SWEPT FREQUENCY EDDY CURRENT TECHNIQUE FOR POOL-SIDE INSPECTION OF ZR-ALLOY FUEL ASSEMBLY MEMBERS

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ABSTRACT

The frequency-scanning eddy current technique (F-SECT) Nuclear Application system is a unique nondestructive testing solution jointly developed by CESI (Centro Elettrotecnico Sperimentale Italiano Galileo Ferraris S.p.A.) and EPRI (Electrical Power Research Institute, Inc.) to estimate the hydrogen content of Zirconium alloy components, based on the minor electrical conductivity reduction induced in Zirconium alloys by the precipitation of hydrides. The system adopts a swept frequency eddy current technique combined with model based analysis of the measured data to provide quantitative estimates of the oxide thickness, residual wall thickness and electrical conductivity of the Zr alloy component, which is correlated to its hydrogen content through alloy-specific calibration curves. A distinctive feature of the method is the capability to account for parameter variations that occur jointly, e.g. a wall thickness variation in combination with a conductivity change due to hydrogen absorption, plus an oxide thickness variation, which is common in practical cases. The possibility to include magnetic permeability in the model parameters allows the user to compensate to some degree for the presence of ferromagnetic crud.

After a 4-year development and a validation phase that included several hot cell inspections on fuel rods and channel boxes of different alloys and manufacturers, the system was successfully tested in 2014 at two nuclear power plants, during two poolside inspections on channel boxes and highly crudded BWR cladding, respectively.

1. Introduction

Quantitative nondestructive assessment of irradiated light water reactor (LWR) fuel assembly components and fuel rod cladding has been a growing need for the nuclear industry due to pending modifications to current regulations and industry expectations for higher fuel reliability. Emphasis on determining fuel reliability margins has pushed for the development of nondestructive characterization techniques that could be deployed poolside at a nuclear power plant that are capable of quantifying hydrogen content, Zr-alloy residual wall thickness and oxide/crud thickness. Similarly, hot cell post-irradiation examination (PIE) would benefit from such novel techniques that could be used to pinpoint in a nondestructive manner portions of the fuel assembly components that require further investigation through focused destructive analysis, thus increasing the overall cost-effectiveness and maximizing the benefit of PIE.

Among the broad range of nondestructive testing techniques already adopted for PIE and poolside inspections, the electromagnetic techniques (ET) – namely eddy current – have been used for many years for oxide thickness measurement and defect detection on zirconium alloy components. In fact, these techniques are extremely sensitive to the distance between the sensor coil and the test material, a characteristic that makes them particularly well suited to measuring the thickness of an interposed nonconductive layer, such as a surface oxide layer, provided the coil perfectly adheres to it. Furthermore, these techniques are also quite sensitive to local variations of the electrical conductivity of metals, possibly induced by defects, variation in geometry like a thickness reduction, and microstructural or chemical composition changes of the alloy. It is not surprising then that state-of-the-art ET techniques, e.g. combining a multi-frequency approach with model based analysis, should be deemed as valid candidates for quantitatively assessing corrosion of Zr-alloy components, providing information on oxide thickness, remaining alloy wall thickness and hydrogen contained in the alloy in the form of Zirconium hydrides, should these hydrides cause a sufficient change in electrical conductivity of the original alloy.
A precursor to the frequency-scanning eddy current technique (F-SECT) Nuclear Application system was developed by CESI in the early 90's with the objective of estimating the thickness and the residual life of the protective coatings applied on the critical and expensive blades and vanes of land-based combustion turbines [1]. The thermal barrier coatings used in that application are a combination of a metallic bond-coat, directly applied on the blade airfoil to protect it against high-temperature oxidation, plus a ceramic top-coat to insulate the blade and reduce the temperature encountered by the blade structure. During operation the metallic bond-coat degrades by losing Al. When its Al content decreases below a certain threshold, it loses protection against high-temperature oxidation and must be stripped off to allow a new coating to be applied. The aim of the F-SECT system was two-fold. First, to check the quality of newly applied coatings in terms of thickness and Al content, which was utilized by manufacturers in the production line and by end users for acceptance tests. Second, to increase the amount of data available on Al consumption in service-run blades for the purpose of optimizing the coating service life, without incurring in the high costs of destructive sectioning. Building on the capabilities of this precursor system, EPRI and CESI worked to address the issue of Zr-alloy corrosion of nuclear fuel components using the F-SECT system. The similarities between the problems posed by quantitative characterization of gas turbine coatings and Zr-alloy components were clear from the beginning and can be summarized as follows:

- detecting small electrical conductivity variations, as induced by the precipitations of Zr hydrides or by Al depletion;
- dealing with layered structures due to the potential presence of crud, oxide, outer and inner liners, a hydride rim in the cladding, and the cladding itself versus non-uniform Al depletion in the coating;
- compensating for disturbing effects caused by the possible presence of magnetic deposits like crud on fuel cladding and iron oxides on gas turbine blades.

The extra challenge for the nuclear application system would be that of delivering a small sensor coil into the spent fuel pool through a 20-meter long connection cable to the high-frequency eddy-current module positioned poolside to inspect fuel assembly components that are potentially highly irradiated.

2. The frequency scanning eddy current technique

The problem of quantitative nondestructive evaluation of both high-temperature metallic coatings and Zr-alloy members of fuel assembly components can be restated as follows: given a layered conductor, it is required to determine the electrical conductivity, the magnetic permeability and the thickness of each layer. The chosen approach to solve the above diagnostic problem relies on eddy-current measurements. Besides, a multi-frequency technique is required to test the material at different depths, allowing in-depth localization of interfaces between adjacent layers. The frequency scanning eddy-current technique was chosen, in which the probe – a simple copper coil - is driven with a fast sequence of

frequencies in the range 0.4 MHz- 8 MHz, corresponding to decreasing inspection skin depths, e.g. from ~0.7 mm to ~0.14 mm for Zr-alloys. The acquired electrical impedance spectrum of the probe placed close to the test material contains the diagnostic information, i.e. the thickness, electrical conductivity and magnetic permeability of each layer used to describe the test material. Extracting this information is usually referred to as solving an "inverse problem," the direct problem being that of computing the impedance spectrum from the known values of these parameters.
Solving the inverse problem requires:

- A direct model for computing the probe impedance. In the F-SECT system a model describing the interaction of an electromagnetic wave - generated by the probe - with a layered metallic material was implemented.
- An iterative inversion algorithm to minimize the difference between the measured and calculated impedance, by changing at each step the values of the parameters until convergence to their best estimates is reached.

