Technical Letter Report: Characterizing Steam Generator Tube Degradation Mechanisms with Eddy Current Technology

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Abbreviations

AECL	Atomic Energy of Canada, Limited
ASME	American Society of Mechanical Engineers
AVB	anti-vibration bar
BLG	bulge
CEI	circumferential expansion zone indication
CMOA	condition monitoring and operational assessment
DA	degradation assessment
DEP	deposit
DNT	dent
DSI	distorted support plate indication
EC	eddy current
EDM	electro-discharge machined
EPRI	Electric Power Research Institute
ETSS	examination technique specification sheet
EZI	expansion zone indication
ID	inner diameter
IGA	intergranular attack
ISI	in-service inspection
LPI	loose part with indication
MAI	multiple axial indication
MBM	manufacturing burnish mark
MCI	multiple circumferential indications
NDE	nondestructive evaluation
NDD	no detectable degradation
NQI	non-quantifiable indication
NRC	U.S. Nuclear Regulatory Commission
OD	outer diameter
ODSCC	outer-diameter stress corrosion crack/cracking
OTSG	once-through steam generator
PLP	possible loose parts
PVN	permeability variation
PWSCC	primary-water stress corrosion crack/cracking
SAI	single axial indication
SCC	stress corrosion crack/cracking
SCI	single circumferential indication
SG	steam generator
S/N	signal-to-noise ratio
SSPD	site-specific performance demonstration
TS	tube sheet
TSP	tube support plate
TTS	top of the tube sheet
TW	through-wall
VOL	volumetric response

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S. Bakhtiari, D. S. Kupperman, and W. J. Shack

Abstract

Steam generator tubes in nuclear reactors must be regularly inspected for flaws during outages. This report provides an overview of the current primary method used for nondestructive evaluation of these tubes, eddy current (EC) testing. It covers three main topics. The first summarizes the generic procedures for the analysis of the data acquired with conventional EC probes. The second describes how these data are used to characterize signals from various types of non-degradation discontinuities on tubes, such as dents, manufacturing burnish marks, loose parts, and deposits. The third covers how these data are used to detect and characterize common forms of tube damage or degradation, such as thinning, wastage, wear, stress corrosion cracking, and intergranular attack. Ample graphical examples are provided to illustrate the interpretation of EC signals from different steam generator tubes. The report emphasizes the fact that the decision-making process must be guided by not only the acquired EC data, but also the operator's knowledge of the steam generator design and its operating history.

1 Introduction

Eddy current (EC) testing is currently the primary nondestructive evaluation (NDE) method used for in-service inspection (ISI) of steam generator (SG) tubes during plant outages. Inspections are performed in accordance with site-specific guidelines that prescribe the equipment, techniques, and analysis procedures, as well as the training of individuals that analyze the data. Eddy current testing provides information about SG tube discontinuities. In general, depending on the technique being employed, the measured probe response can provide information about an indication's location, origin (i.e., initiated from inner or outer surface of the tube), spatial extent, and relative orientation (axial, circumferential, or volumetric), as well as the electrical properties (i.e., electrical conductivity and magnetic permeability, which are indicators of a material's capability to conduct electric current and magnetic flux, respectively) of the tube. The general characteristics of the probe response (e.g., signal shape observed from linear trace and impedance plane trajectory, spatial distribution, and frequency response) can be used to distinguish between consequential indications and non-degradation discontinuities.

Because of the sensitivity of the EC probe to a wide range of tubing discontinuities and the potential similarity of signals from dissimilar flaw types, the probe response alone may not always allow one to definitively associate a signal with a particular mode of degradation. More complete characterization of the degradation and damage mechanisms may only be achieved when NDE evaluations are considered in conjunction with information about the SG design, operating history, active damage mechanisms, and past experience at a particular plant or at other plants with similar SGs. Site-specific performance demonstration (SSPD) documents used for training of operators are intended, in part, to guide the NDE decision-making process based on past experience on known damage mechanisms associated with a particular SG type. It is critical, however, to be attentive to the possibility of new forms of damage that may not have been identified at a particular site. Comparison of EC inspection data from previous outages provide additional means to help discern aggressive damage mechanisms from benign ones. Complementary ISI methods (in-situ pressurization, ultrasonic testing, visual inspection, etc.) may be employed in certain cases to resolve complex forms of tube degradation. Destructive examination of pulled tubes may also be used to verify NDE results. Results from the analysis of tubes pulled from SGs are incorporated into performance demonstration databases and play an important role in the training of analysts.

This report provides a general overview of EC inspection techniques used in the field for characterization of SG tube degradation. It summarizes the capabilities and limitations of EC technology and potential advantages of supplementary EC inspection techniques for more reliable characterization of difficult flaws. Common setup procedures for the calibration and analysis of EC inspection data are discussed in association with a particular inspection technique. Various damage mechanisms and the associated EC signal characteristics are also discussed. In particular, analysis of data associated with the characterization of volumetric degradations is presented in detail. The key EC signal characteristics used in distinguishing various mechanisms and the applicable techniques are noted. In many cases, graphical examples are provided to help better understand the decision-making process.

2 Importance of SG Design and Operating History

Although many damage mechanisms are common to a wide range of SG designs, some have only been found in certain SG models and at specific elevations and locations within the tube bundle. For example, secondary-side intergranular attack (IGA) and stress corrosion cracking (SCC) have been found in all SG designs with Alloy 600 tubing. Pitting, on the other hand, has only been found in recirculating SGs and at specific locations. Steam generator design (basic type, tubing material, fabrication process, support structure design, tube-sheet expansion procedure, properties of U-bends, etc.), industry operating experience, and the history of an individual plant (active damage mechanisms, water chemistry, chemical cleaning, etc.) play an important role in identification of SG tube regions that are considered to be more prone to particular modes of degradation.

Inspection history and the location of an indication must be considered in the process of characterizing an EC indication. Aggressive forms of degradation such as primary-water stress corrosion cracking (PWSCC) are expected to result in measurable changes in EC signals over relatively short time intervals, whereas the signals associated with benign defects such as manufacturing burnish marks (MBMs) and dents are not expected to change significantly between successive reactor outages. In the presence of stresses and other environmental factors, however, such areas could serve as initiation sites for other forms of degradation. The location of an indication can be useful in deciding the character of a difficult–to–identify signal because the underlying tube condition may be inferred on the basis of the potential for the presence of consequential indications. Thus, comparison of EC inspection data between current and past outages can provide vital information about degradation mechanisms. The reliability of such signal comparisons depends on consistent implementation of data acquisition and analysis procedures. Uniform application of the procedures can further help improve the reliability of comparisons when separate databases are used and of establishing baselines when improved or complementary techniques are to be implemented.

3 Conventional Eddy Current Inspection Techniques

Both bobbin and rotating probes are widely used for EC ISI of SG tubes. Bobbin probes typically have a pair of circumferentially wound coils, which may be excited in either absolute or differential mode. In absolute mode, the signal from a single coil is measured; in the differential mode the difference between the signals from the two coils is measured. These probes are commonly used to inspect the entire length of each tube. They provide a single measurement at each axial position along the tube that represents an integrated value over the entire circumference of the tube. Because the induced current flows parallel to the coil's winding, bobbin probes are not sensitive to circumferentially oriented indications. Furthermore, because the coil is not in direct contact with the tube inner surface, geometrical changes in the tube diameter (e.g., dent, expansion, bulge, and ovalization) as well as probe wobble, often as a result of wearing of the centering mechanism, can produce EC responses that are large enough to mask nearby indications. Both geometrical changes and probe wobble, in effect, change the probe's "fill-factor" (i.e., square of the ratio of probe to tube diameter) and thus degrade the signal-to-noise ratio (S/N).

