Eddy Current Signal Analysis Techniques for Assessing Degradation of Support Plate Structures in Nuclear Steam Generators

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Abstract. The steam generator (SG) is one of the most critical components of the heat transfer system in nuclear generation stations. Testing the structural integrity of SG tubing and SG internals is a key element of the fitness-for-service assessments to assure the safe and continuous operation of nuclear power plants.

Recent eddy current (ET) inspections of two nuclear power plants revealed degradation of some of the tube support plate (TSP) structures, which was also confirmed by visual inspection. The phenomena was described as metal loss, caused by flow-accelerated corrosion of the carbon steel trefoil support plate and varying from minor to complete loss of the ligaments. This loss of TSP ligaments results in lack of support for the adjacent tubes making them more susceptible to fretting-wear damage and fatigue cracking.

A signal analysis method, based on the responses at low frequency of two types of eddy current probes, has been developed to assess the degree of degradation. The standard impedance-mode bobbin probe is used to detect and classify degradation, based on stages of partial or complete breach of ligaments. The advanced transmit-receive array X-probe is used to quantify the degree of degradation in the land regions, and to help discriminate from external magnetite and copper deposits. The complementary information obtained from each of the two probes, combined with the visual inspections, helps to assess the overall condition of the support plates. These procedures, applied to present and past ET inspections, provide the technical basis to determine the location and the progression rate of the degradation.

This paper presents the ET analysis methodology along with inspection results showing examples of eddy current signals and visual inspection images.

1. Introduction

The main function of the tube support plates (TSP) in any steam generator (SG) or heat exchanger is to restrain the tubes against lateral displacement and vibration. Degradation of the TSP can, therefore, impair their ability to support the tube and thus, it may potentially impair tube integrity. For instance, excessive lateral displacement of the tube can cause vibration-induced fretting-wear or vibration-induced fatigue of the tubes could result in tube rupture.

This paper provides a brief overview of the TSP degradation problem, describes the non-destructive testing (NDT) technology applied and the ET analysis procedures developed to detect and quantify TSP degradation, along with examples from the field, showing bobbin probe and X-probe signals compared to visual inspection images.

2. TSP Geometry

The geometry of the TSP is a "tri-lobed" shape (broach plate), which leaves three equally spaced lands to support the tube. The flow regions provide space (in the lobes) for the secondary steam and water mixture to rise through each TSP. The array of tri-lobed holes in the TSP leaves ligaments, which can vary from 2.8 mm thick to approximate 4 mm thick, depending on the specific SG design for each station. Figure 1 illustrates the geometry of the Bruce Nuclear Generating Station (NGS) SG supports.

