EDDY CURRENT TECHNOLOGY FOR HEAT EXCHANGER AND STEAM GENERATOR TUBE INSPECTION

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Abstract: A variety of degradation modes can affect the integrity of both heat exchanger (HX) and balance of plant tubing, resulting in expensive repairs, tube plugging or replacement of tube bundles. One key component for ensuring tube integrity is inspection and monitoring for detection and characterization of the degradation. In-service inspection of HX and balance of plant tubing is usually carried out using eddy current (EC) bobbin coils, which are adequate for the detection of volumetric degradations. However, detection and quantification of additional modes of degradation such as pitting, intergranular attack (IGA), axial cracking and circumferential cracking require specialized probes. The need for timely, reliable detection and characterization of these modes of degradation is especially critical in Nuclear Generating Stations.

Transmit-receive single-pass array probes, developed by AECL, offer high defect detectability in conjunction with fast and reliable inspection capabilities. They have strong directional properties, permitting probe optimization for circumferential or axial crack detection. Compared to impedance probes, they offer improved performance in the presence of variable lift-off. This EC technology can help resolve critical detection issues at susceptible areas, such as the rolled-joint transitions at the tubesheet, U-bends and tube-support intersections.

This paper provides an overview of the operating principles and the capabilities of advanced ET inspection technology available for HX tube inspection. Examples of recent application of this technology in Nuclear Generating Stations (NGSs) are discussed.

Introduction: Degradation of SG tubing in NGSs due to both mechanical and corrosion modes has resulted in extensive repairs to and replacement of SGs around the world. The variety of degradation modes challenges the integrity of SG tubing and therefore station reliability and cost effectiveness. One of the key components of fitness-for-service assessments is inspection and monitoring aimed at timely detection and characterization of the degradation. Up to the early 70s, the in-service inspection of pressurized water reactor (PWR) SGs was carried out using single-frequency eddy current (ET) bobbin coils that were adequate for detection of volumetric degradations. By the mid-80s, additional modes of degradation such as pitting at transition regions, inter-granular attack (IGA), axial and circumferential outside diameter (OD) stress corrosion cracking (SCC), and primary water (PW) SCC had to be addressed.

In the last two decades, Atomic Energy of Canada Limited (AECL) has addressed the specific inspection needs of CANDU® SGs and HXs by developing ET probe technology to help in resolving critical detection issues at susceptible areas such as the rolled-joint transitions at the tubesheet, U-bends and tube-support intersections. Thus, tube inspection capabilities have evolved from single-frequency eddy current bobbin probes for detection of volumetric flaws to a full selection of advanced transmit-receive array probes and improved inspection techniques to address specific inspection issues. Transmit-receive (T/R) single-pass array probes offer high defect detectability in conjunction with fast and reliable inspection capabilities. They have strong directional properties, permitting probe optimization for circumferential or axial crack detection and improved performance in the presence of variable lift-off compared to impedance probes. In addition, the array feature combined with C-scan display of data provides flaw imaging that can help characterize degradation modes and define flaw morphology. This ET technology, although initially developed to help resolve critical detection issues in NGS, can be deployed for fast, reliable and cost effective inspection of balance of plant and non-nuclear tubing applications. They can significantly decrease the need for re-inspection, tube replacement and forced outages.

This paper provides an overview of the operating principles and the capabilities of advanced ET inspection technology available for SG and HX tube inspection. Examples of current applications in NGS are discussed.

Background Information: Bobbin probes have been the industry standard for general inspection of steam generator and heat exchanger tubes for many years. They are quite reliable and provide repeatable results, being able to reliably detect and size volumetric flaws such as fretting wear and pitting corrosion.

However, they are ineffective in detecting circumferentially oriented cracks because the induced current in the tube wall circulates parallel to the coil windings and is inherently unaffected by the presence of such cracks. These probes are sensitive to axial cracks at straight tube sections; however, at defect-prone areas such as top of tubesheet (TTS) and U-bend transition, the large signals generated by geometrical tube-wall distortions significantly reduce detectability [1, 2].

To address crack detection, the industry relies on surface-riding rotating probes that can detect both axial and circumferential cracks. This is a very time consuming and costly process. Axial scanning speed is about 200 times slower that of bobbin or array probes. These surface-riding probes are usually spring loaded to minimize lift-off, which makes them prone to failure. This is especially evident in situations where the presence of internal tube deposits can reduce probe life significantly.

