AECL

TECHNIQUES FOR VALIDATING EDDY CURRENT PROBES FOR INSPECTING CANDU STEAM GENERATOR TUBES

by

S.P. Sullivan, V.S. Cecco, L.S. Obrutsky and A.H. Park

ABSTRACT

Requirements for aging nuclear steam generator (SG) tube inspections are becoming increasingly stringent throughout the world, including Canada. The effort of removing tubes, and the special handling required of these radioactive samples makes validating an inspection with in-service tubes an extremely expensive exercise.

A CANDU nuclear reactor was shut down for over one year because steam generator (SG) tubes had failed with outer diameter stress corrosion cracking (ODSCC) in the U-bend section. Novel, single-pass eddy current transmit-receive probes, denoted as C3, were successful in detecting all significant cracks so that the cracked tubes could be plugged and the unit restarted. Significant numbers of tubes with SCC were removed from a steam generator in order to validate the results of the new probe. Results from metallurgical examinations were used to obtain probability-of-detection (POD) and sizing accuracy plots to quantify the performance of this new inspection technique.

Though effective, the above approach of relying on tubes removed from a reactor is expensive in terms of both economic and radiation exposure costs. This led to a search for more affordable methods to validate inspection techniques and procedures. Methods are presented for calculating POD curves based on signal-to-noise studies using field data. Results of eddy current scans of tubes with laboratory-induced ODSCC are presented with associated POD curves. These studies appear promising in predicting the performance of new inspection technologies.

AECL
Nondestructive Testing Development Branch
Chalk River Laboratories
Chalk River, Ontario, Canada, K0J 1J0

Paper presented at the 1998 International Steam Generator and Heat Exchanger Conference, Toronto.

1. INTRODUCTION

Requirements for aging nuclear steam generator (SG) tube inspections are becoming increasingly stringent throughout the world, including Canada. The effort of removing tubes, and the special handling required of these radioactive samples makes validating an inspection with in-service tubes an extremely expensive exercise.

The Electric Power Research Institute (EPRI) of the USA has produced a document called the "PWR Steam Generator Tube Examination Guidelines" [1]. According to these guidelines, eddy current probes/coils are considered qualified if they are proven by a statistically based performance demonstration that meets the minimum requirements documented in Appendix H of these guidelines.

The European Network for Inspection Qualification has issued a document entitled "European methodology for qualification of non-destructive tests" [2]. This document is intended to be used as a "basis for development" of specifications for NDT qualifications. To qualify a technique in accordance with the guidelines in this document, a "technical justification" must be provided. This is composed of experimental evidence and/or theoretical studies .

Canadian designed CANDU reactors have steam generators containing various tube materials. The dimensions and material composition of the tubes can greatly affect design features in the probes required to ensure that eddy current inspections will be reliable. For example, steam generator tubes in the Pickering Nuclear Generating Station (PNGS) are composed of a ferromagnetic copper-nickel alloy called Monel 400. Because these tubes are ferromagnetic, powerful permanent magnets need to be integrated into eddy current probe designs to magnetically saturate the tube material [3,4]. Magnetic saturation is required to ensure adequate eddy current depth of penetration in order for internal probes to detect defects that initiate from the outer diameter (OD) surface of the tube. It is also needed to eliminate probe signal distortions from magnetic permeability variations that can obscure defect signals. The deposits can also be abrasive, leading to rapid probe wear.

Another important and unique characteristic of CANDU steam generator tubes is that they all have deposits of magnetite on the internal diameter (ID) surfaces. Variations in the magnetic permeability and thickness of the deposits can cause distortions in the signal background that obscure defect signals.

When validating inspection techniques, the appropriate field conditions must be considered. In the case of CANDU SG tubes, the effects of ID magnetite deposits must be included in validating eddy current inspections. For some specific CANDU sites the effects of ferromagnetic tube material and/or electrically conducting deposits must also be included in validation exercises.

2. EDDY CURRENT PROBES FOR SG TUBE INSPECTION

Most in-service heat exchanger and steam generator tube inspection is carried out using bobbin coil eddy current probes. These probes consist of coils of wire that are coaxial with inspected tubes. Eddy currents that bobbin probes induce in the inspected tubes are circumferentially oriented. Unfortunately, circumferential cracks do not interact with the circumferential eddy currents generated by bobbin coils rendering these probes insensitive to these types of cracks.

