EDDY CURRENT ASSESSMENT OF SUPPORT PLATE STRUCTURES DEGRADATION IN NUCLEAR STEAM GENERATORS

Laura Obrutsky, Robert Cassidy,
Atomic Energy of Canada Ltd.
Miguel Cazal,
Nucleoeléctrica Argentina Sociedad Anónima
Ken Sedman,
Bruce Power

Testing the structural integrity of steam generator (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 testing (ET) inspections of CANDU® nuclear power plants revealed degradation of some of the carbon steel tube support plate (TSP) structures, which was also confirmed by visual inspection. The phenomenon was described as metal loss, caused by flow-accelerated corrosion of the carbon steel trefoil support plate, generating degradation ranging from minor up to complete loss of the ligaments. This loss of TSP ligaments results in lack of support for adjacent tubes, making them more susceptible to fretting-wear damage and fatigue cracking.

A method for signal analysis, based on the responses at low frequency of two types of ET 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, in addition to helping discriminate degradation from external magnetite and copper deposits. The complementary information obtained from each of the two probes, combined with visual inspections, helps to assess the overall condition of the TSP. These procedures, applied to present and past ET inspections, provide the technical basis to determine the location and progression rate of degradation.

This paper presents the ET analysis methodology along with inspection results showing examples of degradation distribution and progression based on ET signals and visual inspection images.

CANDU® CANada Deuterium Uranium is a registered trademark of Atomic Energy of Canada Limited (AECL).

1. INTRODUCTION

The primary objective of steam generator (SG) tube inspections, driven by regulator and economical requirements, is to ensure that tube integrity will not be compromised during the next operating interval. Typically, this is achieved by utilizing inspection technology and establishing inspection procedures aimed at detecting flaws at their earliest manifestation and to quantify them as accurately as feasible. Eddy current testing (ET) probes have been widely used as the primary inspection method for detection and sizing of the different modes of degradation found in SG tubes. Bobbin probes are used for general inspection whereas more advanced probes, such as the Plus-Point probe and the X-probe, are used for detection of cracking and for characterization of these degradation modes.

In addition to flaw detection, the ET data contain other valuable information about the condition of the tubes and the SG internals, which can be essential for fitness-for-service and plant life management assessments. For instance, the thickness of internal and external magnetite deposits can be quantified by establishing correlations between the ET signals and the density of these deposits. Also, data analysts use tube support plate (TSP) signals to help locate flaw indications, but during recent inspections of Bruce nuclear generating station (NGS) Unit 8 and Embalse NGS SGs, the ET data analysts reported distorted signals from the carbon steel broach plates. The ET experts deemed these distorted signals as indicative of TSP degradation and visual inspections confirmed the ET findings.

This paper provides a brief overview of the TSP degradation problem, and describes the non-destructive testing (NDT) technology applied to detect and quantify TSP degradation, along with examples from the field, showing eddy current 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, 2.8 mm thick in Embalse SG and approximately 3.5 mm thick, in Bruce B SG. Figure 1 illustrates the geometry of the Bruce NGS supports.

The main function of the TSP 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 put tube integrity at risk. For instance, excessive lateral displacement can cause vibration-induced fretting-wear or vibration-induced fatigue of the tubes could result in tube-rupture.