Transmit/Receive (T/R) array probes designed by AECL to address specific inspection needs have been used successfully since 1991 to inspect CANDU SGs. These probes take advantage of the superior properties of T/R technology compared to impedance probe technology. They have a five to ten-fold improvement in signal-to-noise ratio in the presence of lift-off caused by geometrical tube distortion such as U-bend deformations or tubesheet transition [3, 4] as illustrated in Figure 1 using computer simulations of small defect signals in the presence of lift-off. The T/R probe's relative "insensitivity to lift-off" is explained as follows: Signals generated by localized defects between the transmit and receive coils have an amplitude similar to that for a similarly sized impedance pancake coil probe. However, the flux linkage between the transmit and receive coils is less than 10%. Therefore, probe responses to global effects such as change in coil lift-off or sleeve-to-parent tube gap are only 10% of those of a similar-sized impedance coil. This insensitivity to lift-off makes it unnecessary to have moving parts, unlike spring loaded impedance probes, increasing probe reliability.

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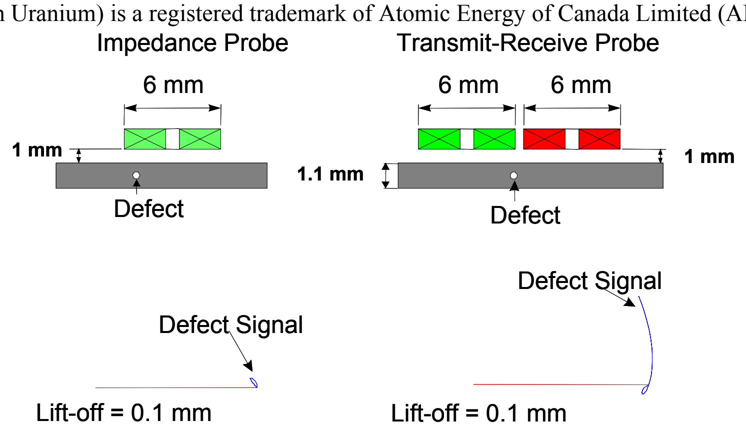


Figure 1: Comparison of signal-to noise ratio for an impedance probe versus a T/R probe

Since T/R probes have directional properties, being sensitive primarily to defects in-line with the T/R coil pairs, the probe design can be optimized to maximize response for different crack orientations [3, 4]. The area of sensitivity of a T/R unit is illustrated by the computer simulation results shown in Figure 2. The probe maximum response corresponds to variations in the induced magnetic field in the region between the transmit and receive coils. Thus, a probe with circumferentially oriented coils provides maximum sensitivity to circumferentially oriented flaws whilst probe sensitivity decreases with diverting flaw orientation. Figure 3 shows the effect of flaw orientation on detection capabilities illustrating the T/R probe directional properties. In this example, a tube sample containing 10 mm long electro-discharge machined (EDM) notches at various angles in 15° increments was scanned with a probe comprising one set of coils optimized for circumferential crack detection and another for axial crack detection.

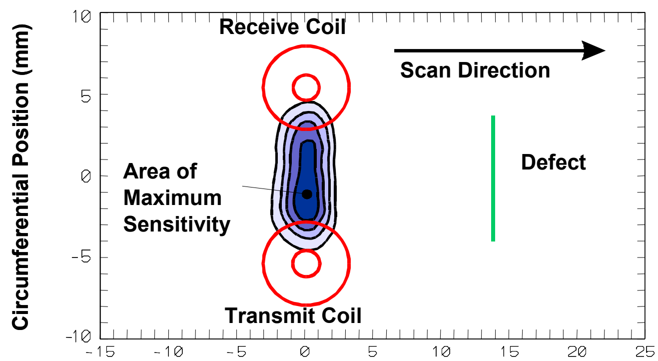


Figure 2: Computer simulation illustrating areas of sensitivity and directional properties of T/R probes