The above approach is well-known [2]; therefore the new idea around which the F-SECT system was shaped was the adoption of a new concept of "normalized impedance" in place of the effective probe impedance [1]. If effective probe impedance depends largely on the electrical characteristics of the sensor and the connection cable and to a lesser extent on test material properties, the situation is completely reversed with normalized impedance which focuses mainly on material properties. By using normalized impedance, the equations governing the direct model can be simplified, the inversion process becomes more robust, and material properties can be more reliably estimated. A special calibration procedure was developed to obtain normalized impedance from raw eddy-current data. It relies on six swept frequency measurements performed at different lift-offs on two homogeneous reference samples with electrical conductivities σ_A and σ_C, different from each other but in the same range of conductivities of the materials to be inspected [3].
After system calibration, component inspection consists of a frequency sweep of 20 to 24 frequencies, each requiring the probe to remain still in position for ~2-3 seconds to complete.
A normalized impedance (NI) vs. frequency curve is calculated and stored for each measurement position. Quantitative analysis of the NI curves is carried out off-line by either a manual or an automated procedure based on application-specific analysis models. It provides the best estimates of the model parameters at each measurement position:

- The residual wall thickness of the Zr alloy is obtained from the estimated layer thickness values.
- Electrical conductivity of the Zr alloy. Hydrogen content can be indirectly evaluated from the estimated electrical conductivity values, provided a conductivity vs. hydrogen reference curve is available for the specific Zr-alloy and other influencing parameters, such as neutron fluence, are known or can be calculated [4,8,10].
- The oxide thickness, corresponding to the sensor lift-off, initially estimated at the acquisition stage, is fine-tuned on the basis of the analysis results.

3. F-SECT development for fuel assembly component materials characterization

3.1 Sensitivity to Zr-hydrides in the alloy

The first step in the development of the new system was to verify the sensitivity to the presence of Zr-hydrides in the alloy. This was accomplished by performing measurements on a series of Zr-4 cladding specimens artificially charged at different hydrogen levels, all other factors remaining constant. The results from these tests showed a clear reduction of the NI curves for increasing hydride concentration in the cladding, as shown in figure 1. Because the NI scale was directly proportional to an electrical conductivity scale, there was evidence that the electrical conductivity of the alloy had reduced due to the presence of hydrogen. Moreover, the greater reduction observed at high frequencies, for which penetration of the probing electromagnetic wave is limited to always thinner surface layers, was immediately recognized as the effect of hydride concentration in an outer rim [4] that was present in these samples.

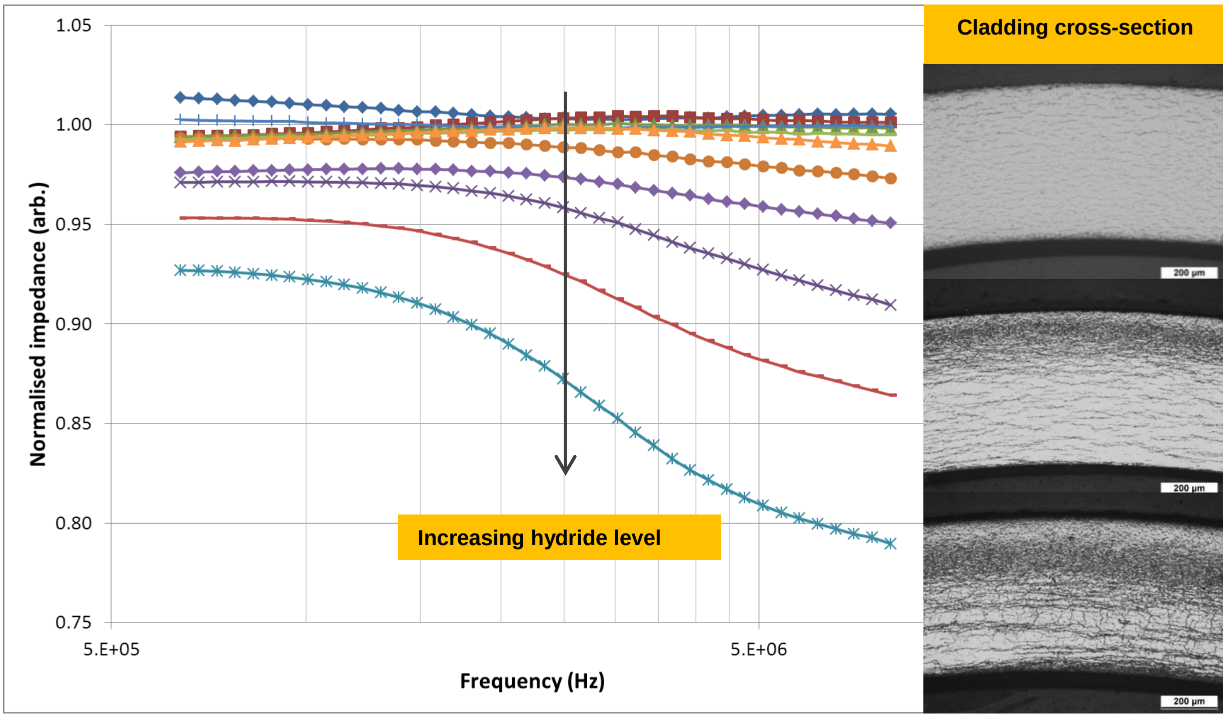

Fig. 1: Correlation between measured normalized impedance vs. frequency curves and cladding condition.