Rotating probes are used to overcome the limitations of bobbin probe inspections. These probes incorporate small surface coils that induce currents only in a localized area so that they provide higher spatial resolution. They are primarily intended for detection and characterization of crack-like indications. Complete circumferential coverage is achieved by helical traversing of the probe through the tube. The helical scan pattern is formed by the rotational motion of the probe head as it moves along the tube axis. Because of their slow scanning speed and high data output, rotating probes are typically used for selective inspection of short tube segments and for SG tube areas that cannot be reliably inspected with bobbin probes. Conventional rotating probes contain either single or multiple coils in the probe head that are mechanically kept in contact with the tube's inner surface (i.e., spring-loaded surface-riding coils) to reduce the influence of tube geometry variations by limiting lift-off of the coil from the surface. The most common rotating probe currently used for ISI applications has two pancake-type coils (i.e., coils whose axis is perpendicular to the tube axis so that the plane of the coil is parallel to the tube surface) and a cross-wound coil with the plane of the cross also parallel to the tube surface. The pancake coils operate in absolute mode and cover the middle and upper frequency ranges. The cross-wound coil operates in the differential mode, which helps suppress the effect of localized variations in tube geometry. The cross-wound differential coil is commercially known as the +Point™ coil (Zetec, Inc.).

4 Eddy Current Inspection Guidelines

The degradation assessment (DA) document at a plant provides the SG inspection plan associated with an outage and defines a common framework to help control the quality of ISI results. The document provides site-specific SG design information as well as the operating history. It also provides information regarding the active and potential damage mechanisms at all susceptible regions within the SG and the extent of the required NDE examinations during an outage. It further identifies site-validated NDE techniques to be used for an outage. As stated in the *PWR SG Examination Guidelines* from the Electric Power Research Institute (EPRI), the DA is intended to ensure that the NDE detection and sizing performance is known and can be appropriately accounted for in condition monitoring and operational assessments (CMOAs).[1] For each degradation mechanism, the DA identifies the appropriate examination technique specification sheet (ETSS) that has been validated for use at that particular site. The DA document provides the site-specific guidelines necessary for consistent evaluation of EC inspection data in accordance with the established industry standards. Typical guidelines provided by such documents include requirements for operator qualification and responsibilities, plant design specifications, data acquisition procedures, calibration standards, and data analysis and reporting requirements. Site-specific performance demonstration (SSPD) data are included with the DA to familiarize the analysts with the history of the SGs at that plant and provide the basis on which operator qualification is tested. The SSPD database is commonly revised to reflect the most recent industry ISI experience.

Plant design specifications provide basic information regarding the model of the SGs at a particular unit. The information provided includes the number of tubes, nominal tube dimensions, tube material, tube manufacturing process, tube support plate (TSP) locations and design (drilled, broached, etc.), type of anti-vibration bars (AVB), tube-sheet (TS) configuration, tube expansion process, the number and location of baffle plates, the number and location of plugged tubes, and the history of EC examinations. An ETSS is available for each data acquisition and analysis technique and defines the applicability of the technique for the inspection of various regions of the SG. Each ETSS also defines the probe type, minimum sampling rate, calibration method, setup procedures, and channel configurations for that particular technique. The calibration methods for bobbin probe techniques are usually based on the American Society of Mechanical Engineers (ASME) calibration standard tube, which as a minimum, contains outer diameter (OD) drilled holes ranging from 20% to 100% through-wall (TW), a 10% OD groove, a 20% inner diameter (ID) groove, and a tube support ring. A typical calibration standard for rotating probe examinations contains ID and OD machined notches with axial and circumferential orientation ranging from 20% to 100% TW. Depending on the history of the SGs at a particular unit, other calibration standards with additional machined discontinuities may be required. For example, wear-scar standards that include machined flaws of different shapes and sizes (e.g., one or two-sided flat or tapered wear scars) are used when the DA document requires sizing of this form of mechanical degradation. Similarly, other manufactured flaws, structural supports, mechanical deformations, and deposit simulants may be included in the calibration standards for more reliable analysis of EC inspection data when the inspection plan requires assessment of such conditions or elements.

For bobbin probe examinations, the selection of the primary test frequency is based on the tube wall thickness. This frequency is selected such that both OD and ID initiated indications can be detected with reasonable sensitivity. Auxiliary test frequencies that provide increased sensitivity to ID initiated (higher frequency) or OD initiated (lower frequency) discontinuities are also used to obtain complementary information about the signals. In modern multifrequency EC inspection systems, data obtained at two or more frequencies are combined by software-based algorithms (commonly referred to as a "mix" process) in order to suppress the probe response from known interfering discontinuities. A common example of this approach is a two-frequency mix for the suppression of probe response from a TSP. This mixing is done by combining data from the primary frequency channel with data from an auxiliary, lower-frequency channel. For a tube with 1.27-mm (0.050-in.) wall thickness, the primary and auxiliary frequencies suggested in standard guidelines are 400 kHz and 100 kHz, respectively. These frequencies are adjusted for other tube wall thicknesses in accordance with equations founded on the EC depth of penetration (i.e., skin depth). Because various forms of degradation mechanisms occur at or near support structures, mix outputs using absolute or differential channels are commonly used for detection and sizing of indications in such regions.

For rotating probe examinations, the primary test frequency is typically based on the coil's frequency response and is usually near the center frequency, where the coil provides the maximum detection sensitivity. Therefore, the same frequencies are often used for a range of tube wall thicknesses. As stated earlier, a typical rotating probe head houses multiple surface coils that operate at different frequency bands. Although technically feasible, mixes are not commonly used for rotating probe examinations. However, the high spatial resolution of the small surface coils on a rotating probe generally allows discrimination of complex signals by analysis of the raw data channels.

Although the entire length of an SG tube is examined by NDE techniques, the site-specific guidelines primarily focus on regions of the SG tubes where known degradation mechanisms are likely to occur. Initial screening of bobbin coil data is performed with prescribed span settings (i.e., where the extent of zooming is generally defined in terms of the percentage of the full scale on the data analysis window that would allow the minimum signal level of interest to be visually discernible) by the analysis setup procedure. More precise examination of a particular region of interest may necessitate temporary adjustment of the span setting. The extent of examinations is based on previously established tube row and column numbers, as well as the elevation for regions of special interest. Bobbin probes are typically used to examine the entire length of tubing, except expansion transition zones at the top of the tube sheet (TTS) and small-radius U-bends. Along with regions of special interest, these particular areas are often flagged by the bobbin coil analysis for further testing with rotating probes.

The raw and processed data that are used during multifrequency EC analysis may be separated into three or four channels, namely, screening/detection, diagnosis/confirmation, sizing and reporting. The primary screening channel for bobbin probe inspections is typically a differential mix processed channel [e.g., 400|100 kHz for a tube wall thickness of 1.27 mm (0.050 in.)] that suppresses the probe response from OD support structures. Secondary screening channels may include a lower frequency absolute channel for monitoring of probe location along the tube and identification of volumetric indications that exhibit a larger amplitude signal at lower frequencies (e.g., manufacturing burnish marks (MBMs) and support structure fretting) and a second differential channel at about half the frequency of the primary channel that is intended for detecting early indicators of corrosion-type damage, especially at tube support structures. Both the axial trace (i.e., expanded strip chart), which displays the amplitude of the signal components, and the lissajous pattern (i.e., impedance plane trajectory), which displays the reactive versus the resistive component of the signal, are monitored during the examination of bobbin coil data. Any variation of the signal outside the baseline level, observed on either the vertical component of the strip chart or the lissajous pattern, is examined in further detail for the presence of consequential signals.

Once a signal is detected, the source of the signal is determined through analysis of its frequency and spatial domain characteristics, as well as general attributes associated with the shape of the signal itself (e.g., discrete or continuous signals associated with crack-like and mechanical volumetric degradation, respectively). This determination is made by examining the phase angle, amplitude, and spatial frequency (i.e., spatial extent or duration of the indication) of the signal deduced from a single frequency channel, as well as the amplitude and phase relationships among multiple test frequencies. Using the signal spatial frequency behavior as an analysis parameter requires a consistent scan speed. Abrupt signals with short duration and phase relationships (i.e., variation or "rotation" of phase angle with frequency) that indicate localized degradation of the tube wall are typically caused by "acute" corrosion-type flaws, such as pitting and cracking. Signals with longer duration are indicative of volumetric wall loss typically caused by "chronic" mechanical damage, such as MBM or fretting wear. Probe responses associated with other conditions such as denting, deposits, and support structure degradation, considered as non-flaw mechanisms with regard to SG tubing, are distinguished from flaws by their unique phase relationships among the excitation frequency channels. Empirical information such as the amplitude relationship between the differential and the absolute channels can also help distinguish between acute and chronic damage mechanisms. Such information, coupled with knowledge of the plant's DA for the particular SG under inspection, permits classification of indication types that are reported according to pre-established criteria.