Because of this shortcoming with bobbin coil probes, mechanically rotating pancake coil (RPC) probes have been implemented world-wide for inspecting tubes that are suspected to have circumferential cracks. Eddy currents induced by these probes have circumferential and axial components that interact with cracks oriented in all directions.

In 1991, steam generator tubes at the Bruce Nuclear Generating Station (BNGS), Unit 2 developed leaks due to circumferential outer diameter (OD) stress corrosion cracks (SCC). Inspections of these tubes with industry standard crack detection probes failed to detect any of the cracks except for some that had propagated completely through the tube wall. The reasons for such poor performance of these probes were that the cracks were located in deformed sections of the tubes; variations in the ID magnetite deposits also obscured crack signals.

A new transmit-receive eddy current array probe, denoted as C3 (Cecco-3), was developed for this application [3]. This probe consisted of two circumferential arrays of transmit (active) and receive (passive) coils as shown in Figure 1. The reason that the transmit-receive configuration was chosen was that computer modelling showed that transmit-receive probes were several times more sensitive to cracks in comparison with lift-off (coil to tube wall proximity variations due to tube deformation) and magnetite deposit variations. Calculated signals from cracks, lift-off and magnetite deposits are shown in Figure 2 for pancake impedance and transmit-receive eddy current probes. These results clearly show that the signal (from the crack) to noise (from lift-off and deposits) ratio is several times better when using a transmit-receive probe than when using a pancake impedance probe with coils of the same size. While the C3 probe is sensitive to circumferential cracks and non-directional flaws, it is insensitive to axial cracks. A similar array probe, denoted as C5, with equal sensitivity to axial and circumferential cracks has been developed and used at Darlington NGS, Gentilly-2, and several PWR generating stations in the United States and Japan.

For higher resolution scans of localized regions, much slower mechanically rotating eddy current probes such as the Zetec "+point" and the AECL "RG3/RG4" probes have been developed. Both of these types of probes have proven to be much more sensitive to tube cracks than the rotating pancake coil probes. The +point probe consists of two differential tangent coils oriented at 90^0 with respect to one-another. One coil is sensitive to axial cracks and the other coil is sensitive to circumferential cracks. Because the coils are differential, interference (noise) due to probe lift-off from tube deformations and rolled joint expansions is significantly reduced. The RG3/RG4 probe is composed of two independent transmit-receive coil combinations. One transmit-receive pair (RG3) is sensitive to circumferential cracks, and the other pair (RG4) is sensitive to axial cracks. Both RG3 and RG4 probe units are also sensitive to flaws such as intergranular attack

(IGA), pitting, wastage and fretting wear. These types of probes have been used mainly for secondary flaw analysis. The +point probe was used for characterizing tubesheet flaws in Bruce NGS SG tubes, and the RG3 probe has been used successfully to characterize flaws at broached support plates.

3. RECOMMENDED CRITERIA

To validate inspection techniques they must be shown to be able to detect flaws at a level which could grow to the minimum tolerable flaw size before the next inspection. The minimum tolerable flaw size should be correlated to possible modes of failure that could occur in subsequent operating cycles. Tolerable flaw sizes should be established through scientific and/or engineering studies of specimens and/or mock-ups that simulate the processes of defect formation and growth, and tube failures.

In addition to being qualified for detecting flaws, techniques may also be qualified to size flaws. The sizing must be accurate enough to show that detected flaws left in service will not grow in a subsequent operating cycle to be large enough to potentially cause a tube failure.

To qualify an inspection technique, documentation (similar to the "technical justification" discussed in reference [2]) should be provided that explains the physical principles that enables a technique to detect that flaws of interest. In addition, documentation must be provided by a performance demonstration that quantitatively shows a technique is capable of detecting flaws at a level which could grow to the minimum tolerable flaw size before the next inspection. This performance demonstration may consist of measurements showing that flaw signals will be distinguishable from the background noise in the field (signal-to-noise ratio > 2), or from probability of detection curves.