3.2 Electrical conductivity of Zr-hydrides and need for alloy-specific conductivity vs. H calibration curves

There is limited literature on the electrical properties of zirconium hydrides. Figure 2 shows two series of data on Zr-hydride electrical resistivity, obtained by Bickel in 1972 [5] and Tsuchiya in 2002 [6]. The conductive nature of this hydride is evident in the fact that for compositions approaching ZrH_2, the hydride is a better conductor than high-purity zirconium. The bump in the data from Bickel below an H/Zr ratio of 1.65 is likely due to the change in crystal structure associated with the transition from ε-phase (body-centred tetragonal, $ZrH_{1.7<x<2.0}$) to δ-phase (face-centred cubic, $ZrH_{1.59<x<1.66}$). The second series of data from Tsuchiya, limited to ε-phase hydrides, deviates significantly from the previous results for H/Zr ratios below 1.74, showing higher resistivity values. Regardless of which data set should be considered more accurate, the interesting point is that only δ-phase hydrides (according to Bickel's data), with the possible addition of ε-phase hydrides with H/Zr ratio approaching that of δ-phase hydrides (according to Tsuchiya data), have electrical resistivity higher (or electrical conductivity lower) than that of Zr-4. If this agrees with the observed reduction of the NI level, it also raises the question of what phases do precipitate in hydrogen charged samples. This is a crucial point as the relationship between the hydrogen level and the electrical conductivity of zirconium alloys would be almost unmanageable if different phases with largely different electrical properties as a function of the H/Zr ratio coexisted in the alloy in different and variable percentages. A thorough review of the vast literature available on the precipitation process of zirconium hydrides and its effects on the mechanical properties of zirconium alloys, and an original experimental work on the identification of hydride phases in hydrogen charged Zircaloy-4 samples by Daum suggest that predominantly δ-hydrides form in hydrogen charged samples, at least for hydrogen contents below 3000 wppm (weight parts per million) [7].

The above literature data provide a frame to explain the conductivity reduction (or resistivity increase) observed by the F-SECT technique in hydrogen charged Zr-4 samples of increasing H contents. From that, it seems reasonable that the sensitivity of electrical conductivity to a variation of the hydrogen content be dictated by the conductivity difference between the original Zr-alloy and the δ-hydrides. Because different Zr-alloys do have different conductivities and therefore different sensitivities to hydrogen content, alloy-specific electrical conductivity vs. hydrogen calibration curves will be necessary to map conductivity estimates to hydrogen content. Besides, also the error associated with these estimates will depend on the same conductivity difference. With regard to irradiated samples it will be shown in section 4.3 that also fast neutron fluence affects electrical conductivity, due to second phase particles dissolution and dislocation build-up promoted by collisions between the highly energetic neutrons and the alloy atoms. This effect will have to be compensated for in order to obtain accurate hydrogen estimates.

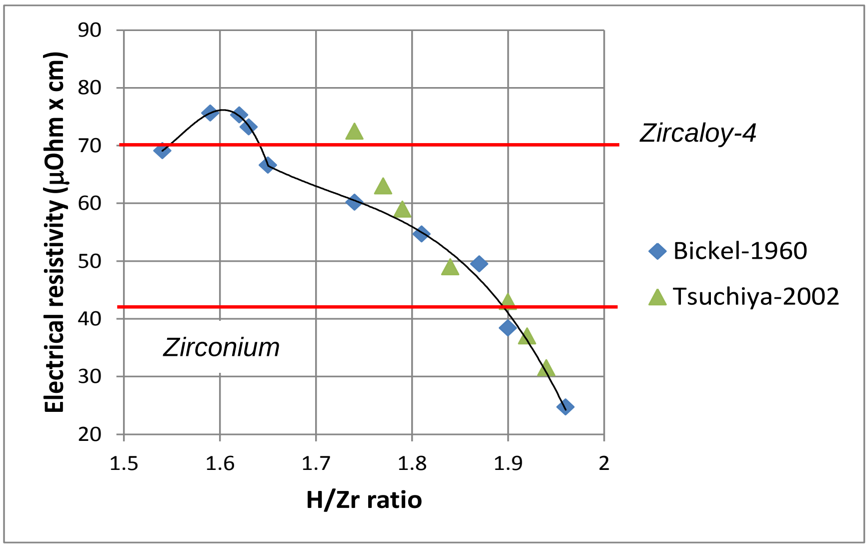

Fig. 2: Literature data on the electrical conductivity of Zr hydrides [5,6] compared to that of Zircaloy-4 .

3.3 Water-tight self-nulling sensor and 20-m long cable assembly

The initial results discussed in the previous paragraph were obtained in a laboratory with a standard probe connected to the high-frequency eddy current module through a short 1.5 m-long connection cable to the F-SECT electronic module. The requirement of delivering the probe to an 8-meter depth in the spent fuel pool called for a dramatic increase in cable length. In eddy current cable length is always a critical factor that may cause severe disturbance to the measurements, particularly at high frequencies where the combination of a cable's distributed capacitance combined with sensor inductance gives rise to nonlinear resonance effects. The longer the cable, the greater the disturbances in terms of number of resonances and disturbance amplitude in the frequency bands used. Even when a small change occurs in a cable, such as a cable displacement or temperature variation, distributed capacitance also changes and the probe response may be greatly distorted. Another potential source of disturbance is the dependence of Zr-alloy electrical conductivity on temperature. Pool water and cladding temperatures could vary along the 4-meter tall fuel assembly/bundle, and if not adequately compensated for, would produce measurement errors and the consequent need for frequent system recalibrations.

Mitigation of both the resonance and temperature effects was achieved by the adoption of a self-nulling configuration for the eddy current sensor, instead of an absolute probe configuration. A laboratory study aimed at characterizing the different sources of errors and assessing the possibility of their reduction was subsequently performed [4]. The self-nulling sensor used for this work, shown in figure 3, consists of two identical sensors connected in series and phase opposition with the following components: a measurement sensor, which adheres to the evaluated component during inspection, and a reference sensor, embedded in the probe and glued to a small reference sample, similar in geometry and material to the test component, which is in contact with the external (measurement) environment. Since the

reference sample is located close to the measuring sensor and in essentially the same environment, it senses almost the same temperature as the inspected component.
In this way the output signal from the self-nulling sensor is the difference between the signals from the two individual sensors and the effects due to a variation of the Zr-alloy conductivity with temperature are compensated as long as the two individual sensors are operating at the same temperature.
Mitigation of the disturbances due to resonance also results from the differential nature of the self-nulling sensor, the output of which is much smaller (because it is a difference) than the output of an absolute sensor, although it contains the same diagnostic information. This results in an increase in the signal-to-noise ratio.