Because bobbin coil probes are known to have little sensitivity to some forms of degradation such as circumferential cracks, supplementary EC examinations of selected regions within the SG are performed with rotating probes. The same electromagnetic principles that govern the response of bobbin probes apply to rotating probes. However, rotating probes offer much higher spatial resolution in comparison to bobbin probes, especially in the circumferential direction; thus, the response of rotating probes to tube discontinuities, in general, is more explicable. Small surface probes with narrow spatial coverage can help better resolve closely spaced indications. Directional probes with axially, circumferentially, or cross-wound coils are more sensitive to the orientation of defects and provide additional information that can be important for the disposition of complex degradation mechanisms. Differential cross-wound coils (e.g., +Point™), which are incorporated into the most commonly used rotating probe head, provide additional suppression of interference from localized tube-geometry variations and help better discriminate crack-like signals in such regions. In addition to strip charts and lissajous plots, data collected with a rotating probe are displayed as a three-dimensional isometric plot (commonly referred to as C-scan plot) of the amplitude versus axial and circumferential position, which significantly improves visual interpretation of EC inspection data.

Typically, plant-specific guidelines have multiple flow diagrams or decision trees to help analysts focus on the areas of interest and increase the likelihood of detection of degradation of concern for that unit. To maintain consistency among analysts, guidance is provided on how each indication type is to be evaluated and reported. Different flow diagrams are commonly developed for the teams that perform the production analysis and for the teams that perform the lead review analyses for each EC inspection technique (e.g., bobbin and rotating probe inspections). The diagrams provide specific guidance for the channels to be used for data screening, confirmation, sizing, and reporting. The diagrams for the production teams terminate either in a specific call (typically characterizing the signals in terms of a three-letter code, signal amplitude and phase, location, extent, and if applicable, an estimate of flaw size) or a finding that there is no detectable degradation (NDD). The flow diagrams for the resolution and lead review could terminate in recommended actions regarding repair or structural assessment of a flaw.

A generic flow diagram for the reporting of EC signals detected with a bobbin probe in a recirculating SG with 1.27-mm (0.05-in.) tube wall thickness is shown in Figure 1. This diagram provides the analysis logic for five locations in an SG unit. A more specific flow diagram for evaluation of signals detected at tube support structures is shown in Figure 2.[2] The diagram in this case terminates in eight different calls. They are deposit (DEP), permeability variation (PVN), dent (DNT), bulge (BLG), manufacturing burnish mark (MBM), distorted support plate indication (DSI), percent TW estimate of an indication, and NDD. The nature of various tube damage mechanisms including those mentioned above is discussed in the following sections. The process begins with detection of an anomalous signal. Once the signal is determined to be in the flaw plane (i.e., the phase angle lies within the first or second quadrant of the impedance plane) at all test frequencies, a series of questions is addressed to further examine the characteristics of the signal. Signals determined to be associated with tube geometry deformation, manufacturing process, or deposits are marked only by a three-letter code, while a depth estimate is recorded for indications associated with tube wall loss. The amplitude ratio of the signals from the primary differential and absolute channel is used to help determine the volumetric nature of an indication.

A generic flow diagram for production analysis of rotating probe data collected from various regions of an SG is shown in Figure 3. In addition to the strip chart and the lissajous trace, the isometric plot is also examined. Once again, the signal attributes in conjunction with the knowledge of plant history guide the analyst's decision-making. Site-specific guidelines define how the calls should be made for specific locations. The rotating probe flow diagrams typically show fewer steps for the production analysis logic in reaching a final decision because of the more descriptive nature of the rotating probe data in comparison to bobbin probes. The guidelines in Figure 3 direct that additional steps be taken to confirm a signal called as an indication based on the primary analysis channel. Such additional confirmatory steps can include verification of the presence of a measurable signal with flaw-like response in the auxiliary frequency channels or confirmation by other coils on a multi-coil rotating probe. More conservative guidelines would call a signal an indication based solely on the primary analysis channel. The orientation (i.e., axial, circumferential, or volumetric) and the number of indications (i.e., single or multiple) in a particular location are the primary characteristics of an indication that are typically reported along with the standard measurement results (i.e., location, extent, amplitude, and phase). Reporting requirements at a particular site may also call for providing isometric plots of the data where a call is made.

For a production analyst, the characterization of damage mechanisms typically involves reporting whether a signal is from a degradation or non-degradation mechanism, its location along the SG tube, the signal amplitude and phase angle (i.e., depth estimate), the signal orientation (i.e., axial or circumferential), the origin of the signal (i.e., from inside or outside of the tube wall), whether it has volumetric or crack-like characteristics, and whether the signal is from a single or multiple indications. Characterization of a particular damage mechanism based on EC inspection data is sometimes achieved through an elimination process that involves determining whether an indication conforms to patterns that are characteristic of known forms of degradation. As shown in Figure 3, calls by the production analyst are further evaluated by the resolution and the lead review team. Their evaluation includes recommendations regarding tube structural assessment and repair. The final analysis of a signal is generally carried out either by the resolution and lead review teams or as part of an engineering assessment that is performed separately. A more detailed site-specific flow diagram is typically used by the resolution or lead analyst for final disposition of indications.

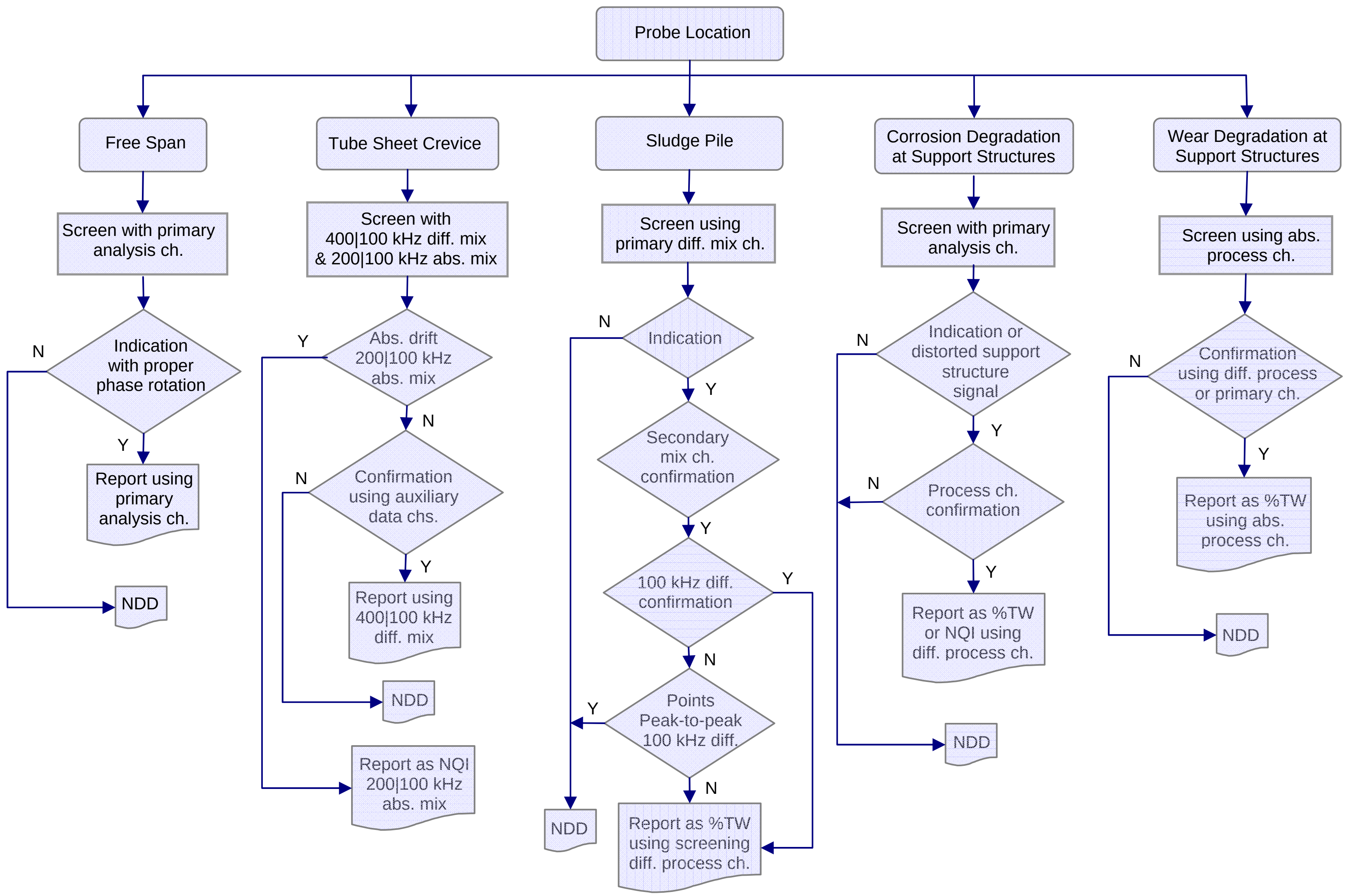


Figure 1. Generic flow diagram for analysis of EC inspection data from a recirculating SG with 1.27-mm (0.05-in.) tube wall thickness. Analysis steps are shown for five locations. NDD = no detectable degradation; NQI = non-quantifiable indication.