Performance demonstrations with statistically significant numbers of flaws do not by themselves acceptably qualify inspection techniques. Physical reasoning (which may include computer modelling) must be employed showing why the specific techniques detect the flaws. If the types of flaws used are slightly different than in-service flaws, then flaws used in a performance demonstration may be detectable when in-service flaws are not. For example, tests with bobbin coil eddy current probes have shown that these probes can often detect circumferentially oriented electric discharge machined (EDM) notches. The reason that this probe can detect such notches is that the notches have finite width. Ideal, infinitesimally thin circumferential cracks are not detectable with bobbin probes because the circumferential eddy currents do not interact with these types of cracks. This understood limitation of bobbin probes' ability has been demonstrated repeatedly in tests with tubes with real (tight) circumferential cracks. However, because of experience obtained by using these probes in detecting circumferential EDM notches, many researchers and inspectors still believe that bobbin coil probes are sensitive to circumferential cracks.

4. QUALIFICATION USING TUBES REMOVED FROM OPERATING STEAM GENERATORS

This method requires a random sample of tubes in operating (or retired) steam generators to be inspected by an eddy current technique, having the tubes removed from the steam generator, and comparing the eddy current results with independent laboratory measurements. These laboratory measurements may consist of scans of the flawed tubes with NDE techniques that were previously qualified for flaw detection and sizing.

C3 probes have been validated by using them to scan several hundred SG tubes at BNGS-2, removing many U-bend sections of inspected tubes, and destructively analyzing the removed tubes in a laboratory. Probability-of-detection (POD) histograms based on comparison of inspection results with laboratory measurements are shown in Figure 3. A depth sizing accuracy plot is shown in Figure 4.

Though effective, the above approach of relying on tubes removed from a reactor is expensive in terms of both economic and radiation exposure costs. This led to a search for more affordable methods to validate inspection techniques and procedures, some of which are described in the following sections.

5. VALIDATION USING LABORATORY PREPARED SAMPLES

One alternative to technique validation based on tubes removed from in-service steam generators is to prepare samples in the laboratory with properties that simulate the field conditions encountered in inspections. For CANDU SG tubes, methods have been developed that produce ODSCC (circumferential and axial) in Inconel 600, pitting in Monel 400, and fretting wear. Figure 5 shows a dye penetrant image and a fracture surface of an Inconel 600 tube with laboratory-induced stress corrosion cracks. The darkened area on the fracture surface outlines the circumferentially oriented crack. Figure 6 compares of a pit found in a Monel 400 tube section removed from an in-service steam generator, and a laboratory-simulated pit. The two through-wall pits have similar diameters and volumes.

A method for depositing magnetite layers on steam generator tubes has been developed. Tube samples are immersed in an aqueous magnetite suspension. After the appropriate exposed surfaces of the tube have been coated with the magnetite particles, the tube is heated in a furnace to dry and sinter the magnetite coating. A comparison of eddy current measurements with these laboratory-induced layers has shown that they cause as much or more distortion in eddy current signals as deposits encountered in the field. Copper layers have been deposited on tube surfaces with an electroplating method. The addition of mockup carbon steel support plates and deformations with the realistic defects and deposits allows the production of laboratory tube samples that properly simulate the field conditions encountered in CANDU SG tube inspections.

6. VALIDATION BASED ON SIGNAL-TO-NOISE COMPARISONS

This method compares eddy current signals from tube flaws with background signals ("noise") from eddy current scans of in-service tubes. The flaws may be laboratory-induced, but they should be equivalent to the in-service flaws for which the eddy current technique is being qualified to detect.

The probability of detecting a particular flaw can then be considered greater or equal to the probability of the flaw signal being larger than the noise by a factor of at least 2.

The amplitude of the background noise can be quantified from data files of eddy current scans of several hundred in-service tubes. The noise amplitudes can then be plotted on normalized population (probability density) plots. The amplitude of the eddy current signal generated by the probe response to the flaw should then be measured. The probability of detecting this flaw is then greater or equal to an integral of the normalized noise population plot. The lower limit of the integral is zero. The upper limit of the integral is the flaw signal amplitude divided by the signal-to-noise ratio which determines detectability (should be at least 2).