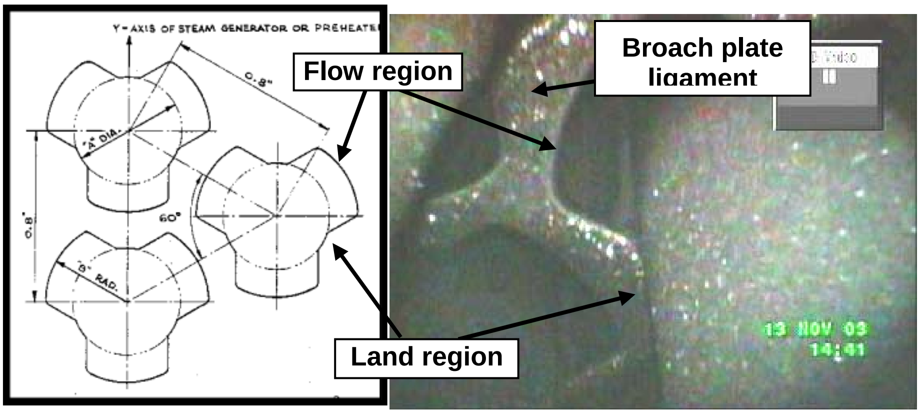


Figure 1. Schematic and an in-situ view of a normal broach plate

3. NDT Inspection Technology

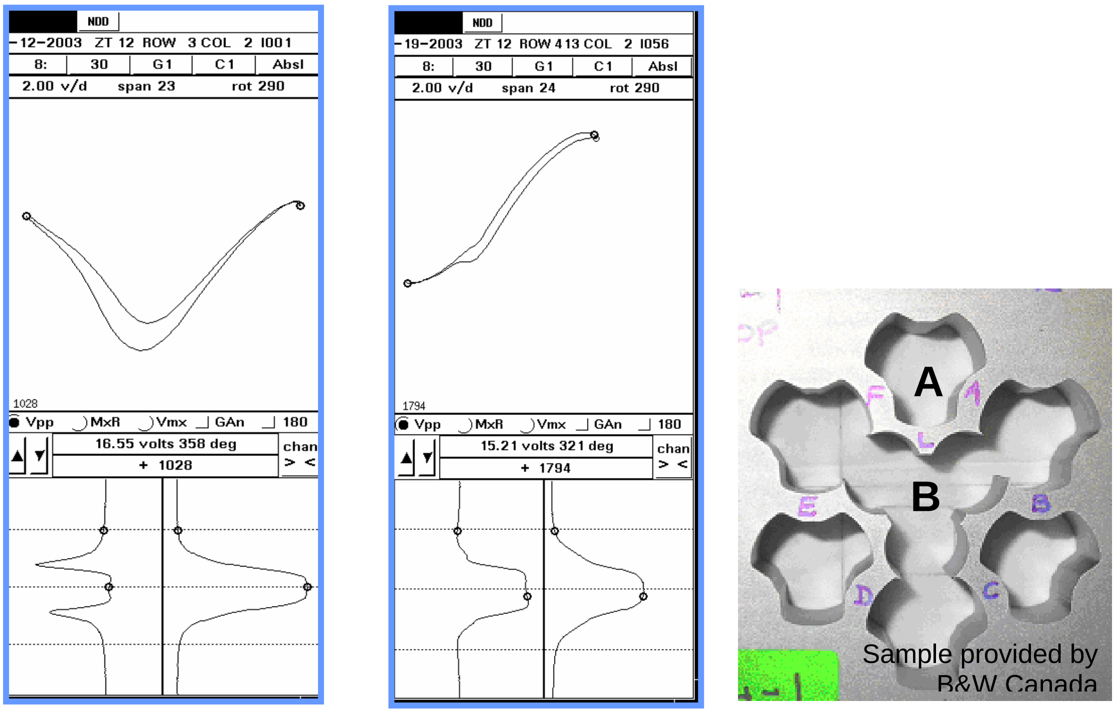
Complementary information obtained by two types of eddy current probes and the images from visual examination helps assess the integrity of the TSP. Bobbin probe data is used to assess the integrity of the TSP ligaments, whereas the X-probe data can be correlated to clearance between the tube-wall and the individual land regions of the TSP and can also help in the characterization of the overall condition of the TSP and determine the presence of external deposits. The visual inspection results provide the "hard evidence" to establish these correlations.

3.1 Bobbin Probe

Bobbin probes are the industry standard for general inspection of SG and heat exchanger tubes. They are reliable and provide repeatable results, being able to reliably detect and size volumetric flaws such as fretting wear and pitting corrosion.

The probe consists of two coils wound in the circumferential direction operating in absolute and differential modes at four test frequencies. Typically, the higher frequencies are used for flaw detection and sizing and a lower frequency, is used to perform multi-frequency mixes for detection of flaws at TSP locations, for locating the TSP and to aid in signal analysis. In this application, the low frequency signals have been used to provide information related to the integrity of TSP.

Figure 2 illustrates a typical broach plate signature obtained with a bobbin probe scanning a tube at a support plate location. The signal from a normal or "healthy" support, seen in Figure 2a which corresponds to location A in Figure 2c, is the result of the change in probe impedance caused by change in the induced eddy currents, which concentrate in the surface of the plate due to the high magnetic permeability of the carbon steel (downwards fraction of the signals) and the magnetic response to the carbon steel (upwards portion of the signal). When the degradation of the TSP has advanced to the point of causing ligament breach, as it is the case in location B in Figure 2c, the flow of eddy currents is interrupted and the signal corresponds only to the magnetic response to the carbon steel as shown in Figure 2b.