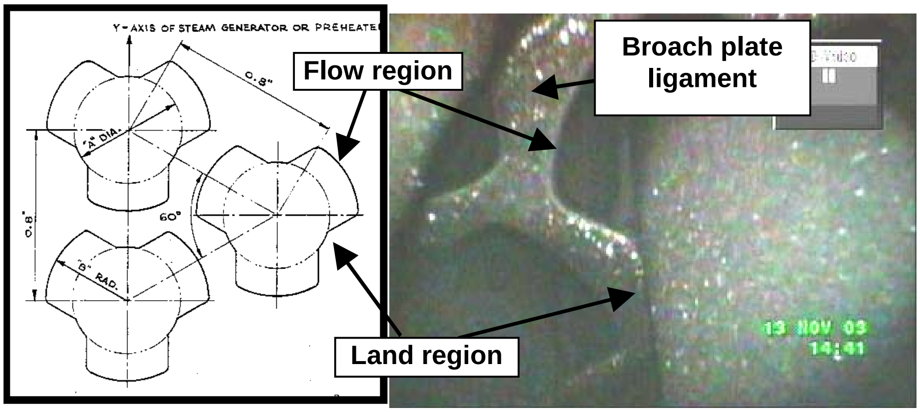


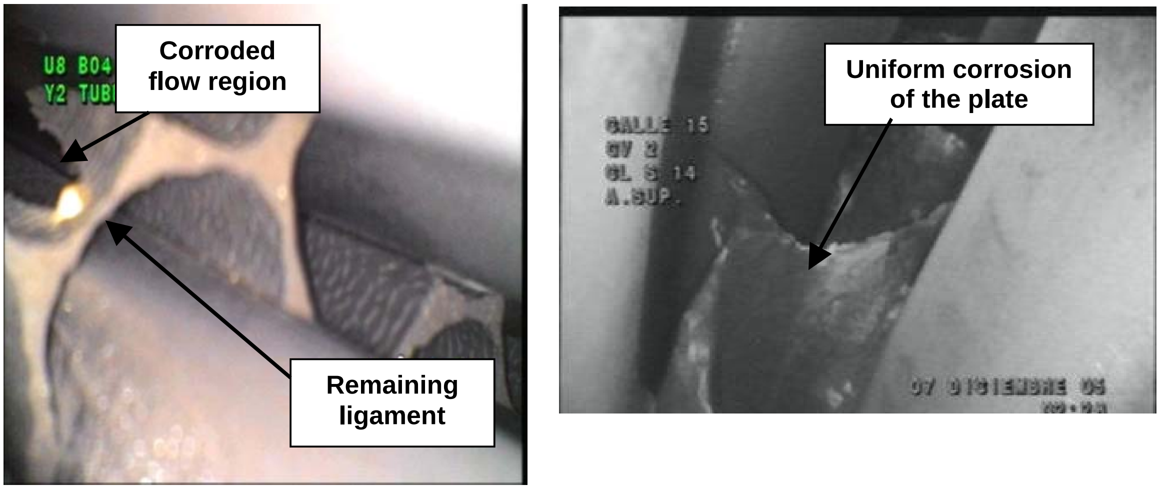
Figure 1: Schematic and an in-situ view of a Bruce B normal broach plate.

3. DEGRADATION MECHANISM

The degradation mechanism was 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 generate high local velocities, flashing and turbulence that enhances the mass transfer from the corroding surface and d) material composition [1].

The root causes for Bruce NGS and Embalse NGS support plate degradation phenomena are different and have been the subject of separate studies. In this paper, we analyze it from an inspection prospective, which takes into account the shape of the degradation in order to establish correlations between the ET signals and the amount of TSP damage that will allow its quantification.

Bruce degradation, primarily found in the hot leg 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 2a. In contrast, the degradation of the Embalse NSG broach plates is found in the cold leg TSP. It also starts in the flow region but typically, is uniform along the plate and it is more pronounced in the flow region, as illustrated in Figure 2b. Because of these two distinctive morphologies, the signals generated by the bobbin probe in each case are somewhat dissimilar and therefore, different criteria were required in each case to categorize the stage of degradation.



(a) (b)

Figure 2: Visual examination images (a) Tapered corrosion in Bruce SG, (b) Uniform corrosion in Embalse SG.

4. NDT INSPECTION TECHNOLOGY

The information obtained by two types of eddy current probes was complemented by the images from visual examination to assess the integrity of the TSP ligaments and to establish voltage criteria to quantify the degradation. Bobbin probe data was used to assess the degree of ligaments loss, whereas the X-probe data, correlated to clearance between the tube-wall and the individual land regions of the TSP, helped in the characterization of the overall condition of the TSP. The visual inspection results provided the “hard evidence” to establish these correlations.

In addition, the ET data provided information about the presence of external magnetite deposits, in particular, at the hot leg TSPs in Embalse SG, which appeared to have caused partial or total blockage of some of the broach holes. This information was of significant importance in the determination of the root cause.