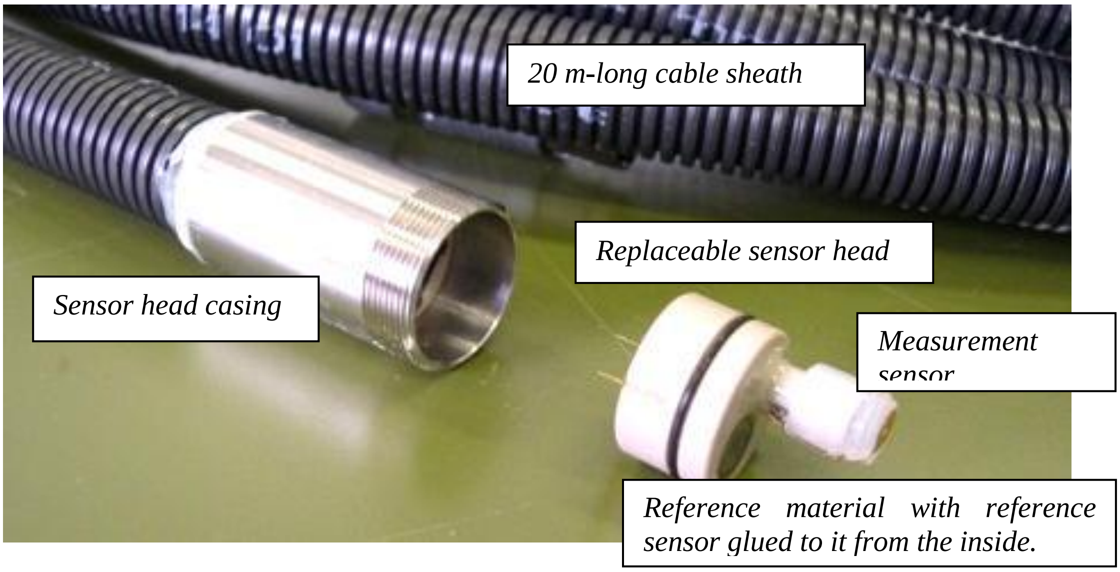

Fig. 3: 20-meter long, water-tight connection cable and replaceable self-nulling sensor.

3.4 Development of analysis models

As previously mentioned, the availability of a baseline direct model for NI is a prerequisite for estimating the solution to the inverse problem, i.e. estimating the material properties and geometric parameters from the measured NI vs. frequency curves. The baseline direct model implemented in the F-SECT system describes the interaction of an electromagnetic wave - generated by an axisymmetric sensor - with a plane multiple layered conductor [1]. The parameters available in the model are the layer thickness, electrical conductivity and magnetic permeability of each layer. A maximum of five layers are available to describe the structure of the inspected material. The best estimates of these parameters are obtained by an iterative algorithm that minimizes the error function, i.e. the difference between the calculated and computed NI curves, through a step-by-step modification of the parameters values. This process of convergence can be made more robust if some a priori knowledge is introduced into the model, e.g. by setting the number of layers and by reducing the number of unknowns by fixing the values of some parameters if they are either well known or can be accurately estimated. An obvious example is that of setting the relative permeability of all layers to 1 if no magnetic effects are expected. In some situations, especially when the number of layers necessary to describe the test material increases, inserting a-priori information in the model may become the most error prone stage of the analysis.
A selection of analysis models used in different measurement conditions is presented below.

<u>*Uniform hydride distribution*</u>

A uniformly-hydrided channel box or cladding can be analyzed with a simple 2-layer model, as in figure 4. This model has just 2 unknowns:

- Zirconium alloy thickness (L_1),
- Zirconium alloy conductivity (σ_1), correlated to the hydrogen content.

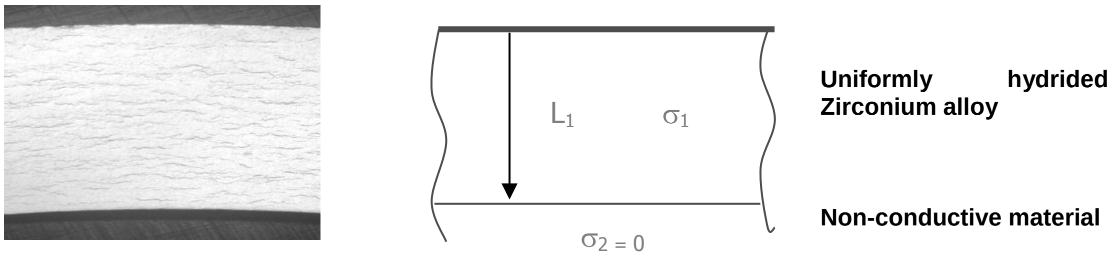

Fig. 4: 2-layer model for uniformly hydrided zirconium alloy.

<u>*Presence of a hydride rim*</u>

In this case a 3-layer model with four unknowns must be used, as shown in figure 5. It is sometimes convenient to reduce the number of unknowns by setting L_1 to a constant reasonable value. From the parameter estimates the following diagnostic quantities can be obtained:

- Zirconium alloy residual thickness (L_1),
- Zirconium alloy average conductivity, given by $\frac{[\sigma_1 x L_1 + \sigma_2 x (L_2 - L_1)]}{L_2}$, which correlates to the average hydrogen content.

