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**Guidelines for Qualifying Eddy Current
Technology for CANDU Steam Generator
Tube Inspection**

S.P. Sullivan

1999 March

AECL

**GUIDELINES FOR QUALIFYING EDDY CURRENT TECHNOLOGY FOR
CANDU STEAM GENERATOR TUBE INSPECTION**

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Components & Systems Division
Nondestructive Testing Development Branch
Chalk River Laboratories
Chalk River, Ontario, Canada, K0J 1J0

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ABSTRACT

Guidelines for qualifying eddy current inspection technology for inspection of CANDU steam generator (SG) tubes are presented. To properly qualify a technique, the physical principles underlying its operation must be documented, as well as its ability to detect and/or size flaws in the presence of background tube noise, which is always present in field inspections. Background noise can be generated by tube deformation, internal and external deposits, support structures, and inspection system electrical noise. CANDU SG tubes require special consideration because they are coated with internal layers of magnetite to varying degrees. Random variations in these magnetite layers interfere with the eddy current probes' magnetic fields, which causes background interference in the signals.

Various methods of evaluating limitations in flaw detection and sizing are discussed, as well as conditions required in applying these methods. These include use of tubes removed from operating units, laboratory-prepared samples, comparing responses from laboratory-prepared flaws with background noise in field scans, signal injection and computer modelling.

Components & Systems Division
Nondestructive Testing Development Branch
Chalk River Laboratories
Chalk River, Ontario, K0J 1J0

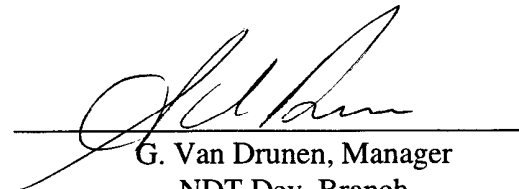
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VALUE & IMPLICATIONS

The tubes in some CANDU steam generators are susceptible to similar problems that plagued PWR steam generator tubing earlier. It has increased the demand for tube inspection as well as a much more careful examination of the reliability of inspection techniques and procedures. The topic has also attracted the interest of regulators because the tubes effectively form part of containment. Some well-publicized cases of the use of inappropriate inspection technology contributing to unexpected tube failures further raised the profile of inspection technique qualification. Rules and procedures for qualifying eddy current inspection methods for PWR steam generator tubing have been established in response to regulatory and industry pressure.

This report draws on the PWR experience and also addresses unique factors that have to be considered for CANDU steam generators. The result is several options for qualifying eddy current inspection methods. Their adoption will bring CANDU steam generator inspection methods up to international standards. It should also help minimize regulatory concerns about the adequacy of inspection methods.



G. Van Drunen, Manager
NDT Dev. Branch

Components & Systems Division
Nondestructive Testing Development Branch
Chalk River Laboratories
Chalk River, Ontario K0J 1J0

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1. INTRODUCTION

Since 1990, there have been significant increases in tube degradation in many CANDU steam generators (SGs). Stress-corrosion cracks (SCC) in the U-bend and tubesheet sections of SG tubes at Bruce Nuclear Generating Station (BNGS), and pitting of SG tubes at Pickering Nuclear Generating Station (PNGS), have caused tube failures. Fretting wear and damage from loose parts have caused forced outages and increased tube plugging.

An acceptable inspection must use the required qualified inspection techniques to detect all significant types of defects in SG tubes to satisfy plugging and/or repair criteria.

“Qualification” of an inspection technique does not guarantee that it will work successfully in every field inspection where it is implemented. Even in so-called identical SGs, there can be significant variability in the form and morphology of flaws, and background noise that a technique qualified to detect and/or size flaws in one set of SG tubes may not work well in another set of tubes. However, qualifying a technique by showing that it can detect and/or size flaws of concern in realistic SG tubes does greatly increase confidence in that technique.

The Electrical 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 to be qualified if they are proven by a performance demonstration. This performance demonstration should meet the minimum requirements documented in Appendix H of the 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 nondestructive testing (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.

The presence of ID magnetite is an important concern for inspections of CANDU SG tubes. Many techniques have been qualified for inspecting PWR SG tubes. However, these tubes are very clean on the interior surface compared with CANDU SG tubes. The presence of ID magnetite can increase background noise, significantly decreasing flaw detectability.

This procedure is generally based on those of references [1] and [2] with modifications to reflect unique CANDU aspects regarding SG tube inspection.

2. SCOPE

This document describes a procedure for validating eddy current inspections of SG tubes for known types of flaws in testing situations where background noise has been quantified. For

periodic inspection for general deterioration, the inspection technique is acceptable if proven capable of detecting expected modes of failure. This can be accomplished by determining probe response to flaws and comparing it with in situ background noise.

