current Manual” Vol.1, Chalk River.

ECT - Eddy Current Technology Inc., 2000, “Electrical Resistivity of Materials”, ECT, Virginia Beach, USA.

Silva Júnior, S. F.; Alencar, D. A., 2005, “Influência da Morfologia das Descontinuidades no Ensaio por Correntes Parasitas”, Proceedings of the VIII Conference on Equipment Technology, Salvador, Brazil.