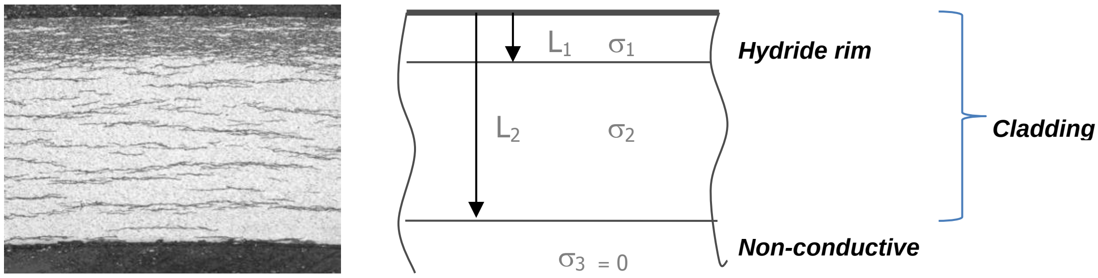

Fig. 5: 3-layer model for zirconium alloy with a hydride rim.

<u>*Presence of ferromagnetic deposits (crud)*</u>

An extra layer must be added to the previous model if ferromagnetic deposits (crud) are present on the cladding OD. As shown in figure 6, layer 1 is used to jointly take into account the effects due to the presence of the magnetic crud and zirconium oxide. Therefore the relative permeability μ_1 of this layer adds to the unknowns. A total of 7 unknowns becomes difficult to account for in the inversion model and may result in not only slow but also potentially unstable inversion results; therefore, appropriate ways of setting some of the unknowns to constant values should be considered and implemented and such complicated models should be avoided when possible.

While still under investigation, it may be possible to accurately estimate oxide thickness (L_1) and Zirconium alloy remaining wall thickness (L_3-L_1) in the presence of ferromagnetic crud. It remains to be seen if sufficiently accurate electrical conductivity estimates can be obtained in the presence of ferromagnetic crud layers to map to hydrogen content of the zirconium alloys.

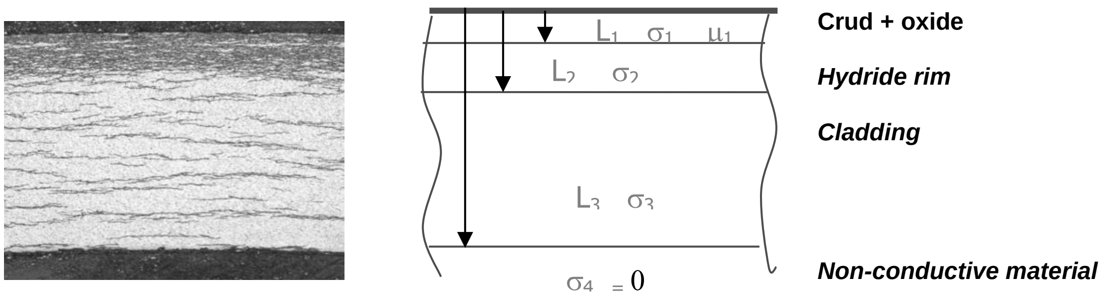

Fig. 6: 4-layer model for zirconium alloy with hydride rim and ferromagnetic deposits (crud).

3.5 Validation activity

System validation included several hot cell inspections on fuel rods and channel boxes of different alloys and manufacturers, conducted in a two-year time span [8-11].

The system was then successfully tested in 2014 at two nuclear power plants, during two poolside inspections on channel boxes and highly crudded BWR cladding, respectively. A water-tight, halogen-free probe with a 20-m long connection cable to the swept frequency eddy current module was used, and showed no signs of degradation due to the high radiation field even when in contact with the fuel rods for a relatively long period of time. The probe, with cylindrical stainless steel casing, was moved along the fuel rods or channel boxes by the same mechanical positioning system used by the fuel manufacturers to carry out other types of poolside inspections.

Good measurement repeatability was obtained due to previously simulating poolside conditions in the laboratory that made use of a flexible eddy current sensor that could conform well to the test surface under a force of ≥15 N even for rather large variations of the probe tilt [9]. Also, the self-nulling sensor solution proved capable of compensating for some degree of water temperature variation at different heights along the inspected component, reducing the need for repeated system re-calibrations during the inspection process down to one additional calibration per measurement sequence along the 4-meter-tall test components. System calibration was carried out underwater at a depth corresponding to mid-span of the fuel rod, which required the six calibration samples to be mounted on the mechanical probe delivery system. For reference, a series of 600 measurements performed along a 4-m long fuel rod could be completed in about 30 to 40 minutes, excluding data processing and analysis.

4. Examples of results

4.1 Oxide thickness measurement

Oxide thickness can be easily estimated on zirconium alloy components by measuring the lift-off, i.e. the sensor-to-metal distance, even using simple single-frequency eddy current instrumentation. The measurement is accurate if no magnetic deposits are present, otherwise, as in the case of BWR fuel rods with highly ferromagnetic crud, the true oxide thickness may be greatly overestimated, even up to 6-8 times larger than the actual value. Thanks to model-based analysis and the possibility to use up to 5 layers to describe the test sample, the F-SECT system can provide improved estimates of the overall oxide + crud thickness even in cases where highly magnetic crud is present. An example of obtainable results is illustrated in figure 7a:

- The measured lift-off (red) shows values up to several hundred microns, mainly tracing the intensity of the magnetic effect of the crud, given by its magnetic permeability times its thickness.
- The compensated lift-off (green), corresponding to the sum of the oxide and crud thicknesses, follows a rather continuous pattern along the inspected fuel rod with maximum values below 100 μm, much closer to the anticipated thickness of the crud plus oxide layer thicknesses. However, these data have not yet been validated by destructive examination.

4.2 Residual wall thickness measurement

This measurement is possible both on plane and cylindrical geometry, i.e. channel box and cladding, even in presence of magnetic deposits of low-to-medium magnetic intensities. Residual wall thickness profiles obtained with the F-SECT system often show a sinusoidal-like pattern, traceable to the manufacturing process, superimposed on the expected wall thickness reduction due to oxidation. Figure 7b shows the residual Zr-alloy thickness estimated on the same fuel rod of which the oxide thickness is represented in figure 7a. Residual wall thickness can also be measured on cladding types with an outer liner. In fact a thin outer layer (i.e. close to the probe) can be well characterized by the high-frequency portion of the impedance spectrum because surface-confined electromagnetic waves at high frequencies interact only with the liner. If the liner is on the inside, the high penetrating waves at low frequency must interact with the entire wall thickness to reach the liner, and the possibility to characterize the inner liner independently from the bulk cladding is drastically reduced. From a practical point of view, a variation of the inner liner conductivity and/or thickness becomes hardly distinguishable from a variation of the overall cladding thickness.