Qualification of NDE may not be limited to options discussed in this document. Prior to the onset of any qualification it must be established that the level or rigor of qualification will meet safety and regulatory requirements [3].

3. CRITERIA

3.1 Required Documentation

The documentation used to qualify an inspection technique must contain a technical justification that explains the physical principles that enable the technique to detect the flaws of interest. In addition, documentation must be provided of a performance demonstration that quantitatively shows that technique is capable of detecting flaws as small as the established flaw size detection requirement.

3.2 Correlation to Failure Analysis Experiments and/or Theory

Limitations of flaw detectability must be correlated to possible modes of failure that could occur in a subsequent operating cycle. Some examples of failure events are severe tube leakage and tube rupture or guillotine breakage. Depth and extent (length, area, and/or volume) criteria for detection and sizing must be correlated to an established detection flaw size requirement for which tube failure will not occur before the tubes are reinspected. This flaw size detection requirement (FSDR) 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. The FSDR should be related to the maximum tolerable flaw size (MTFS), growth rate (GR) and time between successive inspections (T) by Equation (1) below:

$$FSDR = MTFS - (GR)(T) \quad (1)$$

To leave SG tubes with detected flaws in service, they must be inspected with one or more techniques that have been qualified for flaw sizing. Detected flaws must not be allowed to remain in service unless it can be shown that such flaws will not grow to a size where there is a significant risk for potential tube failure leakage. Flaw propagation/growth-rates can be established by industry experience, or by documented scientific and/or engineering studies of specimens and/or mock-ups that simulate the processes of defect formation and growth.

3.3 Technical Justification

Performance demonstrations with statistically significant numbers of flaws do not by themselves acceptably qualify inspection techniques. 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. The principle of operation of an inspection technique must be documented before

it can be considered to be qualified. Physical reasoning (which may include computer modelling) must be employed, showing why the specific techniques detect the flaws of interest. The influence of background noise must be considered for establishing detectability.

For example, because the eddy currents from a bobbin coil probe are circumferential these eddy currents do not interact with circumferential cracks. Because of this, these probes are known to be insensitive to circumferential cracks. In the past, performance demonstrations have been done with bobbin coil probes scanning tubes with circumferential cracks. Many times either the cracks were not completely circumferential (they had some axial directional component), or there were dents at the same locations as the cracks. In one case the probe detected the axial component of a not completely circumferential crack, and the other case the probe detected the dent. However, as a result of these types of performance demonstrations, an impression was left that bobbin coil probes were sensitive to circumferential cracks. In both cases, the detection of cracks was largely coincidental and the chances of leaving seriously flawed tubes in service was significant.

3.4 Sample Set

A sample set used in a performance demonstration must consist of SG tubes with flaws resembling those found in-service. Some of these flaws should be the same size or only slightly larger than the established FSDR. To qualify a technique for flaw sizing, there should also be several flaws that are smaller than the FSDR.

3.4.1 Cracking

To qualify techniques for detecting cracks, it must be demonstrated that the tube specimens used in performance demonstrations have crack-like flaws that resemble cracks found in the field.

In performing an eddy current inspection for detecting cracks, a proper analysis requires that the signals must be normalized to signals from known calibration flaws such as electric discharge machined (EDM) notches. However, a performance demonstration that is based only on detecting EDM notches is not acceptable for qualifying eddy current probes to detect real SG tube cracks. The narrowest EDM notches are extremely wide compared to most types of cracking that have been encountered in the field.

It is preferable to use real cracked specimens to qualify eddy current probes to detect and size SG tube cracks. Laboratory methods have been developed that can induce real fatigue cracks and SCC in SG tubes.

3.4.2 Intergranular Attack

Corrosion from intergranular attack (IGA) can occupy a significant volume, in a way similar to that of pitting and wastage. However, although weakened, some of the grain boundaries can allow conduction of the induced electrical current across them. Therefore, many IGA flaws can be partially conductive.

Because there is no known way to machine equivalent flaws, performance demonstration of eddy current techniques detecting IGA must be done with tube samples with real IGA flaws. Laboratory methods have been developed that can induce realistic IGA in SG tubes.

3.4.3 Volumetric Flaws - Pitting, Wastage, Fretting Wear

Because these flaws have defined geometries, they can be effectively replicated with machining methods for performance demonstrations of eddy current inspection techniques. However, documented evidence must be provided that validates the use of tube samples with machined flaws to qualify inspection techniques for detecting and characterizing volumetric SG tube flaws.