4.1 Visual Inspection

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

4.2 Bobbin Probe

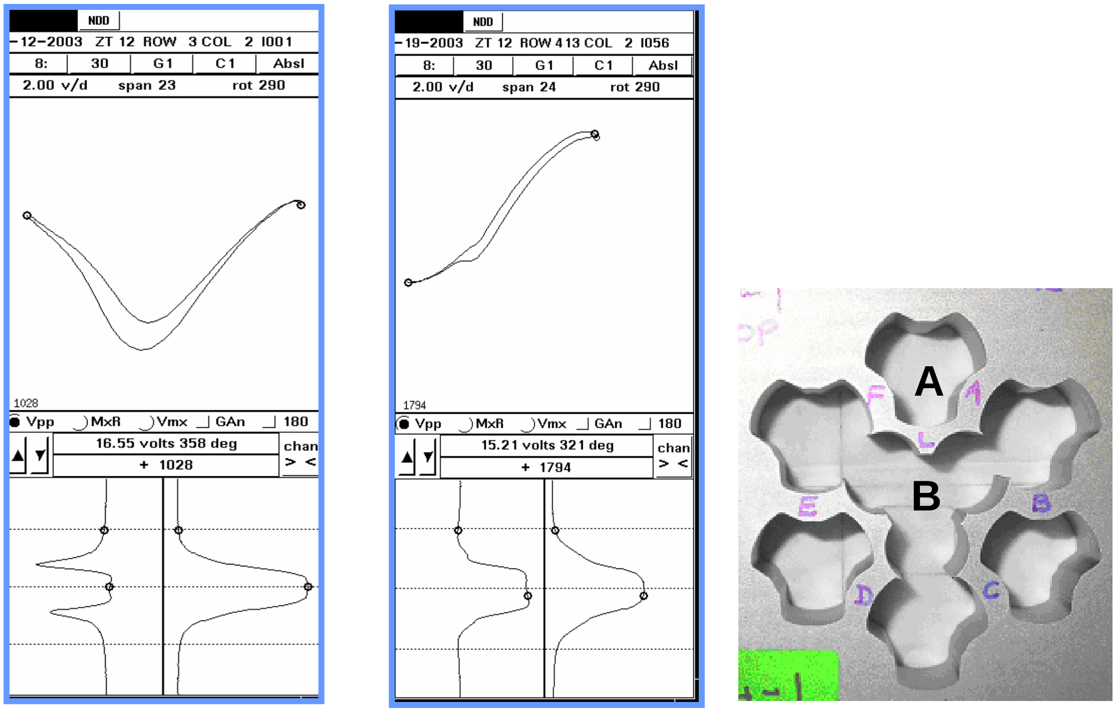
Bobbin probes are the industry standard for general inspection of SG tubes. They are reliable and provide repeatable results, being able to reliably detect and size volumetric flaws such as fretting wear and pitting corrosion.

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 were used to provide information related to the integrity of TSP.

Figure 3 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 3a which corresponds to location A in Figure 3c, has two parts: the downwards fraction of the signal is the result of the induced eddy currents as it approaches the TSP location, and the upwards portion of the signal which corresponds to the magnetic response to the carbon steel. 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 3c, the flow of eddy currents is interrupted and the signal corresponds only to the magnetic response to the carbon steel as shown in Figure 3b [2].

It is important to mention that the eddy currents concentrate in the surface of the plate due to the high value of the carbon steel magnetic permeability and therefore the thickness of the ligament cannot be measured directly. Nevertheless, 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.

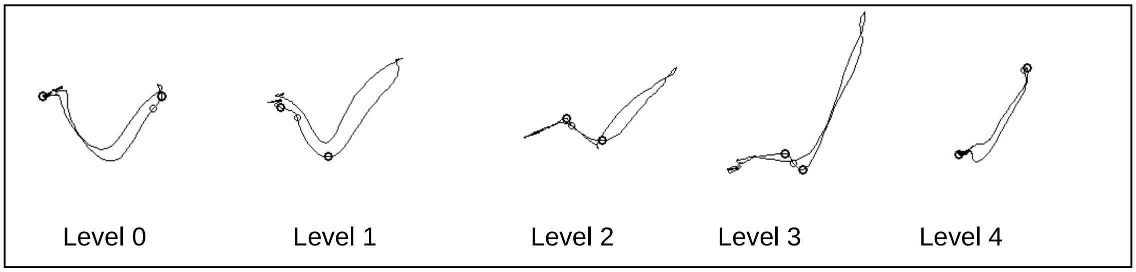
TSPs with early stages of ligament degradation produce small distortions in the bobbin probe signals. The downward portion of the Lissajous signal shown in Figure 3a decreases gradually and the signal rotates counterclockwise. Once the ligament breaches, the eddy currents do not have a return path and therefore the signal only comprises an upward portion as shown in Figure 3b.