(a) (b) (c)

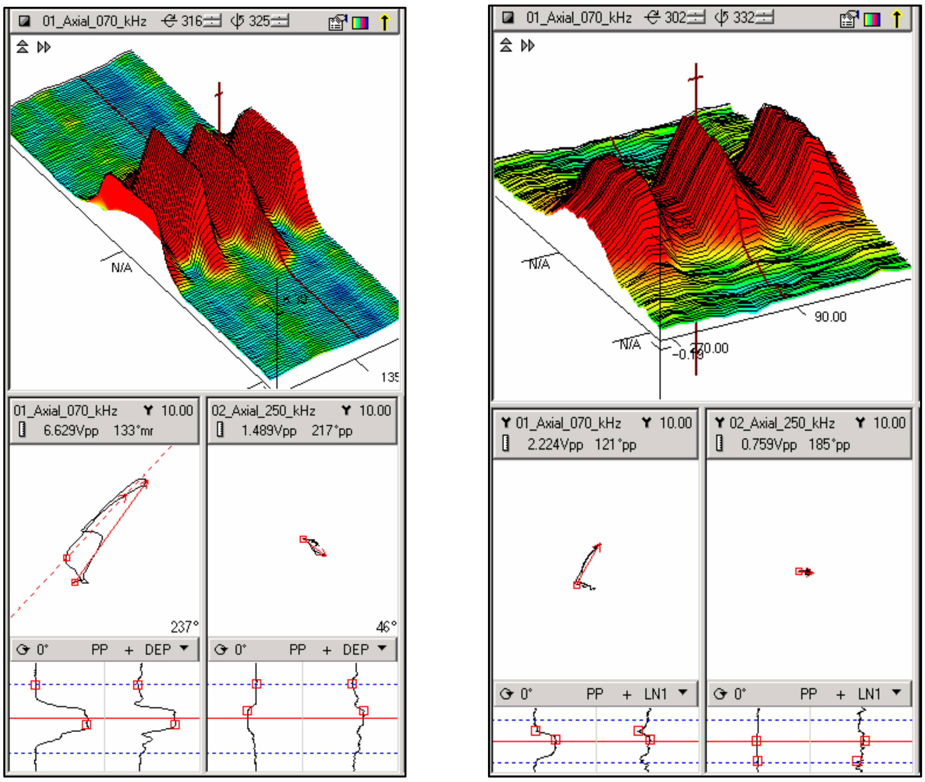
Figure 2. Laboratory simulations of broach plate bobbin probe signals. (a) Normal TSP, (b) total loss of the three ligaments, (c) photograph of laboratory sample

Incipient levels of degradation, partial ligament breach and advanced degradation with disintegration of the supports yield characteristic signals that, properly correlated, can be used to assess the condition of each support and whether it still provides tube support. These correlations will be described later in detail.

3.2 X-probe

The X-probe is a transmit/receive (T/R) array probe, with performance equivalent to rotating probes. Since all the units in the array are virtually activated simultaneously, the probe can perform single-pass, full-length inspection, at speeds comparable to that of bobbin probes. The array operates at four simultaneous frequencies and it combines circumferential and axial detection mode units in a single probe head, for detection of all modes of degradation and flaw characterization in a single scan [1]. The low frequency is typically used to perform multi-frequency mixes for locating support structures and discriminating ferromagnetic indications. In this application, the low frequency signals provide reliable information to help assess the condition of TSP.

The signals from each of the 24 axial detection mode T/R units are displayed in C-scan format, which helps infer the location and morphology of flaws or, in this case, the TSP condition [2]. As explained earlier, the eddy currents concentrate in the surface of the support and are incapable of penetrating the carbon steel TSP thickness and therefore it cannot provide an indication of its thickness. However, the X-probe low frequency response correlates well with the gap between the tube-wall and the TSP material at the broach plate land region (or increasing clearance as the TSP degrade). Figure 3 illustrates signals from a normal broach plate and from a plate with a concentric reduction of 1.7 mm. These values can, therefore, be used to generate sizing curves of signal amplitude versus land region gap as it will be explained in Section 4.3.