3.4.4 Deposits

All CANDU SG tubes have been known to contain magnetite layers on the inside surfaces of the tube walls. These layers usually have high magnetic permeability. Variations in the magnetite layers generate variations in the eddy current signals, which can obscure flaw signals. Therefore, tube samples used in performance demonstrations should address magnetite (i.e., simulating the same degree of magnetite on their inside surfaces as found in equivalent in-service tubes).

Some CANDU SG tubes are known to have significant amounts of electrically conducting deposits on the outside surfaces of the tubes. Conducting deposits on the outside of some tubes have been attributed to transport of copper through the secondary feedwater - steam system (e.g., from brass condenser tubes). Eddy current probes are sensitive to these plated deposits. Signals from these deposits can obscure probe signals. If probes are qualified for detecting and/or sizing flaws in the presence of conducting deposits, tubes used in performance demonstrations should have conducting deposits equivalent to those found on in-service tubes.

3.4.5 Ferromagnetic Tubes

Some CANDU SG tubes are composed of the copper-nickel alloy Monel 400, which is ferromagnetic. To reliably inspect these types of tubes with eddy current techniques, magnetic saturation of the tube wall is required. In qualifying eddy current probes for detecting and/or sizing flaws in these ferromagnetic tubes, flawed tubes used in performance demonstrations must be composed of material that is as ferromagnetic, or more ferromagnetic, than the in-service tubes. In addition, documentation must be provided that proves that probes can magnetically saturate the tube material before they can be considered to be qualified in inspections of ferromagnetic tubes.

3.5 Flaw Detection

To qualify a technique for detection, it must be shown that it is able to reliably detect flaws as large as an established FSDR.

Techniques can be qualified for flaw detection by either proving that the signal-to-noise ratios for flaws of equivalent size to the FSDR are larger than 2, by proving that they have signal-to-noise ratios equal to or better than previously qualified techniques (equivalence requirement), or statistically.

To statistically qualify a technique for detecting flaws that are as small as the established FSDR, the lower-bound probability of detection (POD) for all such flaws must be larger than 80%, at a confidence level of 90%.

True Probability (P) can never be measured [4]. Instead POD is typically expressed in terms of two estimates, the point probability and lower bound probability. Point probability (P_p) is expressed in Equation (2) [3]. The lower bound probability (P_l) is calculated by solving Equation (3) [1,2].

$$P_p = \frac{S}{N} \quad (2)$$

$$1 - G = \sum_{X=S}^N \frac{N!}{(N-X)!X!} P_l^X (1 - P_l)^{N-X} \quad (3)$$

where: G = confidence level ($0 < G < 1$)
 N = number of trials
 S = number of successful detections

The lower bound probability is an estimate that is expected to be less than the true probability within the confidence expressed by G . A value of $G = 0.90$ (90%) is recommended by the Electrical Power Research Institute (EPRI) [1]. With this criterion we are 90% confident that the true probability can never be lower than P_l .

3.6 Flaw Sizing

SG tubes with detected flaws can remain in service after an inspection only if their sizes are measured by a qualified sizing technique. 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.

The parameter recommended by EPRI [1] to evaluate sizing accuracy is the root-mean-square error ($RMSE$), defined below:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (M_i - T_i)^2} \quad (4)$$

where M_i is the eddy current measurement and T_i is the “true” flaw size (depth, length, width or volume) that must be established by more accurate laboratory measurements.

The standard deviation (σ) of the measurement error is

$$\sigma = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^n [(M_i - T_i) - (\overline{M} - \overline{T})]^2} \quad (5)$$

The mean error is defined below:

$$\overline{Error} = \overline{M - T} = \frac{1}{n} \sum_{i=1}^n (M_i - T_i) \quad (6)$$

The mean error quantifies systematic inaccuracies in the eddy current predictions. The standard deviation quantifies the “spread” in the eddy current prediction errors.

The plugging/repair flaw size (PRS) is the measured size of a flaw for which all flaws of greater size must be plugged or repaired. This should be related to the sizing error parameters in accordance with Equation (7):

$$PRS = MTFS - (GR)(T) + \overline{Error} - 1.28\sigma \quad (7)$$

If the error in the flaw size readings can be modelled with a normal distribution, there is a 95% probability that there will not be a negative deviation from the mean by more than 1.65σ , and a 90% probability that there will not be a negative deviation from the mean by more than 1.28σ .