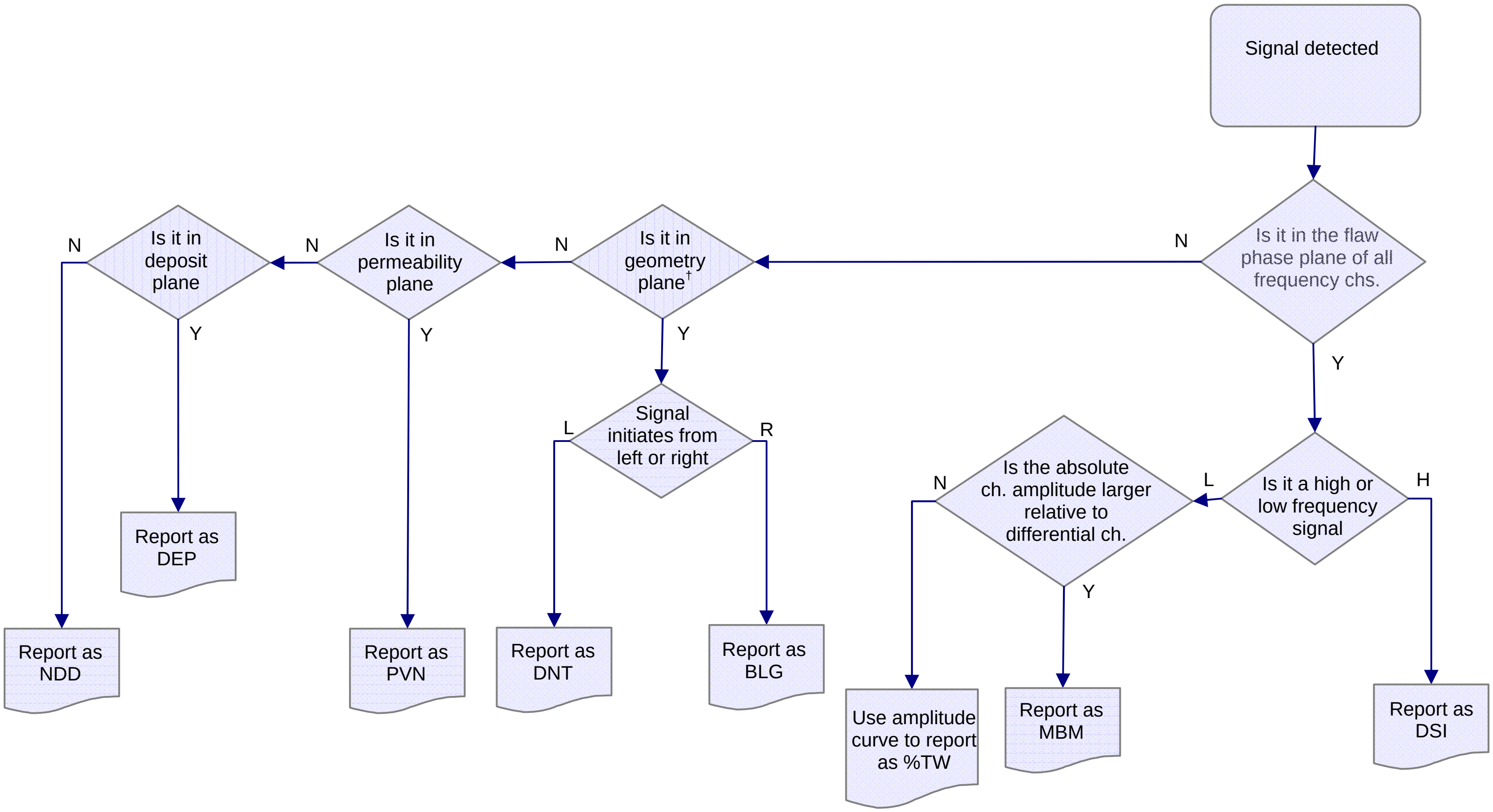


Figure 2. Generic flow diagram for analysis of bobbin probe data at tube support structures. Calls are reported as distorted support plate indication (DSI), manufacturing burnish mark (MBM), bulge (BLG), dent (DNT), permeability variation (PVN), deposit (DEP), and no detectable degradation (NDD). A depth estimate is provided for volumetric degradation based on a pre-established amplitude calibration curve.

† Geometry plane here refers to a narrow region along the horizontal axis of the impedance plane encompassing signal excursions indicative of change in probe lift-off.

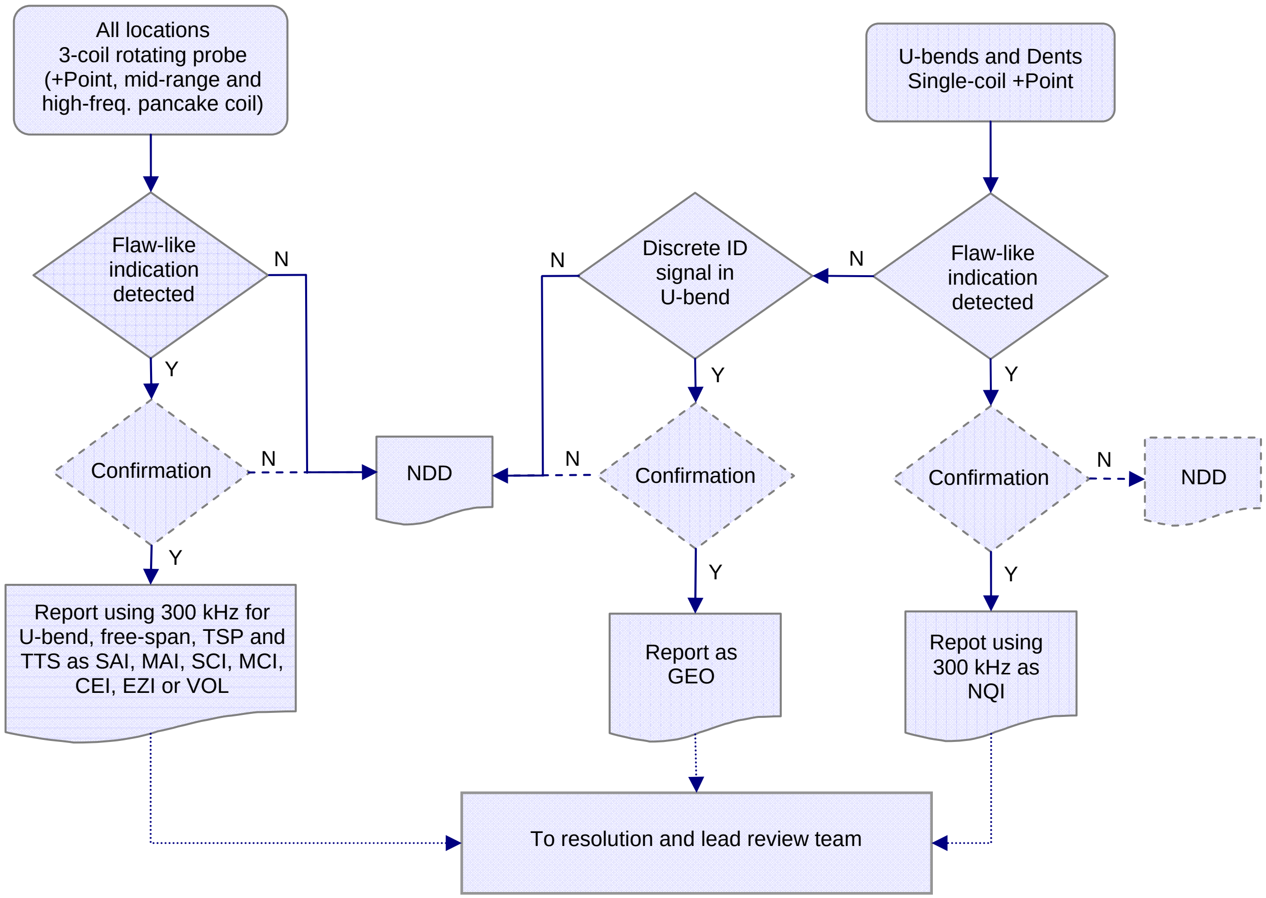


Figure 3. Generic flow diagram for production analysis of rotating probe data. Calls are reported as single axial indication (SAI), multiple axial indication (MAI), single circumferential indication (SCI), multiple circumferential indications (MCI), circumferential expansion zone indication (CEI), expansion zone indication (EZI), volumetric response (VOL), non-quantifiable indication (NQI), geometry (GEO) and no detectable degradation (NDD). Dashed blocks represent discretionary stages that may not be implemented at a particular site.