The flaws should be examined by independent laboratory measurements in order to measure flaw depth, and possibly axial or circumferential extent.

Background noise in BNGS SG tubes at the HU1 support plate locations was quantified in terms of population (number of tubes) plotted as a function of noise amplitude. These noise population plots were used to predict probability of detection as a function of signal amplitude (Vertical component (Vmx)) by defining a minimum signal-to-noise ratio to determine detectability. The detection probability was calculated from the normalized area under the population plot. This was calculated by integrating the population function. The lower limit of the integral was 0 Volts. The upper limit was the signal voltage (from the calibration curve) divided by the minimum signal-to-noise ratio required for detectability. The normalization is performed by dividing these integrals by the integral from 0 Volts to infinity.

To validate this methodology for calculating probability of detection, the background distortion of signals from C3 probes was quantified. Figure 7(a) is a plot of the noise distribution. From this plot, POD curves, shown in Figure 7(b) were plotted for signal-to-noise ratios of 1.4 and 2. Superimposed is the POD curve that was derived from comparing eddy current predictions with destructive analysis of tubes removed from BNGS-2 in 1992. This plot shows that this is a reasonable technique for making conservative estimates of POD curves.

7. VALIDATION BASED ON COMPUTER MODELLING OF EDDY CURRENT PROBES

Computer modelling of eddy current probe responses may offer an inexpensive tool for qualifying inspection techniques. However, in using such a tool, the following conditions should be met:

- The ability of the computer modelling codes to accurately simulate probe responses to flaws equivalent to those found in in-service tubes should be demonstrated.

- If technique qualification is based only on computer modelling then the modelling codes should be able to accurately simulate the background noise which is generated in signals acquired from field inspections. The background noise is partly composed of probe responses to tube support structures, magnetic deposits, conducting deposits, tube deformations, and magnetic permeability variations. In addition, electrical noise from probe cable pick-up, cable cross-talk, and grounding contribute to the overall noise.

Although computer modelling has not yet been used to qualify eddy current techniques for steam generator tube inspection, the practicality of using modelling to estimate Probability of Detection in NDE applications has been demonstrated [6].

8. SUMMARY/CONCLUSIONS

Technique validation for SG tube inspection that relies strictly on using in-service components is extremely expensive. However, care must be taken to ensure that validation exercises using laboratory-prepared tubes accurately simulate the field conditions that are encountered in in-service inspections. Laboratory induced defects, especially cracks, must closely resemble in-service defects. Equally important is the need to have the significant field-like tube deformations, expansions, deposits, and support plates that can obscure defect signals.

A method based on signal-to-noise studies has been proposed that will make validating inspections much more economical. A comparison of defect signals with background noise obtained from real in-service tube scans can help to establish the limits of defect detectability.

ACKNOWLEDGEMENTS

The authors wish to thank Terry Harasym of Ontario Hydro's Specialized Inspection and Maintenance Department (SIMD) for his helpful guidance and discussions. The authors are grateful to the CANDU Owners Group (COG) Technical Committee 19 for their support. This work was funded by Work Package Identification and Release (WPIR) number 1987.

REFERENCES

1. "PWR Steam Generator Tube Examination Guidelines: Revision 4", Volume 1, Draft, Electric Power Research Institute (EPRI), 1996 January.

2. "European Methodology for Qualification of Non-destructive Tests", second issue, pre-print EUR 17299 EN, 1997 February.

3. Cecco V.S., Van Drunen G. and Sharp F.L., "Eddy Current Testing Manual, Vol. 1", AECL Report, AECL-7523, 1981, Chalk River, Ontario, Canada.

4. Cecco V.S. and Van Drunen G., "Recognizing the Scope of Eddy Current Testing", in Research Techniques in Nondestructive Testing, Vol. 8, 1985, pp 269-301, ed. by R.S. Sharpe, Academic Press.

5. Obrutsky L.S., Cecco V.S., Sullivan S.P. and Humphrey D., "Transmit-Receive Eddy Current Probes for Circumferential Cracks in Heat Exchanger Tubes", Materials Evaluation, Vol. 54, No. 1, pp 93-98, 1996 January.