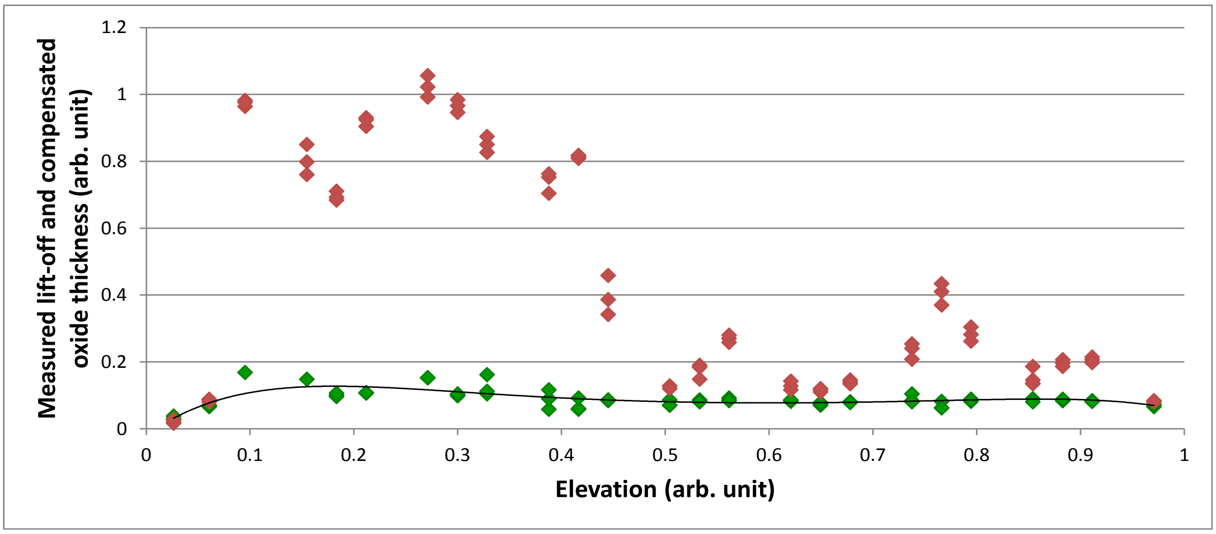

Fig. 7a: Measured (red) and compensated (green) oxide + crud thickness on a fuel rod.

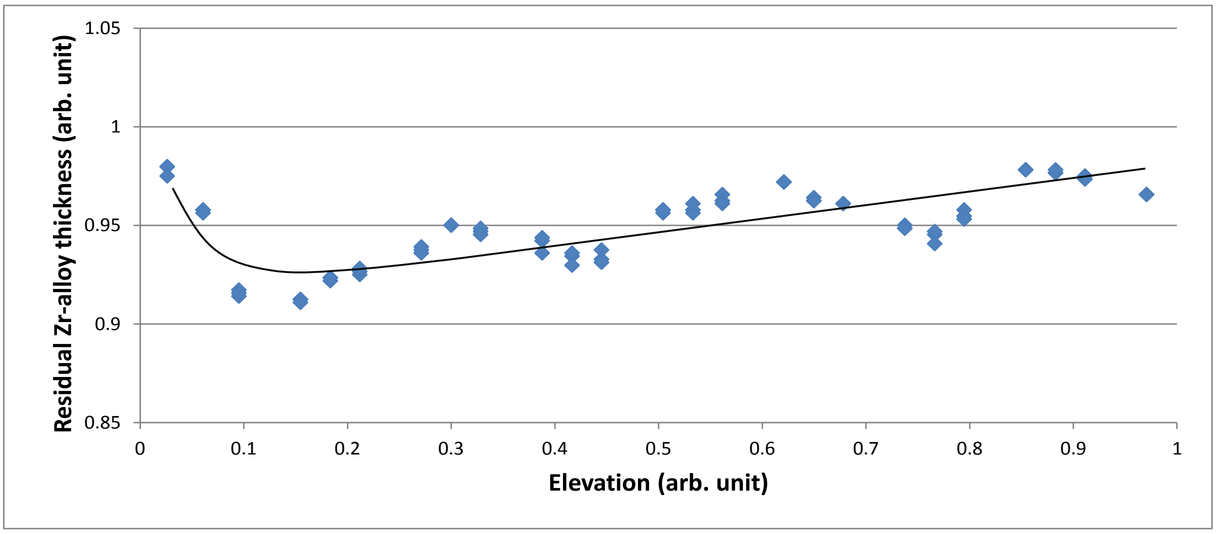

Fig. 7b: Example of residual Zr-alloy thickness measured on the same rod of figure 7a.

4.3 Hydrogen content evaluation

As mentioned previously, hydrogen content estimation is a very challenging task that requires the electrical conductivity of the Zr alloy to be accurately estimated. In fact, the electrical conductivity reduction induced in the Zr-alloy by the presence of hydrides is always quite small. This makes hydrogen content evaluation rather difficult on crudded cladding due to the difficulty in obtaining an exact compensation of the magnetic effect.

The need for alloy-specific calibration curves to map hydrogen content from conductivity estimates has been already discussed in § 3.2. These reference curves can be obtained by comparing F-SECT estimates of electrical conductivity with hydrogen content data from destructive analysis. But even without a reference curve, the electrical conductivity profiles along a fuel rod can be qualitatively used to point out areas with presumably higher hydrogen content to be subjected to further destructive analysis, as shown in figure 8.