(a) (b)

Figure 3. X-probe responses to (a) normal broach plate and (b) broach plate with a concentric reduction of 1.7 mm

3.3 Visual Inspection

Visual inspection with small video cameras, connected to flexible fiber optics, which are inserted in between tube rows and columns, provides images of the SG internals and in particular of the TSP condition. These images are the hard evidence needed to establish correlations between the eddy current signals and the actual stage of degradation.

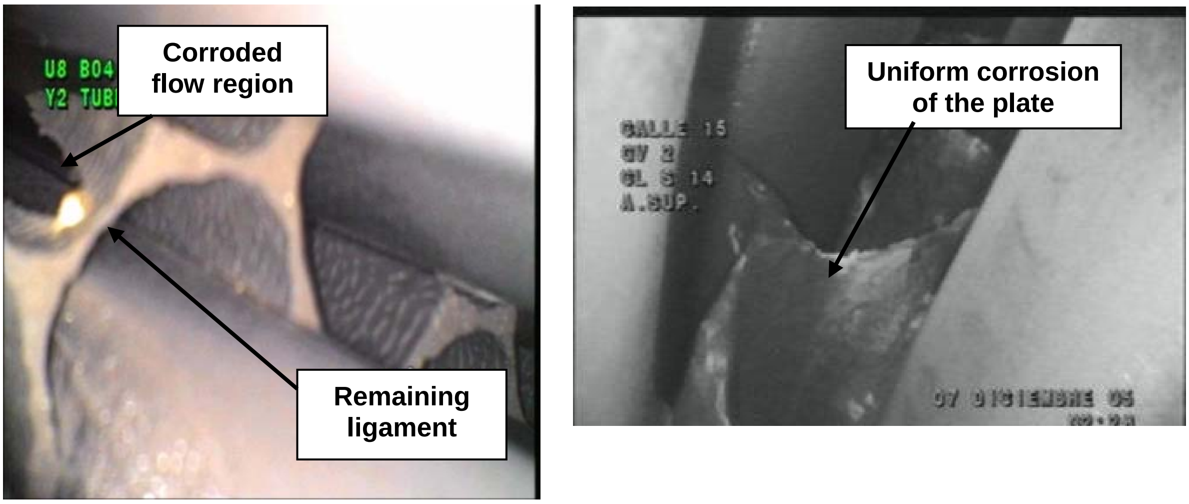
Several access ports were opened to facilitate the insertion of the visual aids at different elevations and sides of the SG. These images helped confirming the eddy current indications of TSP degradation and also the presence of magnetic deposits blocking the steam flow in the hot leg of the Embalse NSG SG.

4. Methodology to Quantify Degradation

4.1 Degradation Morphology

The degradation mechanism is described as flow accelerated corrosion, which depends on a) water chemistry, b) thermal hydraulic parameters such as temperature, steam and water velocities, steam quality and other two phase flow characteristics, c) local geometry causing changes in velocity and pressure, which can cause high local velocities, flashing and turbulence that enhances the mass transfer from the corroding surface and d) material composition [3]. These conditions are different in the two examples cited here and consequently the morphology of the degradation is also different.

The degradation of the Bruce NGS TSP starts typically in the flow region at the bottom of the support and tapers towards the top projecting into the land region, resulting in a conical shape at each land as illustrated in the picture shown in Figure 4a. In contrast, the degradation of the Embalse NSG broach plates also starts in the flow region but typically, is uniform along the plate as illustrated in Figure 4b. Because of these two distinctive morphologies, the signals generated by the bobbin probe in each case are somewhat dissimilar and therefore, different criteria are required in each case to categorize the stage of degradation.