3.6.1 Depth

The root-mean-square error parameter used for evaluating the accuracy of a flaw depth measurement is

$$RMSE(\% \text{ through-wall}) = \sqrt{\frac{1}{n} \sum_{i=1}^n (ED_i - TD_i)^2} \quad (8)$$

where ED_i is the depth predicted by the inspection technique, and TD_i is the “true depth” determined by independent laboratory measurements. These laboratory measurements may consist of scans of the flawed tubes with nondestructive evaluation (NDE) techniques that were previously qualified for flaw depth sizing. Both of these depth values are given in units of percentage through-wall extent.

3.6.2 Axial Extent

The root-mean-square error parameter used for evaluating the accuracy of an axial extent measurement is

$$RMSE(mm) = \sqrt{\frac{1}{n} \sum_{i=1}^n (EA_i - TA_i)^2} \quad (9)$$

where EA_i is the axial extent predicted by the inspection technique and TA_i is the “true axial extent” determined by independent laboratory measurements. These laboratory measurements may consist of scans of the flawed tubes with NDE techniques that were previously qualified for axial extent sizing. Both of these values are given in units of mm.

3.6.3 Circumferential Extent

The root-mean-square error parameter used for evaluating the accuracy of a circumferential extent measurement is

$$RMSE(deg) = \sqrt{\frac{1}{n} \sum_{i=1}^n (EC_i - TC_i)^2} \quad (10)$$

where EC_i is the circumferential extent predicted by the inspection technique and TC_i is the “true circumferential extent” determined by independent laboratory measurements. These laboratory measurements may consist of scans of the flawed tubes with NDE techniques that were previously qualified for circumferential extent sizing. Both of these values are given in units of degrees around the circumference of the tubes.

4. PROCEDURAL OPTIONS FOR PERFORMANCE DEMONSTRATIONS

This section lists several possible methods that may be used as performance demonstrations for qualifying eddy current inspection techniques.

4.1 Performance Demonstrations Using Pulled Tubes

This method requires that a random sample of tubes in operating (or retired) SGs be inspected by an eddy current technique, that the tubes be removed from the SG, and that the eddy current results be compared 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. Acceptable performance demonstrations of flaw detection must show correlation between eddy current predictions and laboratory measurements where one or more of the criteria described in Section 3.5 has been met. Acceptable performance demonstrations of various aspects of sizing (depth, axial extent, and/or circumferential extent) must show

comparisons between eddy current predictions and laboratory measurements that demonstrate that detected flaws left in service will not likely grow and cause tube failures during subsequent operating cycles. A qualification that uses a performance demonstration based on this methodology applies only to inspection of the SGs from which the tubes were removed. It can be extended to other similar operating SGs if it can be proven that the eddy current technique will operate in identical fashion in those other units.

4.2 Performance Demonstration by Comparison with Previously Qualified Techniques

This method can be used on flawed in-service tubes with no need to have them removed. This method qualifies eddy current techniques for flaw sizing by predicting flaw sizes based on the eddy current signals, and comparing these predictions with flaw size measurements using other NDE methods that have previously been qualified for sizing the specific flaws. Acceptable performance demonstrations of various aspects of sizing (depth, axial extent and/or circumferential extent) must show comparisons between eddy current predictions and other qualified flaw size measurements that demonstrate that detected flaws left in service will not likely grow and cause tube failures during subsequent operating cycles. An example would be using a higher resolution technique such as ultrasonic testing (if it has been previously qualified to size the flaws) to measure flaw sizes for comparison with eddy current flaw size predictions.

4.3 Performance Demonstrations Using Laboratory-Prepared Samples

Performance demonstrations using SG tubes with laboratory-prepared flaws are considered to be acceptable in qualifying eddy current techniques if the following conditions are satisfied:

- It must be shown that the eddy current signals from the laboratory-induced flaws are equivalent to the signals from flaws found in operating SG tubes.
- Noise must be quantified in tubes coated with internal magnetite deposits that generate as much or more noise in the eddy current probes as the internal magnetite deposits found in operating CANDU SG tubes.
- If a technique is being qualified for detecting flaws in tube sections with support plates, the laboratory-prepared tubes must have equivalent support plates on them at the flaw locations.
- If a technique is being qualified for detecting flaws in tube sections with deformation, the background noise must be quantified in tubes that are similarly deformed in the vicinity of the flaws.

Acceptable performance demonstrations can be performed with laboratory-prepared tubes that have met the above conditions in a similar manner as qualifications based on pulled tubes. The laboratory-prepared samples should be scanned with the eddy current techniques with flaw detection and/or sizing based on the eddy current data. The laboratory samples should then be examined 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. Acceptable performance demonstrations of flaw detection show comparisons between eddy current predictions and laboratory measurements where one or more of the criteria described in Section 3.5 has been met. Acceptable performance demonstrations of various aspects of sizing (depth, axial extent, and/or circumferential extent) show comparisons between eddy current predictions and laboratory measurements that demonstrate that detected flaws left in service will not likely grow and cause tube failures during subsequent operating cycles.