Another aspect to be taken into account when measuring hydrogen content is temperature. Metals become less conductive as temperature increases. It was estimated that a difference of 2°C - 3°C between the average temperature of the cladding and that of the surrounding water – felt by the reference sensor/material embedded in the self-nulling sensor and used to

compensate for temperature variations - would produce an error in the electrical conductivity estimates of the Zr alloy equivalent to a 100 wppm variation of its hydrogen content.
Recently, fast neutron fluence was shown to have an apparent effect on electrical conductivity, which was observed working on low hydrogen pick-up Zr-alloys [10]. This is believed to be a result of both dislocation defects introduced into the zirconium material's microstructure and the dissolution of secondary phases due to the neutron fluence. Conductivity may also be influenced by material strain due to swelling and creep in the components. Figure 9 shows the experimental evidence of fluence effect. Multiple linear regression was applied to electrical conductivity data estimated on cladding samples from different alloys, for which both the hydrogen content and fast neutron fluence had been independently estimated. The electrical conductivity variation of the low hydrogen pick-up alloy, represented by the purple X marks at higher conductivity values had to be attributed almost entirely to fluence due to the low hydrogen content in the alloy.

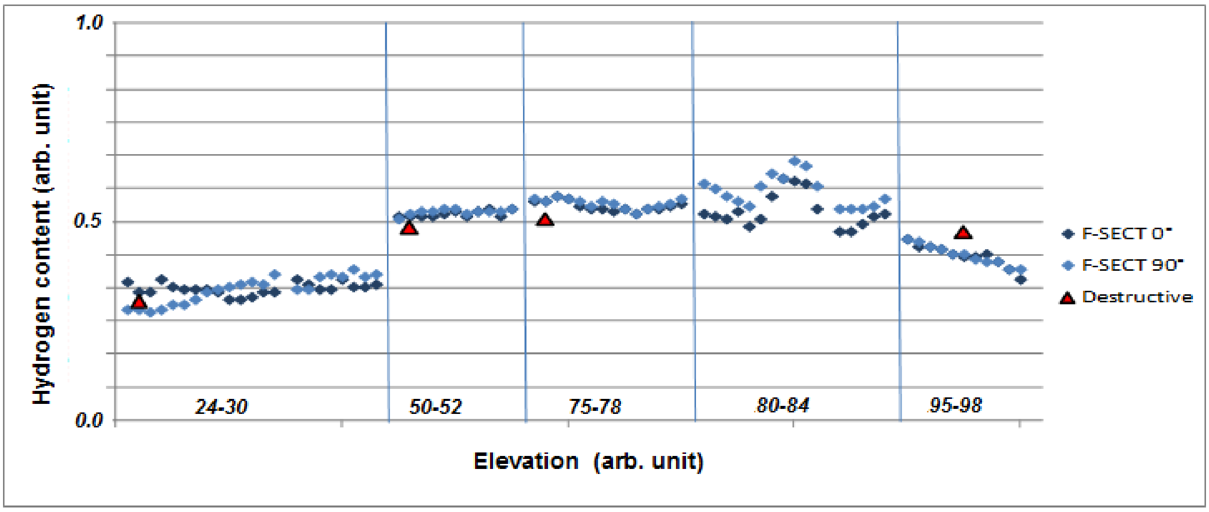

Fig. 8: Correlation between estimated electrical conductivity (blue point) and hydrogen content from destructive analysis (red points).

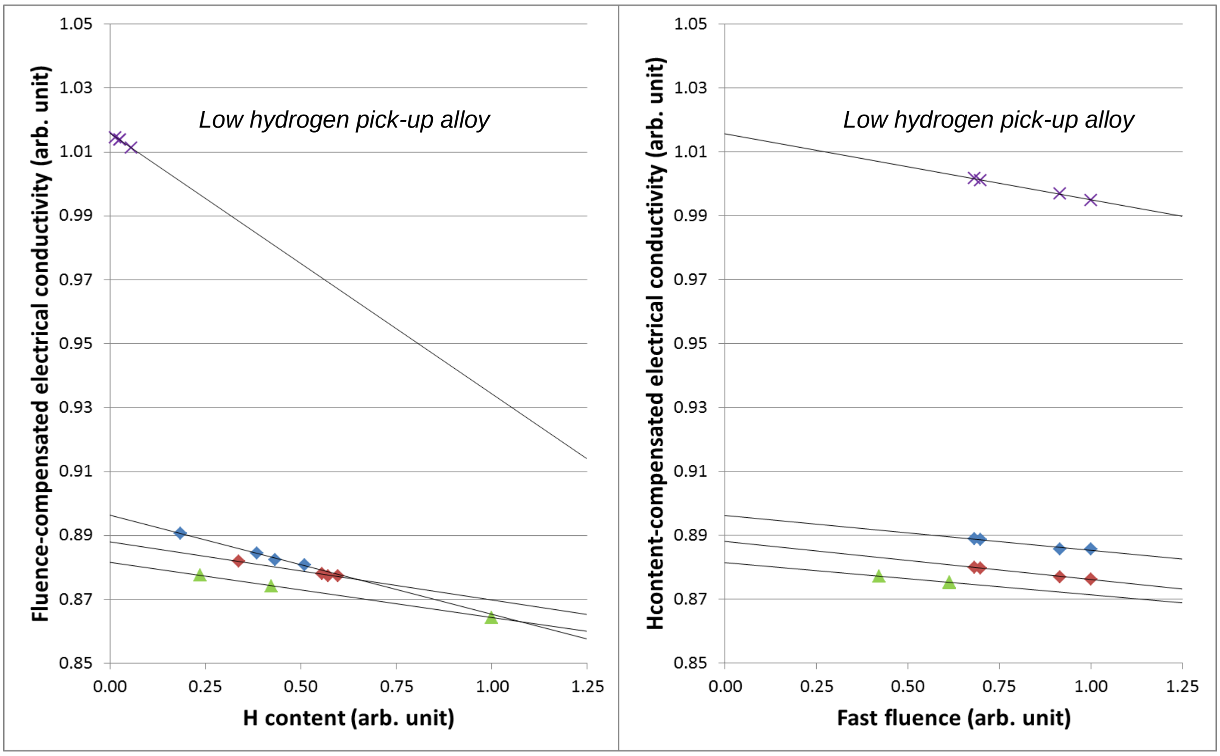

Fig. 9: Separation of the effects due to hydrogen absorption and fast neutron fluence on the electrical conductivity of different Zr-alloys.