5 Characterization of Non-degradation Mechanisms

The response of the EC probe to various discontinuities that are not considered detrimental to the integrity of SG tubes is discussed below. These discontinuities include signals associated with localized tube deformation (e.g., dents), manufacturing artifacts, loose parts (excluding wear attributed to loose parts), and non-uniformities in electrical properties produced either by deposits or variation of the tube material properties.[3] Although these can be categorized as non-degradation mechanisms, EC inspection data in locations where such mechanisms are present should be examined carefully because of the potential susceptibility of these areas to various forms of degradation. For example, the stresses present at deformed regions of the tube or the accumulation of deposits could promote initiation of corrosion and cracking of the tube wall. From an NDE standpoint, the probe response from non-degradation type discontinuities could distort or, in extreme cases, completely mask the signal from nearby consequential indications. Implementation of appropriate EC inspection techniques (i.e., probe and analysis procedures) thus plays a vital role toward reliable detection and characterization of such indications.

5.1 Dents and Dings

A dent is typically defined as deformation of a tube at a support structure, while a ding is an indentation in the free-span region of the SG tube. Dents generally occur as a result of gradual accumulation of corrosion products that compress the portion of the tube confined by the support structure (Note: Some plants define dents as deformation as a result of corrosion or service induced conditions and dings as a result of initial manufacturing conditions.) Although the mechanism of damage for dents and dings is different, the deformation of the tube in both cases produces a similar EC probe response. For bobbin probes, the localized reduction of the tube wall diameter increases the probe fill-factor, which, for large deformations, could be a first-order contribution to the probe response in that location. For rotating probes with small surface coils that operate in the absolute mode, the deformation of the tube can increase the lift-off and, in turn, the coil coupling, which could also produce a large probe response.

Figure 4 shows the bobbin coil response to a free-span ding and a dent at a TSP intersection. In both cases, the strip chart trace and the lissajous figure are shown for the primary processed channel (400|100 kHz differential mix). The second strip chart in the analysis window shows the trace for the 100 kHz differential channel that is used to determine the location of each signal along the tube. Other than the location of signals along the SG tube, the two signals display similar characteristics. The impedance plane pattern shows a smooth excursion that follows the expected trajectory for a change in the probe's fill-factor. For calibrated data with the response from probe wobble set nearly horizontal, the lissajous plot for dents is expected to display an oblate pattern along the horizontal axis at all test frequencies. In accordance with the generic flow diagram of Figure 2, the initial excursion of the impedance plane trajectory could be used to separate dents from bulges (i.e., outward deformation of the tube wall). The localized change produced by the deformation of the tube wall gives rise to a strong signal that distinguishes a dent from small baseline fluctuations associated with probe wobble. Because of the vectorial addition of EC signals, the bobbin probe response from large dents could mask signals from flaws within the dented region. The capability of the bobbin probe to detect a signal due to degradation within a dented region depends, in part, on the location of the indication within the dented region. This subject is discussed later in this report in association with characterization of degradation mechanisms in dented regions of the SG tube. Three-frequency mixes, commercially referred to as a "turbo mix," are sometimes used in site-specific applications to reduce the influence of dents during bobbin probe inspections. Plants commonly set an upper limit on the magnitude of the EC signal from dents (e.g., 2 volts on the primary mix channel) above which bobbin probe data would be considered unreliable in terms of detection of degradation within the dent region. If the bobbin probe signal exceeds this limit, additional measures are then taken, such as supplementary inspection of the dented region with a rotating probe.

Eddy current rotating probes are used to overcome the limitations of bobbin probes. The surface-riding feature of the embedded coils helps to minimize the effect of probe lift-off at deformed regions of the tube and thus improves the S/N. Furthermore, the high spatial resolution of such probes allows discrimination of other signals that may be present at or near the dented region of the tube. A differential cross-wound coil (e.g., +Point™) probe helps suppress the influence of volumetric discontinuities (such as dents and dings) under the probe. The directional sensitivity of the coil additionally helps to discriminate volumetric from crack-like signals.

5.2 Manufacturing Burnish Marks

A manufacturing burnish mark is a shallow depression in the outer surface of the tube that is caused by final polishing of the tube during the manufacturing process. Because of the availability of pre-service EC inspection data, identification of an MBM is not expected to pose a major NDE challenge. Reviews of historical EC data from existing indications, including MBMs for which signals would be traceable back to pre-service inspections, are routinely carried out during ISI. Any measurable change in the probe response between successive inspections could be associated with other forms of damage at the SG tube location previously identified as MBM.

The bobbin probe response from an MBM is expected to resemble that of a shallow volumetric indication (i.e., extended signal with large phase angle). Figure 5 shows the bobbin probe signals at several test frequencies from an MBM in the free-span region of a tube. The signal from the MBM is detectable from the primary screening channel (400|100 kHz differential mix). The portion of the signal being examined, which is displayed in the expanded strip chart on the bottom right corner of the analysis window, is indicated by the horizontal line in the long strip-chart trace. The signal is also clearly detectable from the long strip-chart trace of the auxiliary absolute channel (100 kHz). Multiple lissajous plots of the same signal are also shown for three differential channels (400 kHz, 200 kHz, and 100 kHz) and an absolute test channel (100 kHz). The counterclockwise rotation of the impedance plane trajectory from the highest to the lowest test frequency is indicative of a very shallow OD indication (<10% TW). The axial extent and small but clearly measurable peak-to-peak voltage (V_{pp}) of the signal are further indicative of a shallow volumetric indication. The generic flow diagram of Figure 2 may be used to identify MBMs.

5.3 Permeability Variation

Standard alloy tubes (e.g., Alloy 600, 690, and 800) have relative magnetic permeability $\mu_r \approx 1$, which places them into the category of non-ferromagnetic materials. Microstructural inhomogeneities, however, can alter the electrical properties of the conducting material and create either localized or extended regions of the tube with higher magnetic permeability ($\mu_r > 1$). Heat treatment and cold work are two mechanisms that can alter the magnetic permeability of the alloy tubing. Eddy current probes are particularly sensitive to changes in the magnetic properties of the material under interrogation. Figure 6 shows the localized permeability variation near a TSP intersection on the cold-leg side of an SG tube that was detected with a bobbin probe. Typical probe response associated with localized permeability variation (commonly identified with the three-letter code PVN) is a large amplitude signal with a phase angle that resembles that of a shallow ID indication. However, unlike signals associated with tube wall loss, the lissajous figure for bobbin probe signals associated with permeability variations is a tight oblate trace with a nearly straight impedance plane excursion. In Figure 6, the signal is detectable at all test frequencies (400 kHz, 200 kHz, 100 kHz, and 400|100 kHz mix) with nearly identical lissajous figures. Because the probe response associated with permeability variations could potentially mask nearby signals from consequential indications, site-specific guidelines for data analysis often call for recording of PVN signals that are deemed by the analyst to affect the ability to detect flaws.