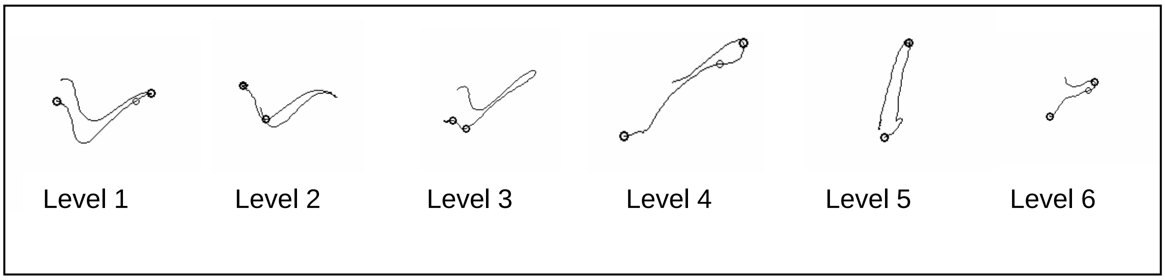


(a) (b)

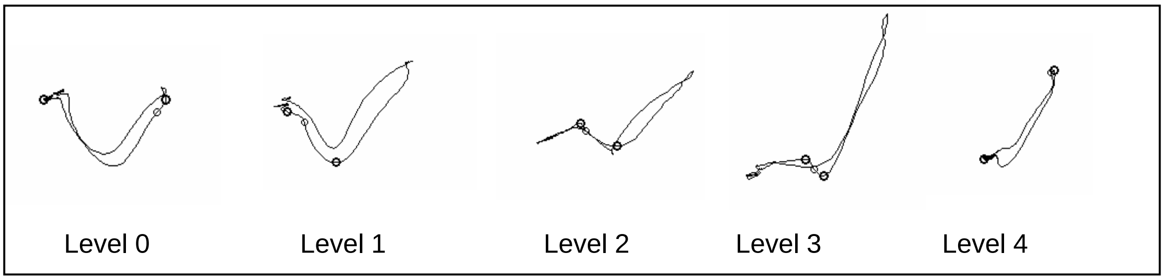
Figure 4. Visual examination images (a) Tapered corrosion in Bruce SG, (b) Uniform corrosion in Embalse SG

4.2 Assessment of Degradation Progression with Bobbin Probe

TSP with early stages of ligament degradation produce small distortions in the bobbin probe signals. The downward portion of the lissajous signal shown in Figure 2a decreases gradually and the signal rotates counterclockwise. Once the ligament breaches, the eddy currents do not have a return path and therefore the signal only comprises an upward portion as shown in Figure 2b. These gradual changes in the eddy current signals, correlated to the different stages of degradation, allow a classification into 6 categories or degradation levels using signal amplitude-based criteria. Figure 5 shows examples of field signals in these categories from (a) Bruce SG and (b) Embalse SG. The first two levels correspond to distorted broach plate signals (DBP) with no breach of the ligaments. The peak-to peak voltage (Vpp) of the signal, the phase angle and the vertical voltage (Vmx) of the initial downward portion of the signal are monitored. This vertical component, Vmx, decreases as the ligament deteriorates and when it reaches a 0.5 volts threshold, it is usually a good indication that the ligament is either partially or totally broken. Once the degradation has reached this point, the Vpp and the phase angle of the signal are monitored to determine the different degradation levels. Further reduction of Vpp, i.e.: less than 5 volts for Bruce and 3 volts for Embalse, is indicative of advanced deterioration of the TSP, to its virtual disintegration. The images in Figure 6 illustrate the levels of degradation from level 1 to level 4.



(a)



(b)

Figure 5. Degradation progression based of bobbin probe signals from (a) Bruce SG and (b) Embalse SG