4.4 Secondary degradation

By using appropriate analysis models, the F-SECT system can be used to evaluate the electrical conductivity of the inner and outer parts of the cladding separately. This can be utilized to determine whether an electrical conductivity reduction, and the correlated increase of the hydrogen content, should be attributed to cladding secondary degradation, and the depth to which such degradation has progressed through the cladding wall. Figure 10 shows color-coded maps of the electrical conductivity of the inner and outer layers of a small portion of cladding with intentional secondary degradation that was formed by injecting water into an operating fuel rod. The conductivity estimates were obtained by performing measurements at different elevations and circumferential orientations. The darker spots in the maps correspond to local conductivity reductions. The greater concentration of conductivity reductions on the inner layer map (left) is a warning on the existence of secondary degradation while the map focused on the outer cladding layers (right) shows that some secondary degradation has penetrated deeper through the cladding wall than in other areas.

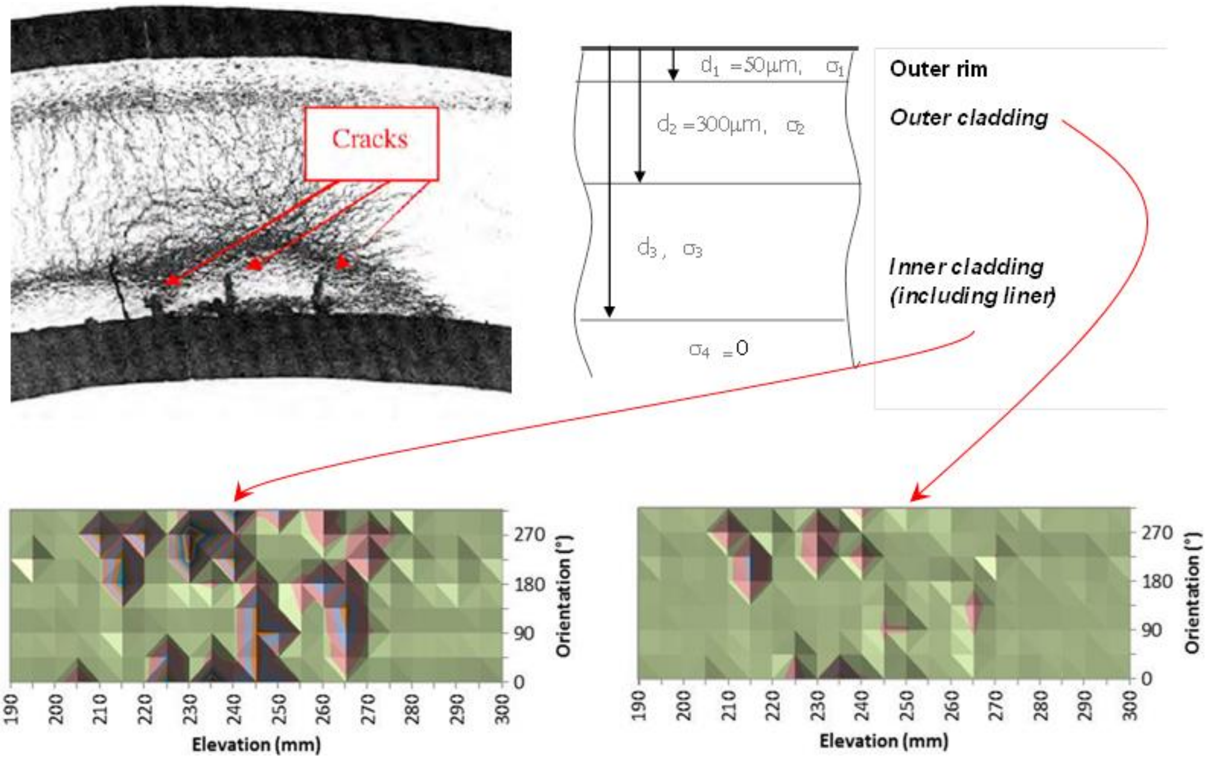

Fig. 10: Model used to analyse F-SECT data from fuel rods affected by secondary degradation, and color-coded maps of the electrical conductivity of the inner and outer parts of the cladding.

5. Conclusions

The frequency scanning eddy-current technique (F-SECT) “Nuclear Application” system, developed through a joint EPRI-CESI effort, is a unique solution to the problem of quantitative nondestructive characterization of irradiated Zr-alloy fuel assembly materials and components. After a 4-year development phase and several tests in hot cells and nuclear power plants, the system has been shown to be effective in both hot cells and for poolside inspections with the aim of increasing the cost-effectiveness and maximizing the benefit of PIE activities.

The F-SECT’s distinctive features come from a balanced combination of state-of-the-art techniques, like multi-frequency probe excitation, model-based analysis, a self-nulling sensor configuration, combined with the concept of normalized impedance that allows for simplification in the analysis algorithms, and in the end, to obtain more reliable estimates of material properties such as oxide thickness, residual metal wall thickness and Zr-alloy

electrical conductivity. This latter quantity can be correlated to the hydrogen content of the Zr-alloy in most cases as the precipitation of Zr hydrides, predominantly occurring in the form of δ-hydride, slightly reduces the electrical conductivity of the original alloy.
Being multiparametric by nature, the system is capable of dealing with parameter variations that occur jointly, like e.g. a wall thickness variation superimposed to a conductivity change due to hydrogen absorption, plus an oxide thickness variation, which is common in practical cases. Besides, the possibility to include magnetic permeability in the model parameters and to use up to five layers to describe the test material, allows the operator to compensate to some degree for the presence of ferromagnetic crud. While still under investigation if oxide thickness and Zirconium alloy remaining wall thickness can be reasonably estimated in the presence of ferromagnetic crud, the possibility exists to also obtain electrical conductivity estimates of sufficient accuracy to map to hydrogen content of the zirconium alloys.
Several additional technology improvements are currently being investigated:

- to assess the influence of fast neutron fluence on hydrogen content estimates,
- to better compensate for the effect of ferromagnetic crud layers,
- to provide robust and sound procedures to carry out the inspection on duplex and other types of cladding,
- to improve some manufacturing details of the probe to further increase its service life in the quite high radiation field near the test components.

Acknowledgments

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