6. Rajesh S.N., Udpa L. and Udpa S.S., "Numerical Model Based Approach for Estimating Probability of Detection in NDE Applicaions", IEEE Transactions on Magnetics, Vol. 29, No. 2, March 1993.

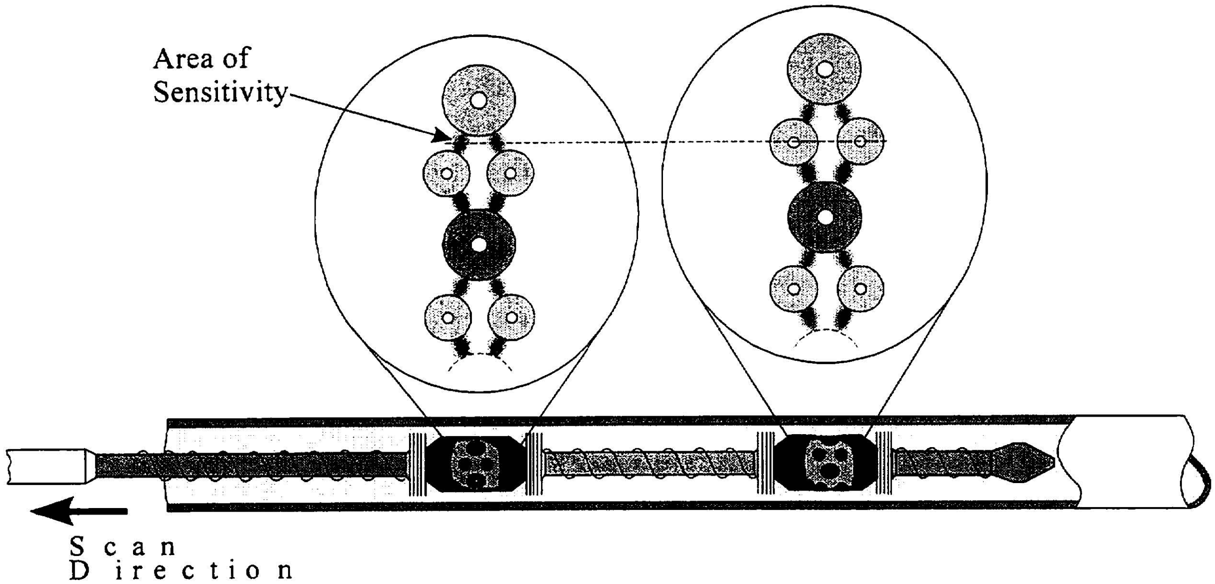


Figure 1: C3 probe showing transmit-receive coil configuration.