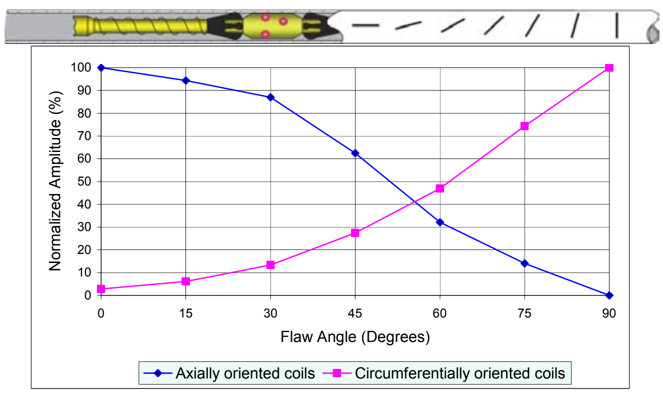


Figure 3: Effect of flaw angle on T/R coil detection capabilities

Array probe technology for tube inspection: Single-pass T/R array probes have been successful in addressing specific inspection needs in CANDU SG. The probe illustrated in Figure 4a, denoted as C3, was designed to be primarily sensitive to circumferential cracks. It proved effective in detecting cracks as shallow as 40% through-wall at deformed U-bend transitions and TTS in Bruce NGS. The C4 probe, illustrated in Figure 4b for axial crack detection was deployed for inspection of Pickering NGS SG tubing. Both probes can be used for detecting flaws with no directional properties such as pits or fretting wear. The C5 probe, comprising coil units oriented at 45° to have similar detection capabilities for circumferential and axial cracks, is being used at Darlington NGS and Gentilly II NGS, but does not possess the capability to discriminate between the two orientations.

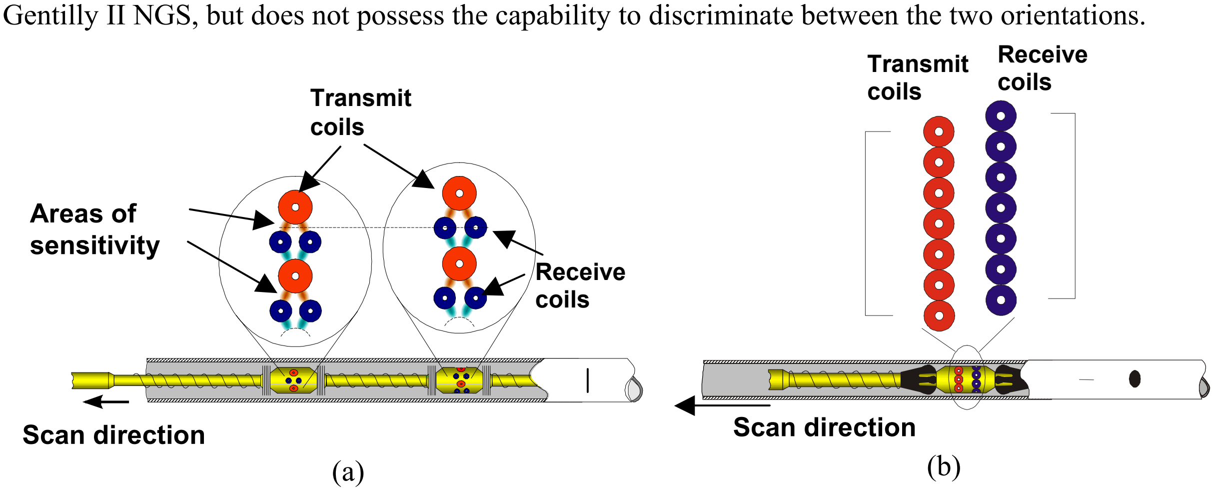


Figure 4: (a) C3 probe for circumferential crack detection showing coil configuration and areas of sensitivity. (b) C4 probe for axial crack detection showing coil configuration.

The new generation eddy current probe, developed in collaboration with R/D Tech and denoted as the X-probe, is a fast single-pass T/R array probe that combines circumferential and axial modes of detection units in a single probe head. This is made feasible by including microelectronics at the probe end. It is coupled with new and versatile instruments operated by fast computers, showing performance equivalent to rotating probes for full-length inspection. As such, this probe is capable of discriminating between axial, circumferential and volumetric flaws in a single scan. It significantly decreases the need for re-inspection and tube sampling [5].

The microelectronics permit the use of more coils while simplifying cable requirements. Figure 5 shows a schematic of the probe coil arrangement. The number of T/R units can vary from 8 to 18 coils depending on tube diameter, with the T/R coil spacing as the limiting factor. Two axial mode units and one circumferential unit are generated per operational unit. This results in twice as many axial mode units as circumferential units. This difference can be compensated for by the utilization of the combined data from two rows of staggered circumferential mode units, with the added advantage of providing excellent coverage for short, circumferentially oriented flaws.