When probe response from localized permeability variations is large or when extended lengths of a tube are affected, supplemental examinations with magnetically biased bobbin or rotating probes (commonly referred to as "mag-biased" probes) are performed. Such probes incorporate rare-earth magnets in the probe head to magnetically saturate the region under the coil and thus reduce the effect of permeability variations on the probe response. The signal from a shallow OD indication obtained with a standard bobbin probe and the signal from the same indication obtained with a magnetically biased probe are shown in Figure 7. The signals display similar amplitude and phase angle responses in both cases. The strip chart traces for the primary differential mix (400|100 kHz) and the 200 kHz absolute channel clearly indicate the suppression of baseline noise associated with permeability variations by the magnetically biased probe. The use of such a probe significantly improves the S/N, with minimal distortion of the signal of interest.

For situations in which the tube permeability variations are large, conventional magnetically biased probes may not provide the level of magnetization necessary to suppress the baseline noise.[4] In such cases, specialized probes (e.g., high mag-bias bobbin and rotating probes) may be needed to provide a higher degree of magnetization (i.e., stronger magnets). Site-specific qualifications, however, may have to be performed to demonstrate the applicability of the technique. In some instances, tubes are preventively plugged when the permeability variations potentially affect the ability to reliably inspect the tube.

5.4 Loose Parts

The location of the SG tube within the bundle generally plays an important role in the characterization of potential damage from loose parts. Loose parts are normally found at the top of the tube sheet and near peripheral tubes. Loose parts, however, are sometimes found near interior tubes and at higher elevations within the tube bundle. The preheater region (in units with preheaters) is another region where loose parts are typically found. Electrically conducting loose parts are themselves detectable at low test frequencies. In the absence of any detectable damage to tubing, a signal from an extraneous object on the secondary side of the SG is recorded as a possible loose part (PLP). Eddy current signals are shown in Figure 8 for two PLPs near the TTS on the hot-leg side of the SG. These signals were obtained with a bobbin probe in one case, and with the pancake coil of a rotating probe in the other case. Both signals are at a frequency of 20 kHz. Such low excitation frequencies are used primarily for locating support structures. Because of the lack of sensitivity at this low frequency to typical tubing degradation, any signal detected away from the support structures could be associated with a loose part. The relatively large amplitude and phase angle of the bobbin probe signal shown in Figure 8 suggest the presence of a large OD discontinuity outside the tube wall and slightly above the TTS. Since such a discontinuity does not conform to any known OD discontinuities such as deposits, support structures, and tube deformations (i.e., dents or bulges), it could be a PLP. A PLP call made from a bobbin probe signal can be confirmed by EC examination with a rotating probe. An isometric plot obtained with a rotating pancake coil is given in Figure 8, which clearly shows an OD indication a small distance from the TTS. The localized nature of the signal rules out the possibility of extraneous discontinuities such as deposits. If a clear signal can be obtained, the rotating probe data at higher frequencies can be used to confirm that the phase angle rotation of the PLP does not conform to known forms of tubing damage.

Site-specific guidelines assign a different analysis code to consequential indications, such as a loose part with indication (LPI), when tube wall degradation or damage is detected in connection with a loose part. When tubing damage is detectable at higher frequencies, the LPI signal from a volumetric indication, such as tube wear, can be characterized on the basis of common signal features that are discussed later in this report.

5.5 Characterization of Deposits

Deposits which are typically composed of corrosion products like magnetite, can accumulate either on the inside or outside surface of SG tubes. Most deposits in the U.S. plants however, are located on the external surface of the tubes. Such deposits can exhibit a wide variability in composition and electrical properties (conductivity and permeability). Ferromagnetic corrosion products such as magnetite in the crevice region between a support structure and the outside surface of a tube are not characterized as part of the conventional ISI data analysis. The influence of magnetite on the outside surface on EC signals is considered to be negligible at the test frequencies that are used for detection and characterization of tube wall degradation. However, the presence of conducting constituents or films can induce a large response that may be difficult to separate from flaw signals. Accumulation of conducting and ferromagnetic deposits inside flaw openings can produce an opposite effect and reduce flaw signal response, which could potentially mask flaws. Random distribution of particles further complicates the analysis of data at such locations.

Accumulation of corrosion products and other impurities can lead to other damage mechanisms of concern such as denting, and such deposits can serve as the initiation site for various forms of tube wall degradation. If it is deemed necessary, the ferromagnetic deposits can be examined by low-frequency EC excitation. Characterization of highly conducting constituents within the deposit layers often requires use of multiple test frequencies. Consistency of the probe response (i.e., similar rotation of signals at all test frequencies) is the primary characteristic that separates signals associated with tube wall degradation from signals associated with deposits and extraneous discontinuities.

Thicker sludge deposits that can accumulate on the outside surface of the tube above the tube sheet and low elevation support plates that do not contain highly conducting constituents also have a negligible effect on the EC probe response at the frequencies used for detection of tube wall degradation. The portions of the tubes within the sludge, however, are more prone to a wide range of tube wall degradation. The sludge pile is typically monitored by use of a bobbin probe at a very low frequency (e.g., 20-50 kHz absolute mode). The probe response from sludge is a long and uniform change in the baseline extending above the TTS and TSP intersections. The non-uniform accumulation of deposits may be confirmed by data from rotating probes. Figure 9 shows an isometric plot of rotating probe data with a 2.92-mm (0.115-in.) pancake coil at 20 kHz. The probe response from the sludge shows up as a smooth increase in signal amplitude with no transition between the sludge and the TTS response. The sludge depicted in Figure 9 only affects a small portion of the circumference of the tube.

Because the conductivity of copper is greater than fifty times that of Alloy 600, the presence of copper on the outside surface of the tube within the deposit layer can significantly affect the probe response and thus complicate the analysis of EC inspection data. Copper deposits are not currently considered to be a major SG issue (due to the replacement of copper containing components on the secondary side of the plant). Nevertheless, interference from a significant amount of copper deposits could render EC inspections unreliable. The inability of EC techniques to detect consequential indications in the presence of an excessive amount of copper deposits may call for other actions to be taken, including supplementary inspections with other NDE techniques of the affected regions.

Site-specific data analysis procedures have been developed for characterization of tube degradation in the presence of copper deposits based on bobbin-coil inspection data. Identification of the copper deposit itself is based on a comparison of the probe response between the primary differential channel [e.g., 400 kHz for tube wall thickness of 1.27 mm (0.05 in.)] and the corresponding mix-frequency process channel (e.g., 400|100 kHz) for suppression of the TSP response. Unlike signals from tube wall degradation, the initial excursion of the impedance plane trajectory from copper deposits in the primary differential and the mix channels occurs in different quadrants (i.e., downward and upward, respectively).

Figure 10 shows examples of signals detected in the sludge pile region with a bobbin probe. An empirically deduced procedure is used for characterization of such signals in the presence of copper deposits. The primary screening channel for the deposit region is a high-frequency differential mix (typically, 600|100 kHz or 600|200 kHz) that is generated based on suppressing the probe response from a copper ring placed on the calibration standard tube. Any remaining signal from the imperfect suppression process is referred to as the “copper residual.” The high frequency is selected to limit the influence of OD discontinuities. A TSP differential mix (i.e., 400|100 kHz) and a lower auxiliary frequency (e.g., 100 kHz differential) are used for confirmation purposes. The middle pane of the analysis window in Figure 10(a) shows a signal detected at the TTS within the sludge pile region using the screening mix channel. The right-hand pane of that window shows the same indication detected with the 100 kHz differential channel. In Figure 10(a), if the peak-to-peak marker points measured with the copper mix channel and confirmed by the TSP mix channel do not encompass the entire signal in the lower-frequency auxiliary differential channel, then the signal is identified as a flaw indication and reported as percent through-wall. In Figure 10(b), if the marker points encompass the entire signal at the low-frequency confirmation channel, then the indication is identified as a copper residual signal. Two more examples of indications detected in the presence of copper deposits in the cold-leg side of the SG in the sludge pile and in the crevice region below the TTS are shown in Figures 10(c) and 10(d), respectively. Once again, the signals were detected with the screening differential mix channel and were confirmed with the TSP mix and the lower-frequency auxiliary differential channel. In both cases, the indication was identified with the copper-suppression process channel and reported as percent through-wall.