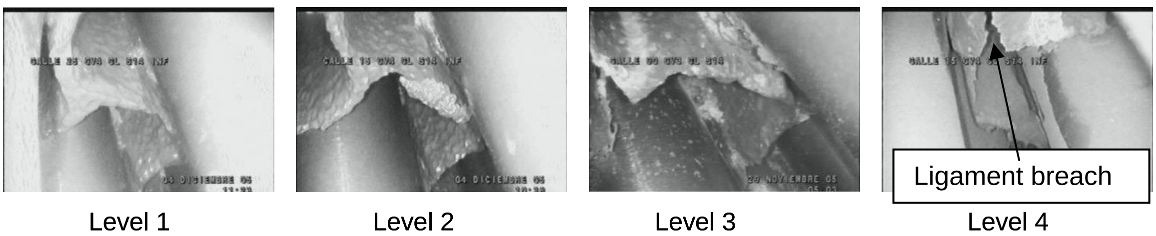


Figure 6. Degradation progression based of visual examination from Embalse SG

4.3 Assessment of Degradation Progression with X-Probe

While the bobbin probe data provides information about the overall degradation of the supports and the condition of the ligaments, the X-probe data provides a tool to assess the amount of tube-support provided by the remaining lands at each location. The signal amplitude from each land decreases rapidly as the land deteriorates. A 1 mm gap between the tube wall and the land area is almost ½ of the probe response from a non-degraded land; probe response from a 2 mm gap is approximately ¼ of the signal from a non-degraded land. Therefore, the normalized probe response from the land region, Vpp, is plotted to produce sizing curves that are used to measure the clearance between each land and the tube-wall as illustrated in Figure 7 [4].

The signals from the carbon steel ring in the calibration tube are normalized to 10 volts peak-to-peak and hence, the average response from a non-degraded TSP is nearly this value. Theoretically, the minimum value in this curve corresponds to a completely degraded land region, or the TSP ligament thickness, and therefore, any lower values are hypothetical. Since the broach plate geometry in each of the two cases is different, these values are also different. A completely degraded TSP in the Embalse case corresponds to a 2.8 mm gap whereas, in the Bruce case, the gap is 4 mm. If the tube is centred relative to the original location inside a degraded broach plate, the signals from a completely degraded land region should be zero (broken ligament). However, due to eccentricity inside the broach plate this value can be larger and therefore, extrapolated values have been added to quantify these cases [3].

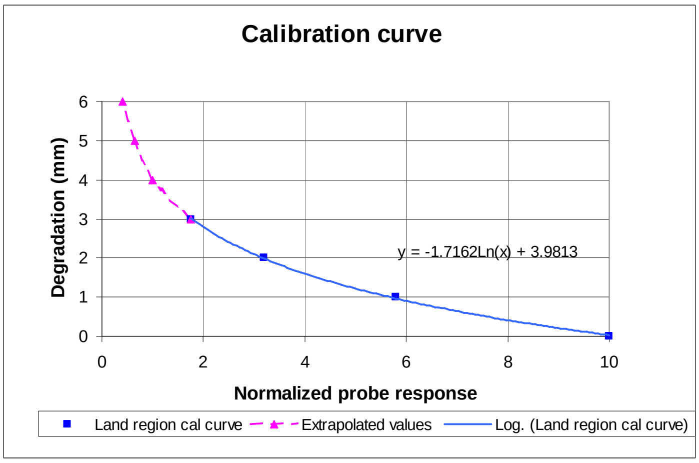


Figure 7. Sizing curve of land degradation vs. normalized probe response

5. Field Examples

The results from the field shown in Figure 8 illustrate the excellent correlation and complementary information obtained from the NDT techniques. In this example, we show the bobbin probe signals from a broach plate typical of ligament breach (level 4), while the X-probe and the photograph show large deterioration of two land regions. In fact, the signals with both probes and the photograph confirm that one portion of the broach plate has actually fallen down and it is sitting on top of the next broach plate.