To simplify the process of signal analysis and make it more user-friendly, the data are displayed in C-scan format. This display method is a valuable tool in helping to visualize flaw morphology and location while reducing the number of data channels to be analyzed retaining all the original data. Furthermore, these C-scans can be combined to generate differential channels and multi-frequency mix or filter channels, to aid in detection and characterization of defects.

Field Experience: Field experiences with T/R array probes at CANDU NGSs have demonstrated excellent probe performance while achieving high inspection speed and clear imaging to help define defect morphology [5,6].

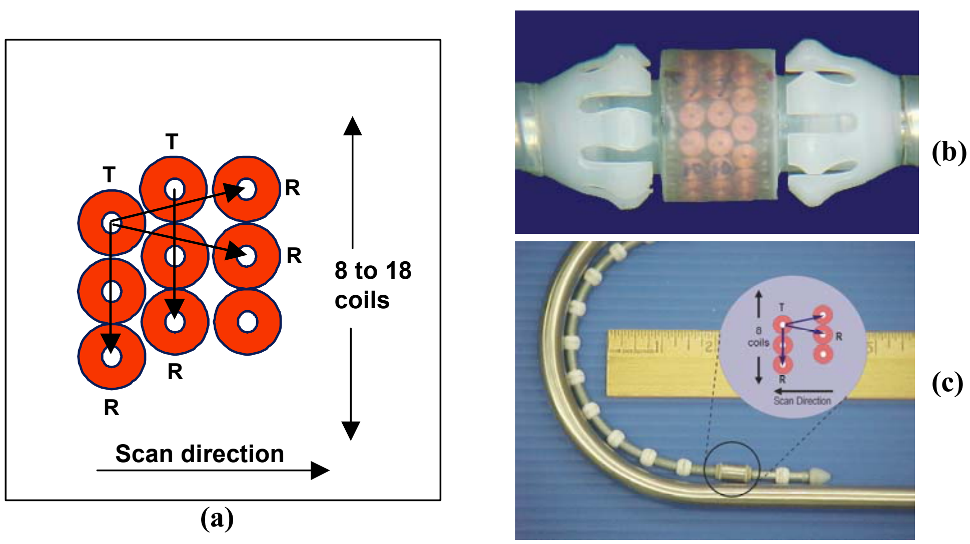


Figure 5: X-probe for axial and circumferential crack detection (a) coil configuration (b) View of an X- probe for 22.3 mm diameter tubing (c) View of an X-probe for 12.9 mm diameter tight radius U-bend tubing

In the following section, we will describe results of field experiences inspecting 15.9 mm diameter Incoloy 800 SG tubing, 12.7 mm diameter Monel 400 SG tubing and 12.9 diameter Inconel 600 SG tubing.

SG inspections of I800 tubing are carried out using bobbin probes for general inspection purposes. Although Alloy 800 is not susceptible to SCC under normal operating conditions, the X-probe is deployed for detection of cracking at the TTS location and the U-bend regions to confirm that this mode of degradation is not present and as a re-inspection tool for flaw characterization The example in Figure 6 shows signals from a tube with two small fretting wear signals (<20% and <10% deep) at the U-bend staggered scallop-bar location. A comparison is made between signals obtained with the X-probe and both the absolute and the differential bobbin probes. Although the bobbin probe provides good flaw detection with the aid of multi-frequency mixes, flaw quantification is compromised; signal phase is distorted due to the U-bend lift-off noise, and signal amplitude is dependent on flaw volume. The X-probe provides more accurate sizing and the C-scan image aids in the characterization of the flaw, indicating that the degradation is occurring at the edge of the scallop bars. The depth of the indication is sized using an amplitude calibration curve built based on the 250-70 kHz axial mix response to machined fretting-wear scars contained in laboratory specimens.