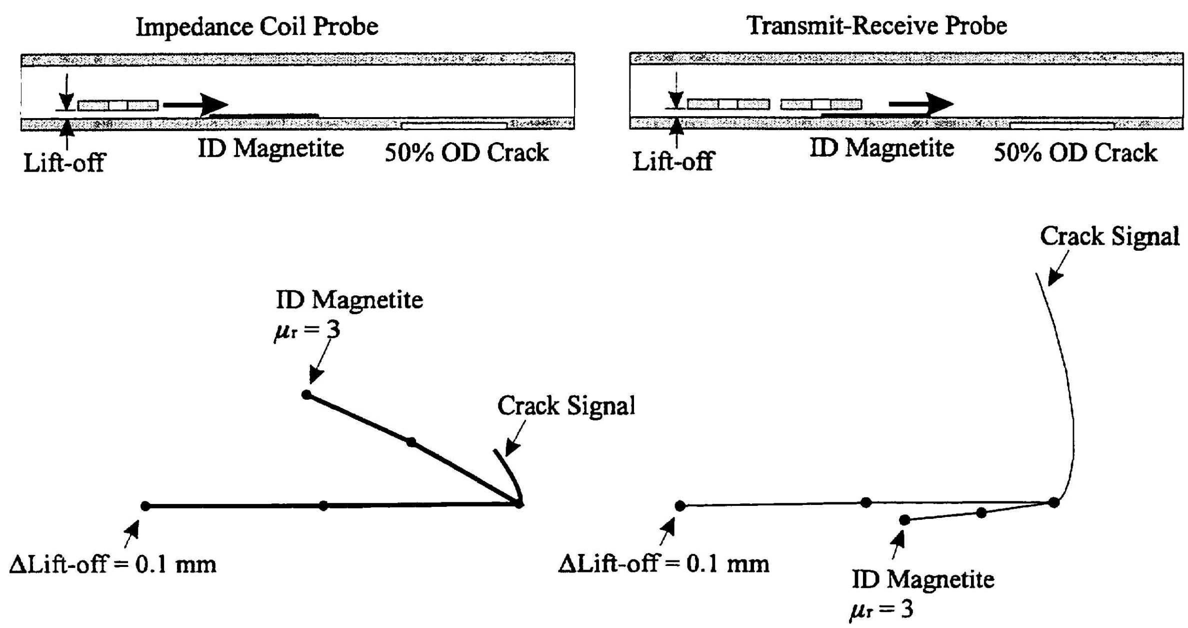


Figure 2: Computer modelling results comparing signal (from a crack)-to-noise (from probe lift-off or ID magnetite deposit) for a pancake impedance coil probe and a transmit-receive eddy current probe.

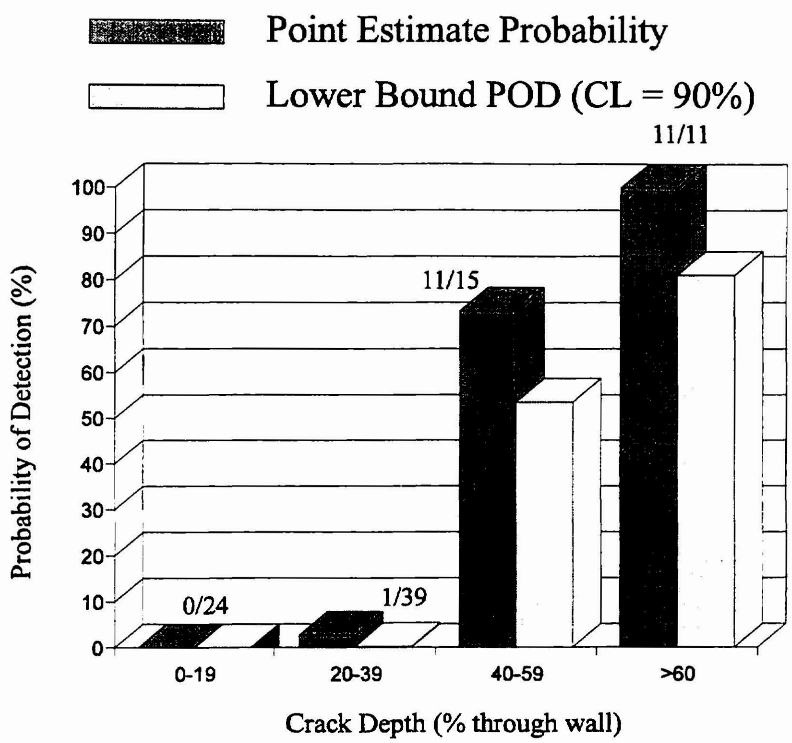


Figure 3: Probability of detection histogram for C3 probe detecting OD stress corrosion cracks in Bruce A Nuclear Generating Station steam generator tubes.

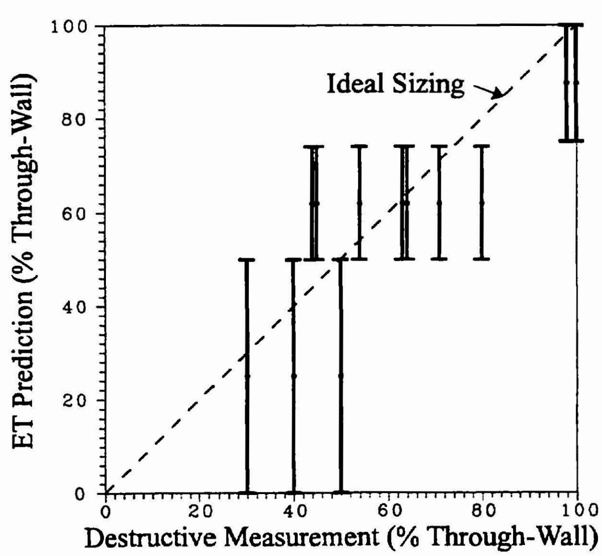


Figure 4: Sizing accuracy curve for C3 probe detecting ODSCC in CANDU SG tubes which were subsequently removed and analyzed destructively.