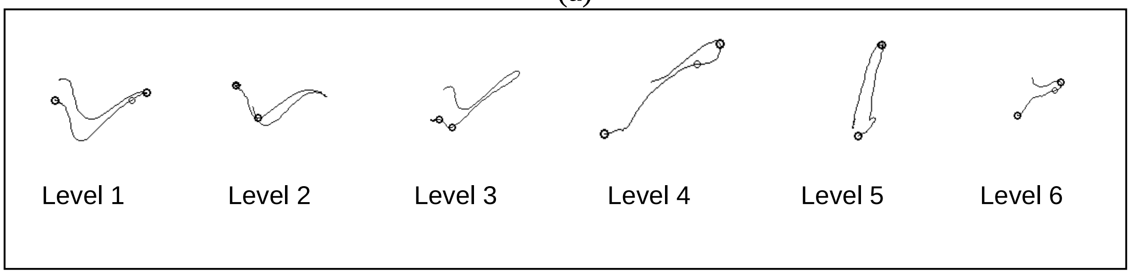
(a) (b) (c)

Figure 3: Laboratory simulations of broach plate bobbin probe signals. (a) Normal TSP, (b) total loss of the three ligaments, (c) photograph of laboratory sample.

These changes in the eddy current signals, correlated to the different stages of degradation, allow a classification into various categories or degradation levels using signal amplitude-based criteria. The first two levels correspond to early stages of ligament loss and correspond to distorted broach plate signals (DBP) with no breach of the ligaments as the signal still shows a large downward portion. The peak-to peak voltage of the signal, the phase angle and the vertical voltage of the initial downward portion of the signal are monitored. This downward vertical component decreases as the ligament deteriorates and when it reaches a voltage threshold, it is usually a good indication that the ligament is either partially or totally broken and the tube lacks support. Once the degradation has reached this point, the voltage and the phase angle of this mostly upward signal are monitored to determine the different degradation levels. Since the morphology of the degraded support is different at both stations, the voltage criteria are also different. Figure 4 shows examples of field signals from (a) Bruce SG and (b) Embalse SG and the pictures in Figure 5 illustrate the levels of degradation from level 1 to level 4. These images were instrumental in developing the Embalse voltage criteria.

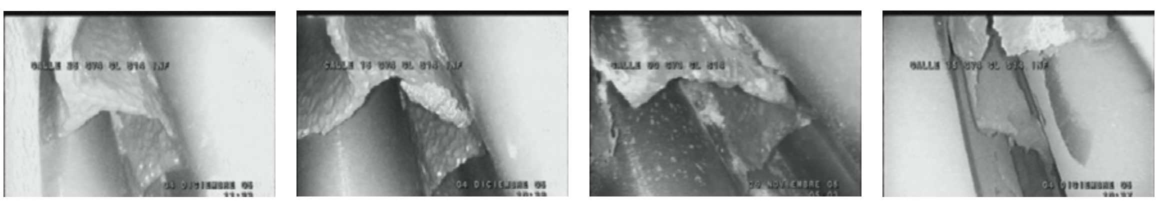


(a)



(b)

Figure 4: Degradation progression based of bobbin probe signals from (a) Bruce SG and (b) Embalse SG.



Level 1 Level 2 Level 3 Level 4

Figure 5: Degradation progression based of visual examination from Embalse SG. The Level 4 corresponds to a TSP with ligament breach.

Figure 6 illustrates a tubesheet map with the detailed distribution of the TSP degradation based on bobbin probe data that had been classified as per these criteria. This information was essential for the fitness-for-service assessment of the SG.