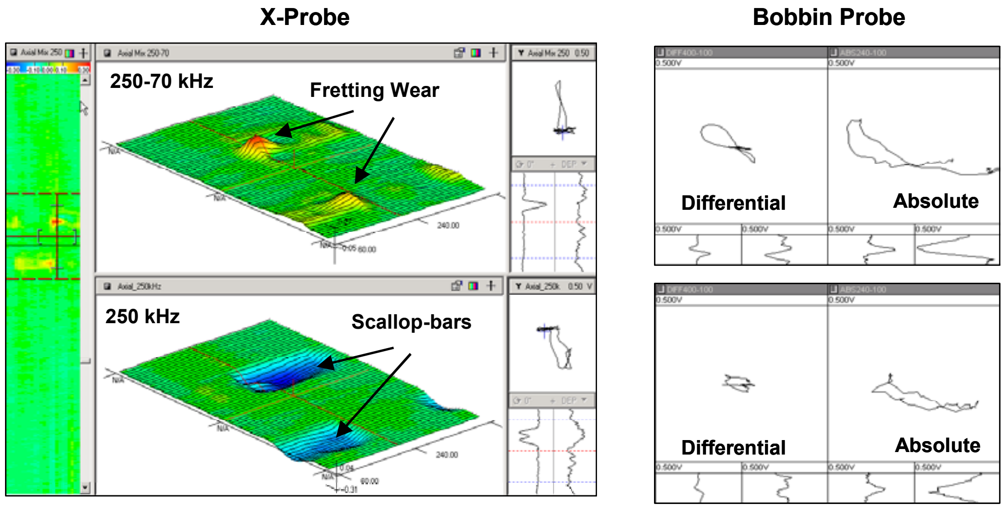


Figure 6: X-Probe signals from edge fretting-wear under scallop-bars in Incoloy 800 tubing compared to bobbin probe signals. These flaws are sized using a calibration curve based on the 250-70 kHz axial mix channel.

The example in Figure 7 shows X-probe signals from a heat exchanger that had failed due to circumferential fatigue cracking at the TTS. In this case, the analysis of the X-probe provides fast and reliable circumferential crack detection capabilities without having to resort to slow industry standard rotating probes. Furthermore, analysis of the array probe data helps in establishing the degradation mechanism; for example, the flaw indication at TTS, as illustrated in Figure 7, is only detected by the circumferential detection mode, indicating that this a perfectly circumferentially oriented crack, typical of fatigue. In addition, the indication at the freespan region between the TTS and first support plate is due to fretting wear between the two adjacent tubes, caused by excessive tube vibration. Notice that this volumetric flaw is detected in both modes. It was this excessive tube vibration that caused the tube failure.

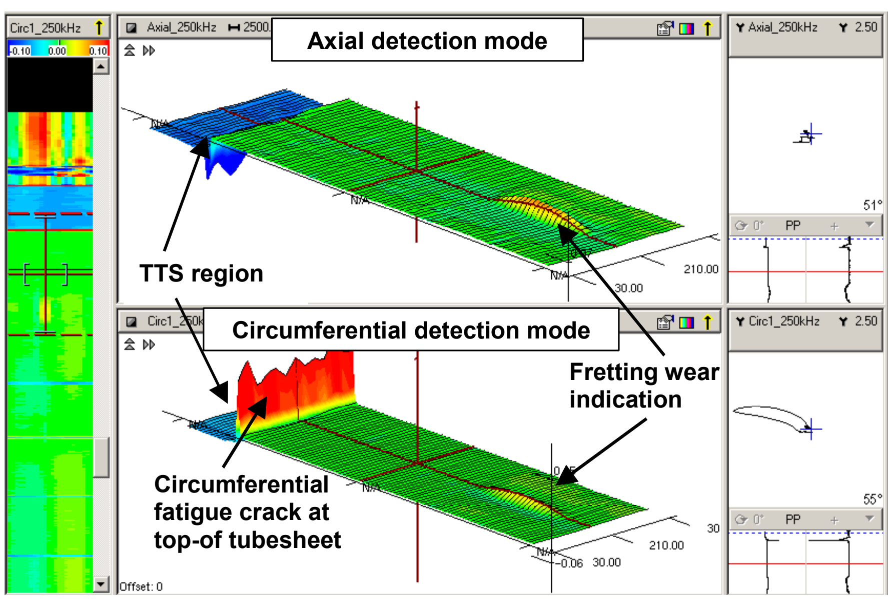


Figure 7: Array probe helps in assessing degradation mechanism. Example of X-probe signals from an Incoloy 800 tube with fatigue cracking induced by excesive tube vibration.

The next example refers to the inspection of a Pickering NGS SG. The tubing material is Monel 400. This slightly ferromagnetic material requires the use of magnetic bias eddy current probes to magnetically saturate the tube wall. Inspection plans for these SGs comprise the deployment of magnetic bias bobbin probes, denoted CTR1 probes, for 100% general inspection purposes. The specialized magnetic bias CTR2-C4 array probe is often utilized as a re-inspection tool when further information is required or to better characterize indications detected with the CTR1 probe.