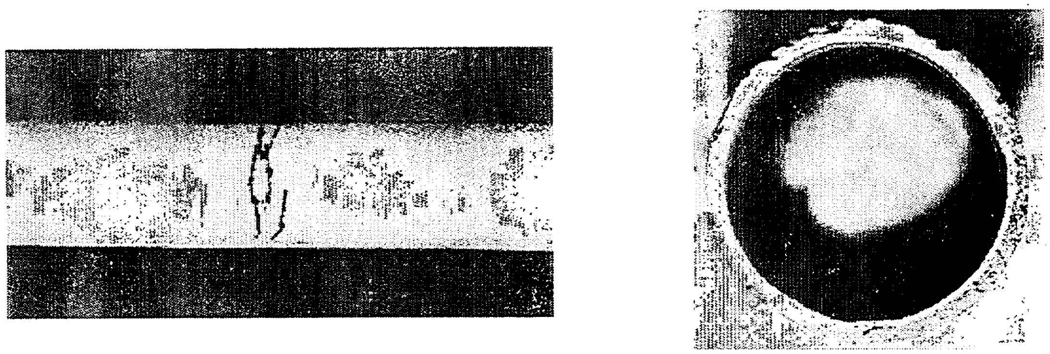
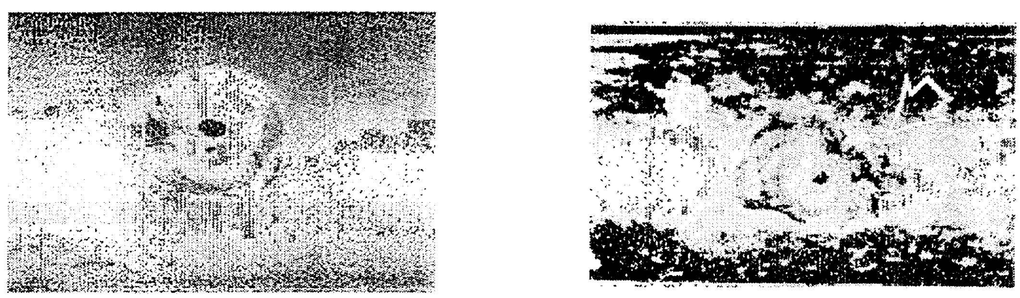
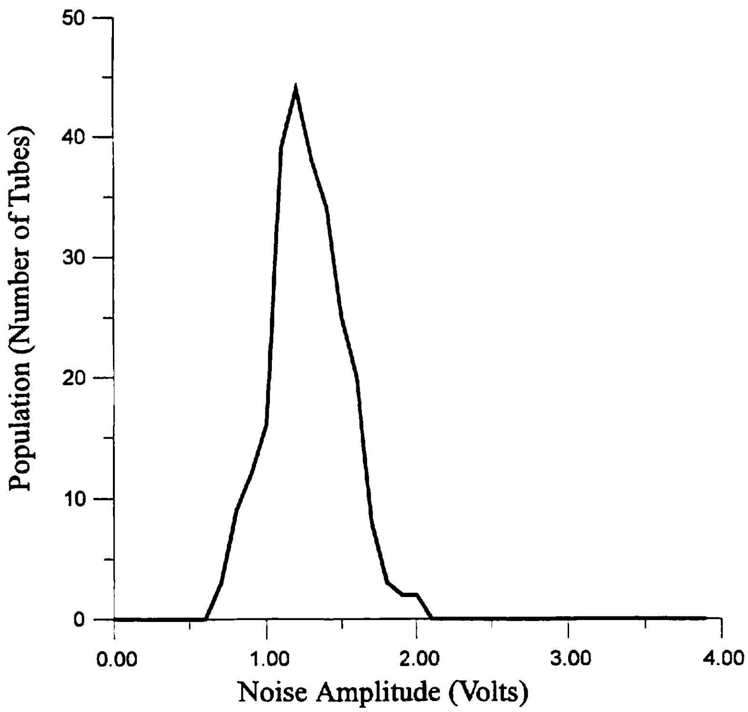