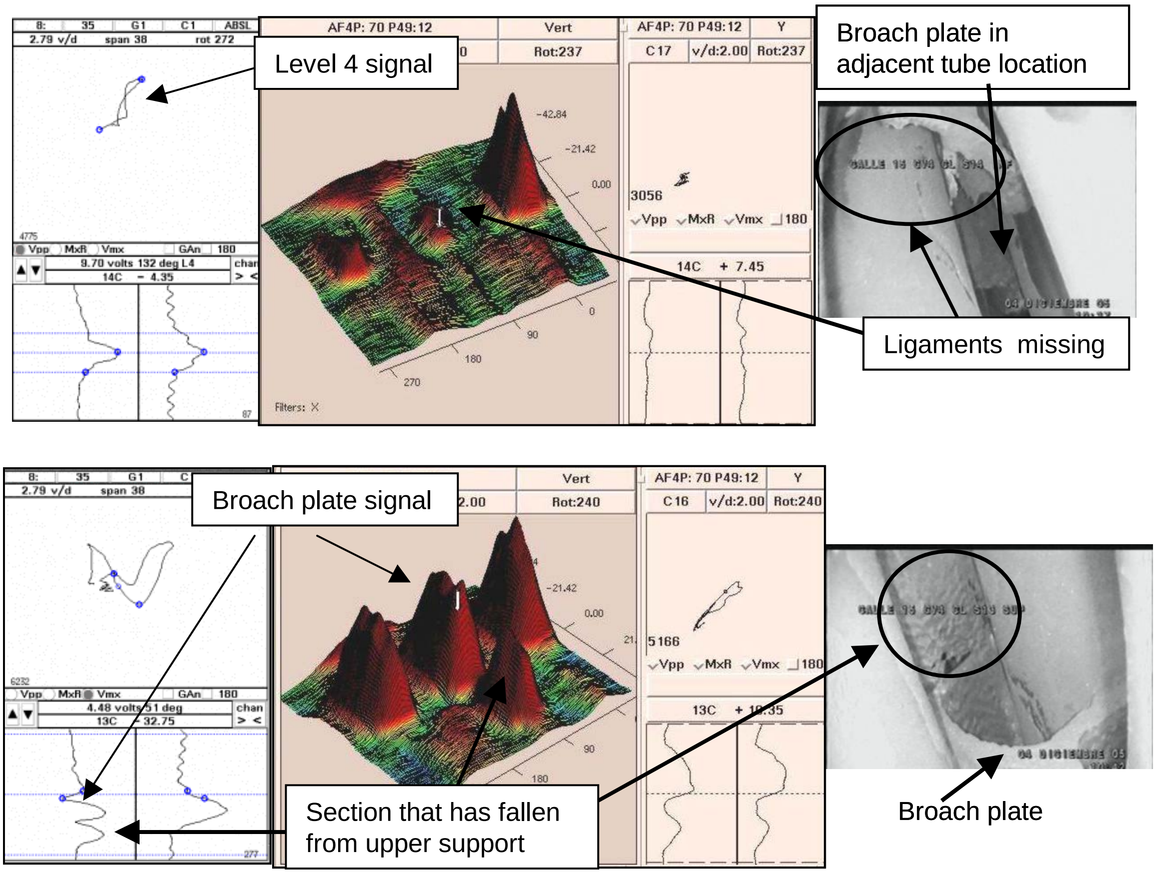


Figure 8. Eddy current signals and visual inspection images from a tube location where the upper TSP has total ligament breach. The images and signals shown in the upper figures indicate that part of the ligaments are missing, which have fallen down on top of the next broach plate as shown in the bottom figures.

6. Conclusions

A method for signal analysis to assess the degree of degradation of carbon steel TSP has been developed. It is based on the responses at low frequency from two types of eddy current probes. The standard impedance-mode bobbin probe is used to detect and classify degradation, based on stages of partial or complete breach of ligaments. The advanced transmit-receive array X-probe is used to quantify the degree of degradation in the land regions, and to help discriminate from external magnetite and copper deposits. The complementary information obtained from each of the two probes, combined with the visual inspections, helps to assess the overall condition of the TSP.

These procedures can be applied to present and past ET inspections and therefore provide the technical basis to determine the location and the progression rate of the degradation.

These techniques can also be applicable to assess structural integrity of other SG or heat exchanger internals.

7. References

[1] L. Obrutsky, N. Watson, C. Fogal, M. Cantin, V. Cecco, R. Lakhan and S. Sullivan, "Fast Single-Pass Eddy Current Array Probe For Steam Generator Inspection", Proceedings of the 4th CNS International Steam Generator Conference, Toronto, 2002.

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