Although the CTR1 probe is adequate for detection and sizing of pitting corrosion found in Pickering NGS B SG tubes at freespan and support plate locations, pitting corrosion has been found at the TTS location. In these cases, the signal from the flaws can be partially masked by the large signal from the TTS, making signal identification and flaw sizing very difficult. When this occurs, the tubes are re-inspected with the CTR2-C4 array probe. Figure 8a shows signals from a flaw-free TTS signal obtained with the bobbin probe. The next example in Figure 8b shows signals from a pit located at approximately 1 cm above the TTS. In this case, the bobbin probe indication from the pit is clearly identifiable. However, when the pit is located closer to the TTS, such as in the case shown in Figure 8c, detection is compromised. The C-scan display obtained with the CTR2-C4 probe from the same flaw illustrates the improved resolution and sizing capability obtained with the array probe [7].

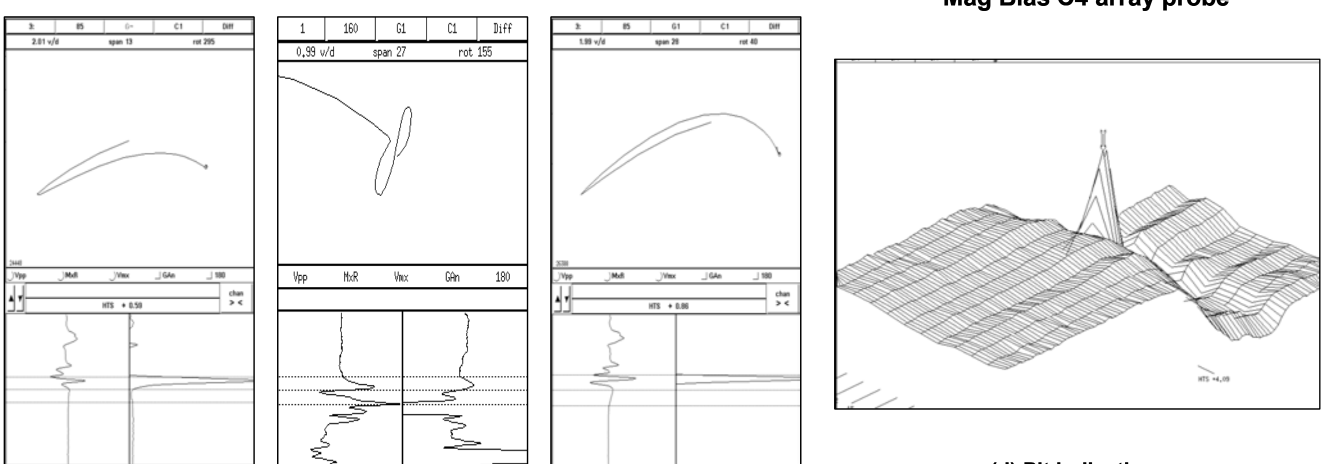
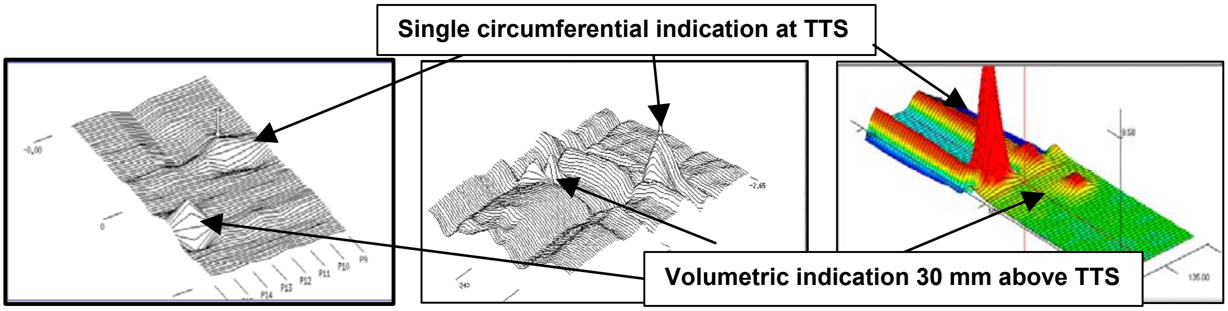


Figure 8: CTR1 probe impedance display from TTS location in a section of Monel 400 tubing with a pit-like indication, compared CTR2-C4 probe C-scan display.