Figure 5: (a) Dye penetrant photograph of a steam generator tube sample with laboratory-induced outer diameter stress corrosion cracks. (b) Fracture cross section of a circumferential stress corrosion crack in a steam generator tube.

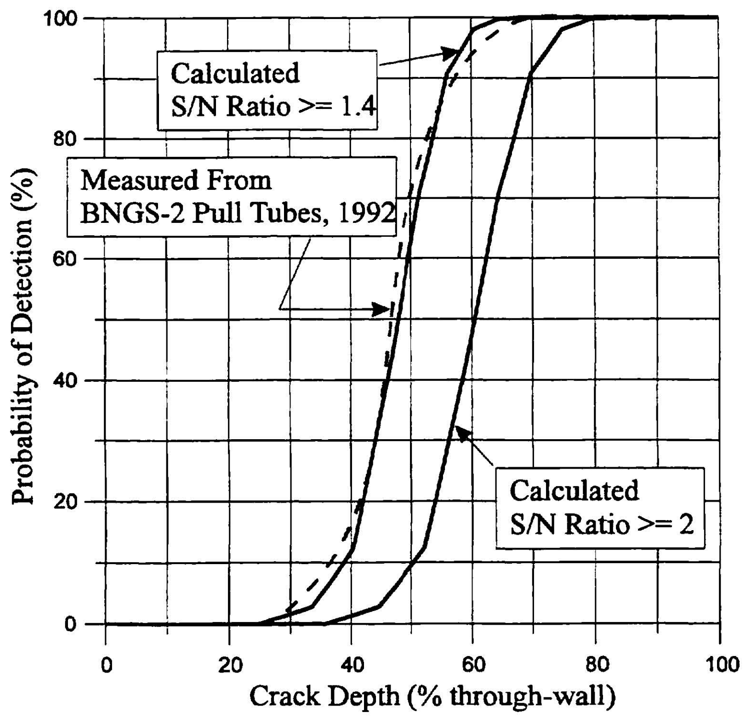


(a) (b)

Figure 6: (a) Photograph of a laboratory-induced, 100 % OD pit in a Monel 400 SG tube. (b) Photograph of a 100% OD pit in a tube removed from PNGS-B. Both pits are of similar diameter.



(a)



(b)

Figure 7: (a) Noise distribution plotted for 4 T/R unit C3 probe (version 1) at the HU1 support plate location in BNGS-2 SG tubes. (b) POD curves for 4 T/R unit C3 probe (version 1) detecting circumferential OD stress corrosion cracks at the HU1 support plate locations in BNGS-2 SG tubes.

DISCUSSION

Authors: S.P. Sullivan, V.S. Cecco, L.S. Obrutsky, A.H. Park, AECL

Paper: Techniques for Validating Eddy Current Probes for Inspecting CANDU Steam Generator Tubes

Questioner: R. Garg, AECB

Question/Comment:

C3/4 probes have 4 coils and C3/8 probes have 8 coils which in your view increases the resolution and hence detection capability. What about sizing capability. Why do you think it has also improved sizing capability?

Response:

Correction to the question: The C3/4 probe has 4 probe channels (not coils). Also the C3/8 probe has 8 probe channels (not coils). Both probes use 12 coils, but they are wired to the instrument in different ways.

(1) The C3/8 performed better in sizing the laboratory prepared ODSCC's than the C3/4 probe. In these tests, the C3/4 probe had a Root mean Square Error (RMSE) of 13%. The C3/8 probe had an RMSE of 11% on the same tubes.

(2) Because the C3/8 has better circumferential resolution (with 8 probe channels around the circumference as opposed to 4), it senses more localized sections of each circumferential crack and therefore performs better in depth sizing.