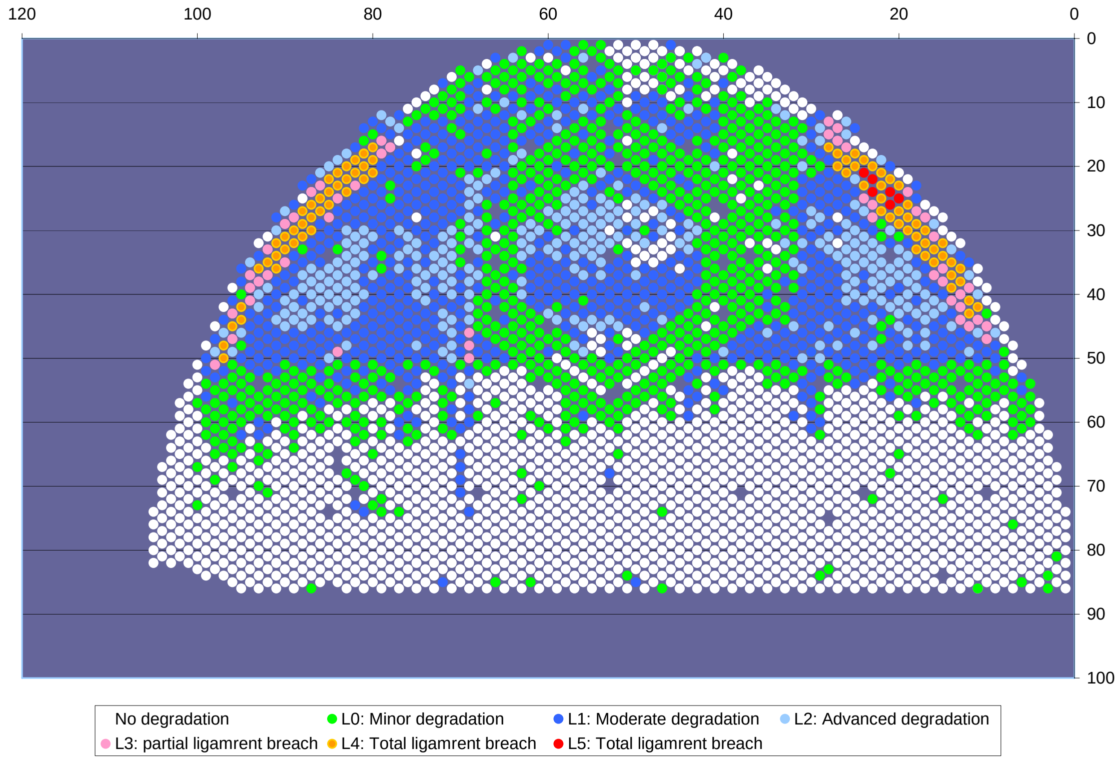
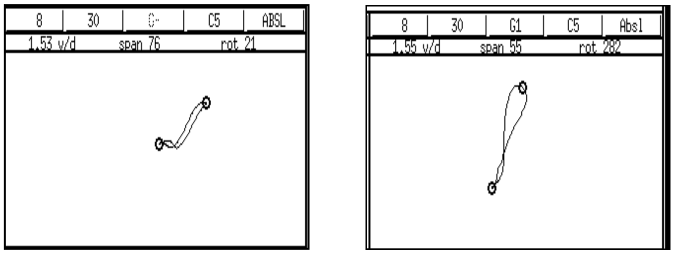


Figure 6: Tubesheet map showing tube-by-tube assessment of the TSP degradation based on the analysis of bobbin probe data classified as per the 6-level voltage criteria.

These criteria can be applied also to compare the data from present and past ET inspections and thus help assessing the progression rate of the degradation. In the example shown in Figure 7 the signals from the 1993 and 2001 Bruce NGS inspections are compared. This data indicates the presence of significant degradation in the first few years of operation and the evolution from a Level 3 or a partial ligament breach indication to a Level 5 or total ligament breach with some loss of support plate material.