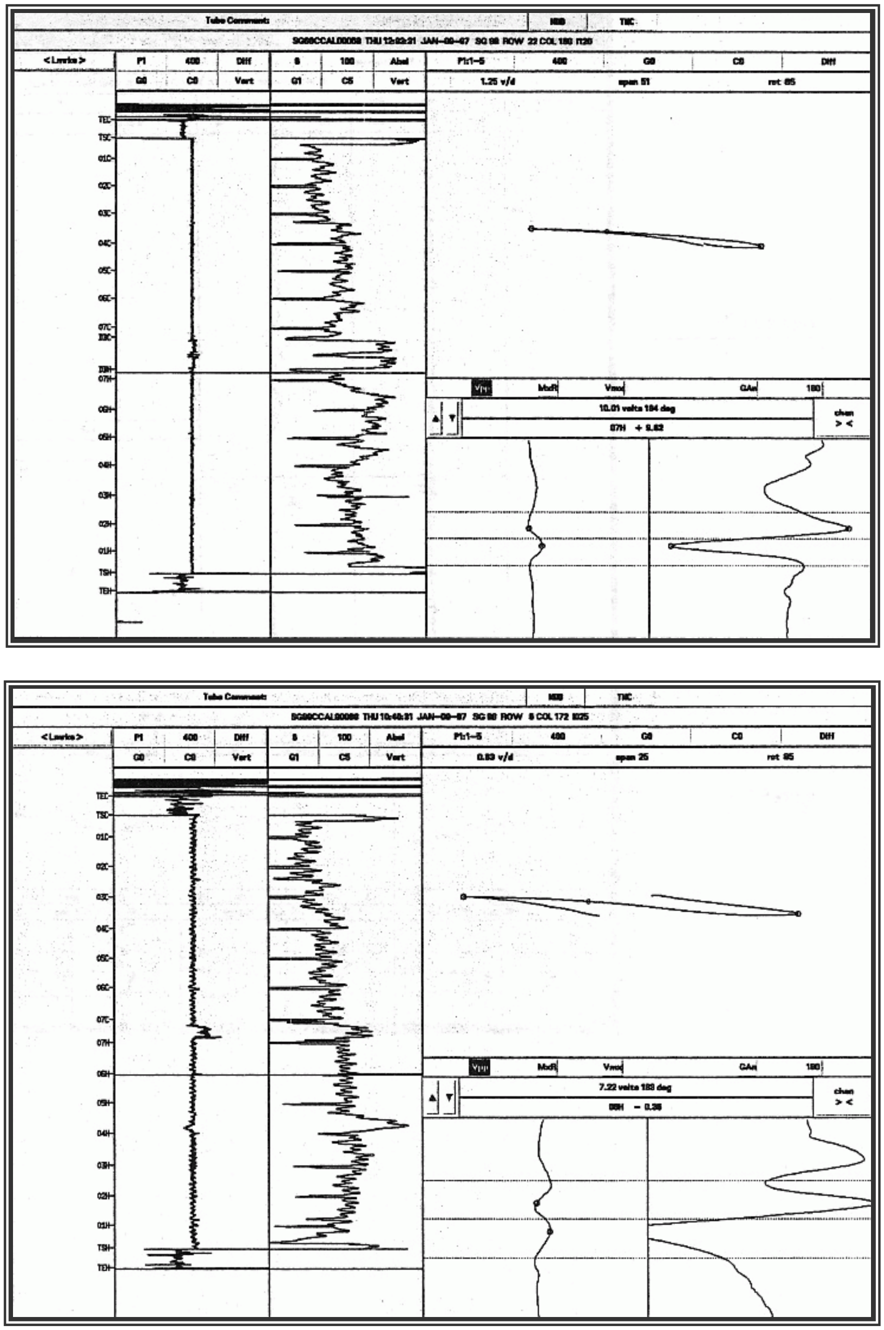


Figure 4. Bobbin probe response from differential mix channel (400|100 kHz) to a (top) free-span ding and (bottom) dent at a tube support. The strip chart on the left-hand side of the analysis window shows the data obtained from the 400|100 kHz (P1) and 100 kHz channels for the entire length of the SG tube. The mix eliminates much of the extraneous response seen in the 100 kHz trace. The horizontal line across the strip charts is set by the analyst and locates the expanded strip charts shown on the lower right corner, in which both the horizontal and vertical components of the EC signal are displayed. Shown in the upper right corner of the analysis window is the lissajous (impedance plane) figure obtained by plotting the portion of the horizontal and vertical components of data within the measurement window (upper and lower horizontal lines) in the expanded strip chart.

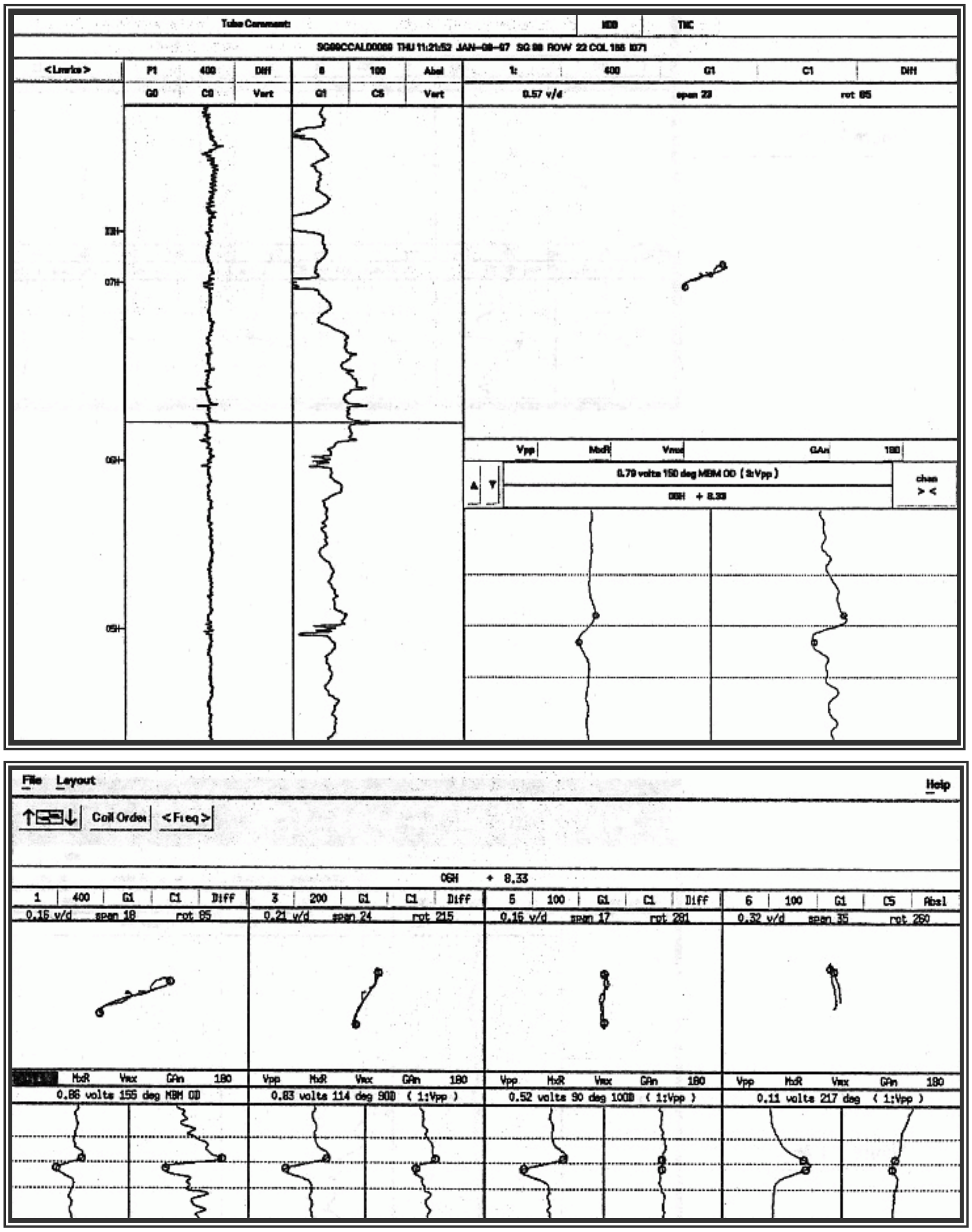


Figure 5. Bobbin probe response from a manufacturing burnish mark (MBM) in the free-span region of tube. The long strip charts of the main analysis window (top) show the data from the TSP suppression mix (400|100 kHz differential) and an auxiliary absolute channel (100 kHz). The expanded strip chart and the lissajous figure display the mix channel data within the measurement window. Multiple lissajous (impedance plane) figures and expanded strip charts (bottom) are shown for the 400, 200, and 100 kHz differential channels and the 100 kHz absolute channel, respectively.