Detection of SCC has been a major issue for Bruce NGS SGs. Usually the inspection plans comprise the deployment of bobbin probes for general inspection purposes and a crack sensitive probe for 100% hot leg (HL) TTS inspection for detection of circumferential SCC. A large number of tubes are inspected with the fast scanning C3 probe and a smaller fraction with Plus Point rotating probe. In addition, the Plus Point probe is used as a re-inspection tool to resolve ambiguous indications detected with bobbin or C3/8 probes, or for confirmation of flaw indications. Recently, the X-probe has been incorporated in the inspection plans. Figure 9 shows signals collected with various ET probes from a 12.9 mm diameter, Inconel 600 tube containing two indications. It illustrates the complementary information obtained with the different probes. C3 data in Figure 9a shows two indications: one at the TTS and one 30 mm above the TTS in the sludge pile region. The Plus Point data in Figure 9b shows that the indication at TTS is a single circumferential indication and the one shown 30 mm above TTS is characterized as a volumetric flaw. The X-probe signals from the same tube after pulling it from service show the volumetric flaw and circumferential indications. Signal amplitude from the circumferential indication increased approximately 20 times after pulling, due to crack opening [6]. The characterization of these flaws was later confirmed by metallographic examination.

The X-probe has the potential of replacing the three-probe inspection strategy by combining all the capabilities in a single scan.



(a) **(b)** **(c)**

Figure 9: ET signals from a hot leg TTS section in Inconel 600 tubing containing two indications. It illustrates the complementary information obtained by the different probes. (a) C3 data, (b) +Point data and (c) X-probe data after pulling.

Conclusions: The common factor in the inspection approach taken at all CANDU stations is the use of a general inspection probe and the deployment of various probes to obtain complementary information for timely, fast detection and characterization of the diverse modes of degradation.

Transmit/receive array probes and, in particular, the X-probe as a single-pass array probe have shown similar capabilities to rotating probes. However, their advantages lie in their capabilities to detect all degradation mechanisms in a single scan at a scanning speed similar to that of bobbin probes.

Simultaneous detection and discrimination of circumferential and axial cracks in addition to flaw sizing and characterization capabilities can help reduce the need for re-inspection, tube replacement and forced outages.

Signal analysis with the aid of C-scan display is simple and reliable, providing a very valuable tool for flaw characterization.

References:

[1] Cecco, V.S., Van Drunen, G. and Sharp, F.L., "Eddy Current Testing Manual, Vol. 1", *AECL Report AECL-7523*, Chalk River, Ontario (1981).

[2] Cecco, V.S., and Van Drunen, G., "Recognizing the Scope of Eddy Current Testing", *Research Techniques in Nondestructive Testing*, *Vol. 8,* ed., R.S. Sharpe, Academic Press Inc., pp. 269-301 (1985).

[3] Obrutsky, L.S., Cecco, V.S., Sullivan, S.P., Humphrey, D., "Transmit-Receive Eddy Current Probes For Circumferential Cracks In Heat Exchanger Tubes", *Materials Evaluation, Vol. 54,* No 1, pp. 93-98. The American Society for Nondestructive Testing, Inc. (January 1996).

[4] Sullivan, S.P., Cecco, V.S., Obrutsky, L.S., Humphrey, D., Smith, S.P. and Emde, K.A., "Computer Modeling of Eddy Current Transmit-Receive Probes for Tube Inspection" *Review of Progress in Quantitative Nondestructive Evaluation, Vol. 17,* pp. 283-289. Ed., D.O. Thompson and D.E. Chimenti, Plenum Press, New York (1998).

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

[6] Obrutsky, L.S., Watson, N.J., Fogal, C.H., Cantin, M., Cecco, V.S., Lakhan, R.J. and Sullivan, S.P. “Experiences and Applications of the X-Probe for CANDU Steam Generators”, *20th EPRI Steam Generator NDE Workshop*, Orlando, Florida (July 9-11, 2001).

[7] Sullivan, S.P., van Langen, J.P., Cecco, V.S., Lakhan, J.R. and Carter, J., “Application of Magnetically Biasing Eddy Current Array Probes in Ferromagnetic Steam Generator Tubes”, Presented at the 20th EPRI Steam Generator NDE Workshop, Orlando, Florida, (2001 July 9-11).