1993 signal **2001 signal**

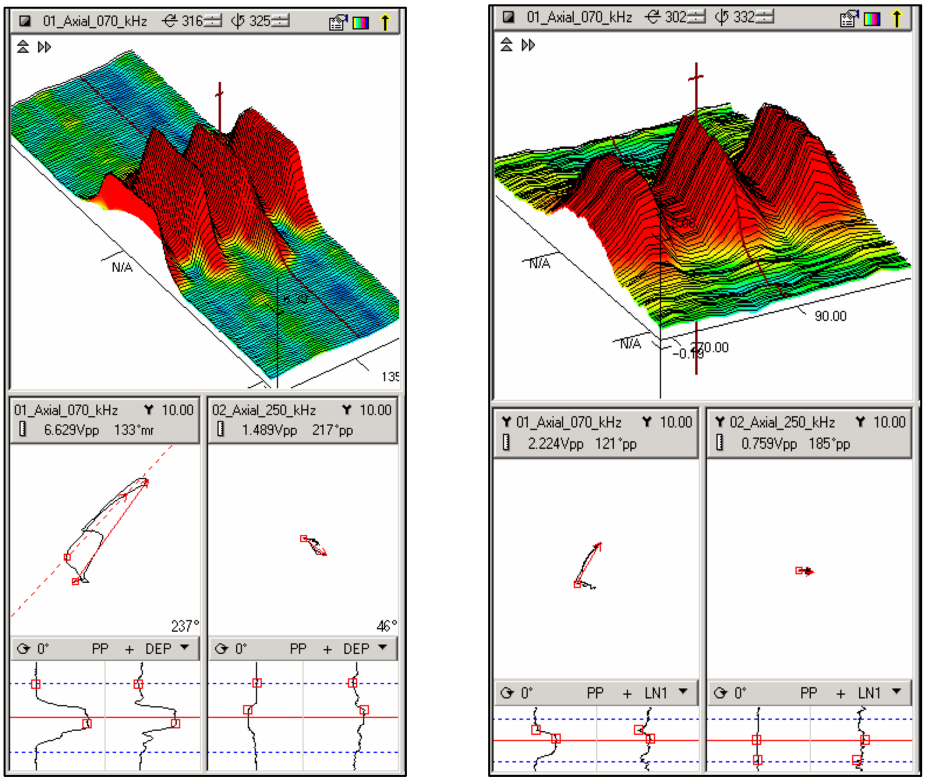
Figure 7: Degradation progression between 1993 and 2001 inspections.

4.3 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 [3]. The low frequency is typically used within multi-frequency mixes, for locating support structures and discriminating ferromagnetic indications. In this case, the low frequency signals provided 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 the analyst to infer the location and morphology of the TSP condition [4] as well as to detect the presence of magnetite deposits. 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 degrades). These values can, therefore, be used to generate sizing curves of signal amplitude versus land region gap. Figure 8 illustrates signals from a normal broach plate and a plate with a concentric reduction of 1.7 mm.

The signal amplitude from each land decreases rapidly as the land deteriorates. A 1 mm gap between the tube wall and the land area produces a response that 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 can be plotted to produce sizing curves to measure the clearance between each land and the tube-wall [2]. While the bobbin probe data provides information about the overall degradation of the supports and the condition of the ligaments, the X-probe data can provide a tool to assess the amount of tube support provided by the remaining lands at each location.



(a) (b)

Figure 8: X-probe responses to (a) normal broach plate and (b) broach plate with a concentric reduction of 1.7 mm.

This technique has, however, some limitations since the tubes are not always centred in the remaining broach plate and therefore quantification of the land region requires more detailed analysis of the signals. Another approach is to express these measurements in terms of TSP clearance by combining the information from the three lands.

5. FIELD EXAMPLES

The results from the field shown in Figure 9 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.