4.4 Performance Demonstrations of Flaw Detection Based on Signal-to-Noise Ratios

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 must resemble the in-service flaws the eddy current technique is being qualified to detect.

The probability of detecting a particular flaw can then be considered to be 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 in-service tubes.

The flaws should be examined by independent laboratory measurements in order to measure flaw depth, and possibly axial or circumferential extent. These laboratory measurements may consist of scans using NDE techniques that were previously qualified for detection and sizing.

Performance demonstrations of flaw detection are considered to be acceptable when the results of the results of these lower-bound POD calculations meet one or more of the criteria described in Section 3.5.

4.5 Performance Demonstrations Using the Signal Injection Method

The “signal injection” method can superimpose flaw signals upon signals in data files from eddy current scans of in-service tubes. This is accomplished by selecting a certain portion of a data file with a flaw signal in it, subtracting the baseline value from all the data points (both the horizontal and vertical vectorial components), and adding the result to appropriate sections of a data file generated from a scan of an in-service tube. This method can be used to simulate the distortion of flaw signals by the background noise encountered in scans of the in-service SG tubes.

Data files generated by the signal injection method can be used to train and qualify eddy current data analysts. The signal injection method can also be used to qualify eddy current techniques.

POD statistics can be determined by observing the number of flaw signals that eddy current data analysts report from the signal injected data files. The eddy current techniques may then be qualified for detection if the signal-to-noise ratio or POD meets one or more of the criteria

described in Section 3.5. Sizing accuracy can be determined by comparing the analysts' depth and/or lateral extent predictions with laboratory measurements of the flaws. These laboratory measurements may consist of scans of the flawed tubes with NDE techniques that were previously qualified for flaw detection and sizing. Performance demonstrations of techniques for flaw sizing must show that detected flaws left in service will not likely grow and cause tube failures during subsequent operating cycles.

4.6 Qualification Based on Computer Modelling

Computer modelling of eddy current probe responses may offer an inexpensive tool for qualifying inspection techniques. However, in using such tools, 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 must be demonstrated. This can be achieved by comparing field inspection eddy current signals with those calculated using computer modelling codes with both real and simulated signals normalized to that from a common calibration flaw.
- If technique qualification is based only on computer modelling, the modelling codes must be able to accurately simulate the background noise encountered in signals acquired from field inspections. The background noise is partly composed of probe responses to tube support structures, magnetic deposits, conducting deposits, tube deformation, and magnetic permeability variations. In addition, electrical noise from probe cable pickup, cable crosstalk, and grounding contribute to overall signal noise.

To qualify a probe, flaw signals must be accurately calculated. The signals must then be compared with realistic background noise to determine when flaws are detectable. Background noise can be either measured from eddy current scans of in-service tubes, or calculated with appropriate computer modelling codes.

A comparison of flaw signals with background noise can be used to predict the probability of detection. The probability of detecting a particular flaw can then be considered to be equal to the probability of a flaw signal being larger than the noise by a factor of at least 2.

5. SUMMARY

Recommended procedures for qualifying eddy current testing of SG tubes have been presented. A technique qualification requires a Technical Justification that documents the physical principles used in the operation of the technique, and a Performance Demonstration that documents the technique's ability to detect and/or size the flaws of concern.

Techniques are qualified in detecting flaws by demonstrating that flaws deeper than an established FSDR will be detected with high confidence. This can be demonstrated by showing

that the eddy current response to flaws as small as the FSDR have signal-to-noise ratios of 2 or greater. Techniques can also be qualified for flaw detection in statistically based performance demonstrations. However, the flaws and background noise in the performance demonstrations must resemble what is found in in-service tubes.

Tubes with detected flaws may be allowed to remain in service if it can be shown that they will not likely grow to a size where they could potentially cause a tube failure before they are inspected again. This assurance can be obtained only if the flawed sections of the tubes are inspected by one or more techniques that are qualified to size these flaws. To qualify an eddy current technique for sizing, several SG tube flaws must be scanned, flaw sizes must be predicted based on the flaw signals, and the sizing predictions must be compared with an independent technique (a laboratory method or NDE) that has previously been qualified to size the flaws. The error parameters (mean error, standard deviation, RMSE) must then be documented for incorporation into the plugging and/or repair criteria, and statistical projections.

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