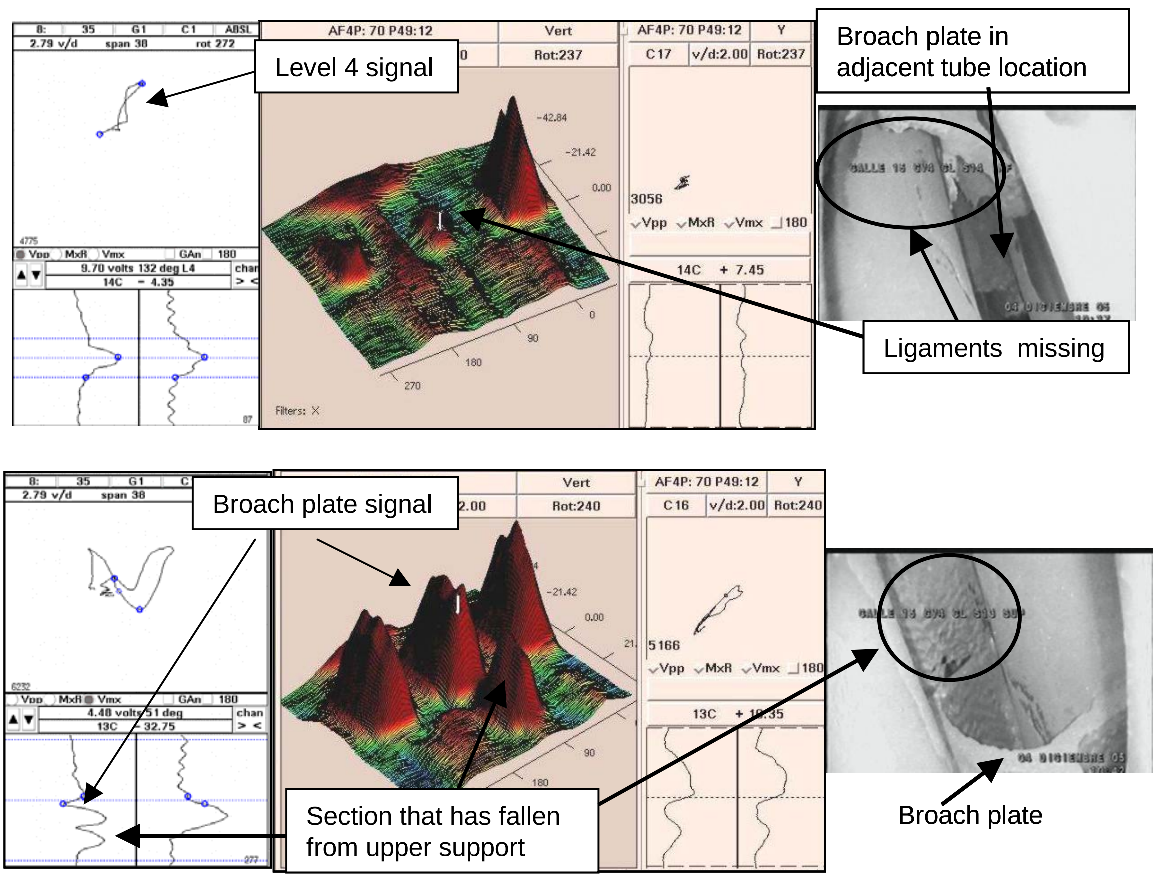


Figure 9: Eddy current signals and visual inspection images from a tube location where the upper TSP has total ligament breach. The images and signals shown in the upper

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

Eddy current data can be used to quantify the degree of degradation of carbon steel TSPs. The responses from two types of eddy current probes provide complementary information, which combined with the visual inspection images, helps in assessing the overall condition of the TSP. In addition, the ET data can provide information regarding fouling of the secondary side.

Furthermore, this technology can be applied to compare the data from present and past ET inspections and thus help assessing the rate of the degradation.

7. REFERENCES

[1] K.G. Sedman, G.E. Galan and B. Dicks, "Boiler Tube Support Plate Degradation in Bruce Unit 8", Proceedings of the 7th CNS International Conference on CANDU Maintenance, Toronto, 2005 November.

[2] L. Obrutsky, N. Valliere and I. Vela, "Inspection Techniques for Detecting Degraded Support Plates in Bruce B Steam Generators with Bobbin Probe and X-probe", 23rd EPRI Steam Generator NDE Workshop, Chicago, Illinois, 2004 July 11-14.

[3} 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.

[4] L. Obrutsky, B. Lepine, J. Lu, R. Cassidy and J. Carter, "Eddy Current Technology for Heat Exchanger and Steam Generator Tube Inspection", Proceedings of the 16th World Conference in Nondestructive Testing, Montreal, Canada, 2004 August 30 - September 3.