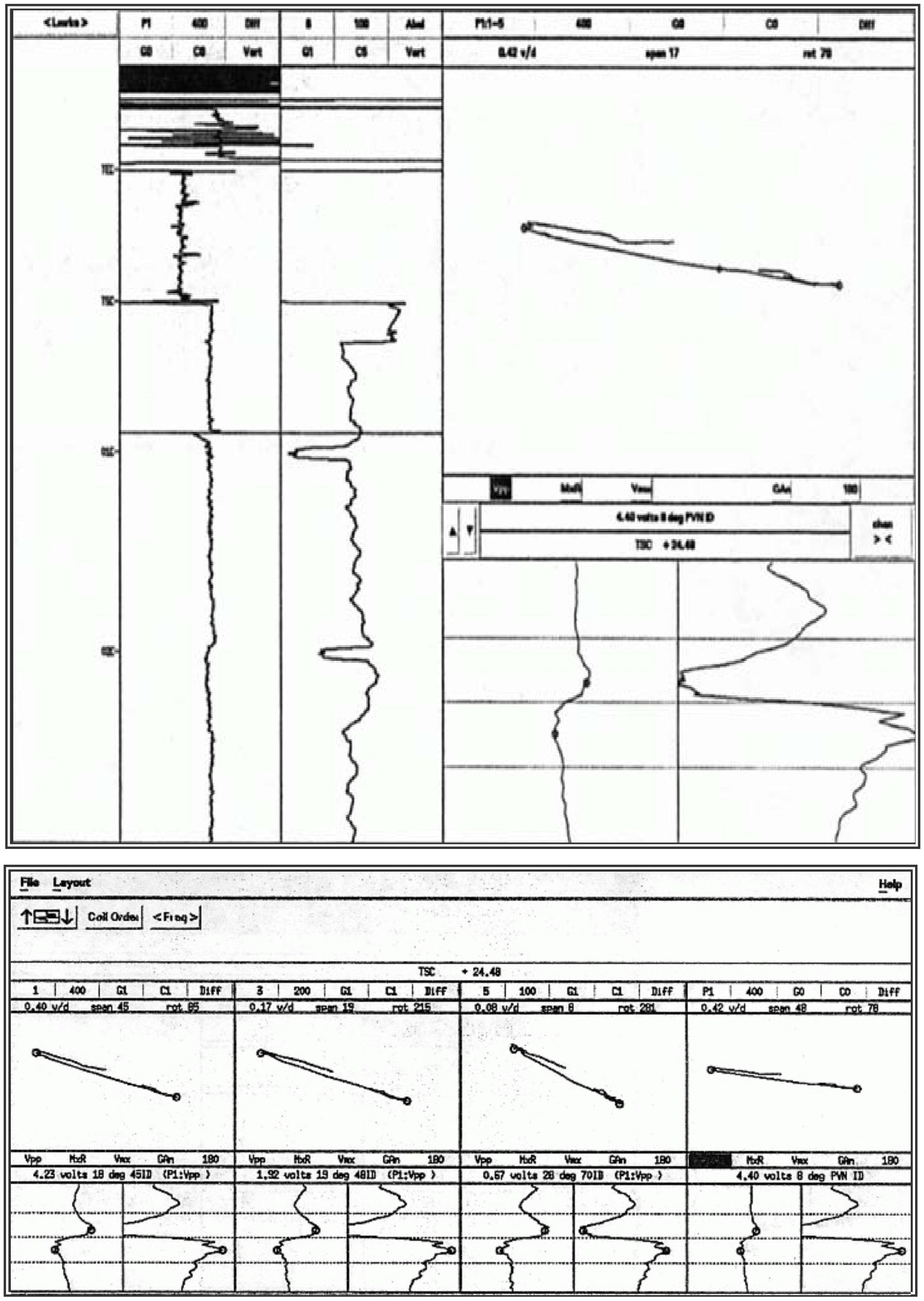


Figure 6. Indication of localized permeability variation (PVN) detected with a bobbin probe near a TSP intersection on the cold-leg side of an SG tube. Lissajous figures are shown for differential channels at 400 kHz, 200 kHz, and 100 kHz and for the 400|100 kHz mix process channel (P1), respectively.

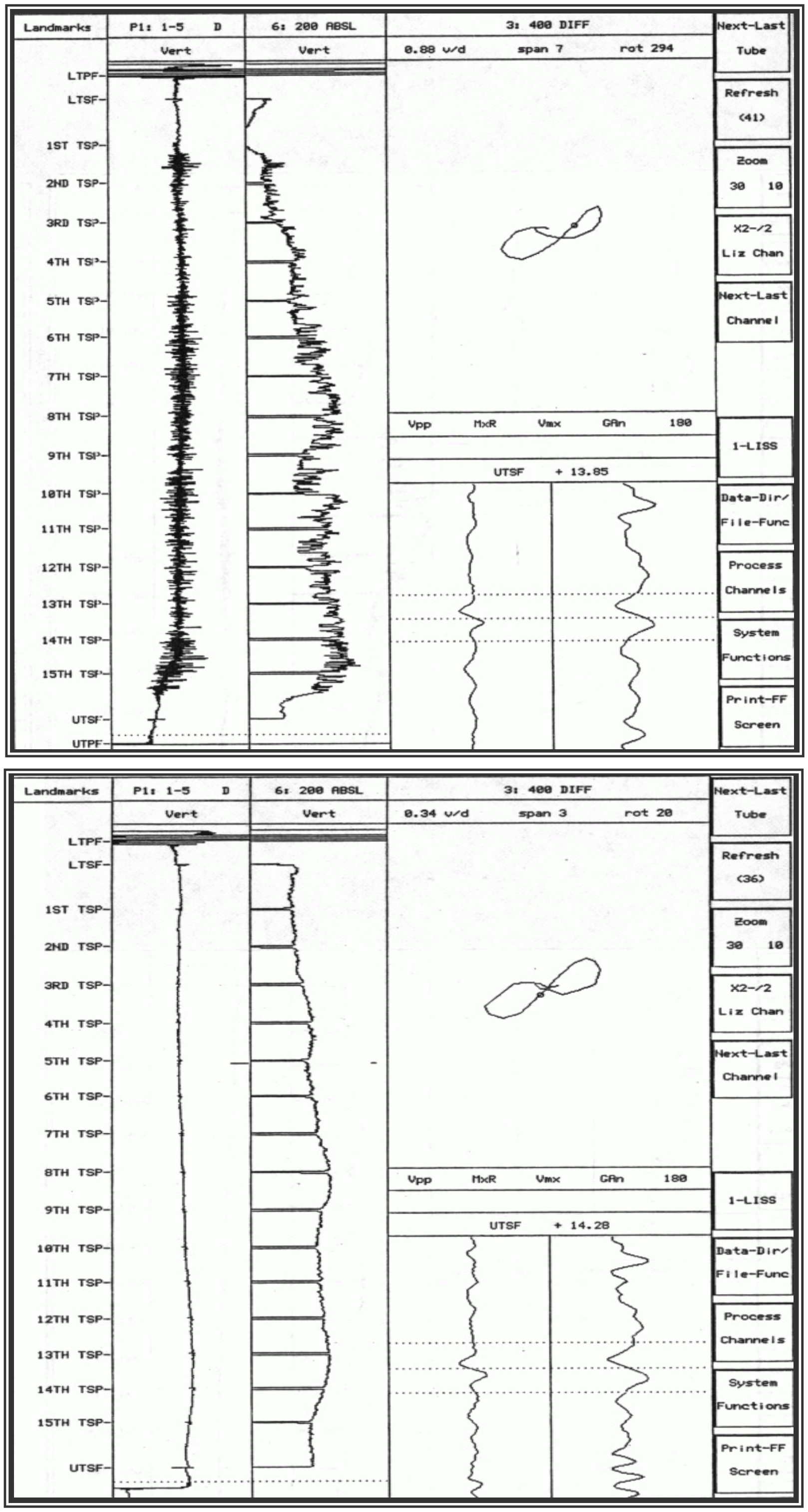
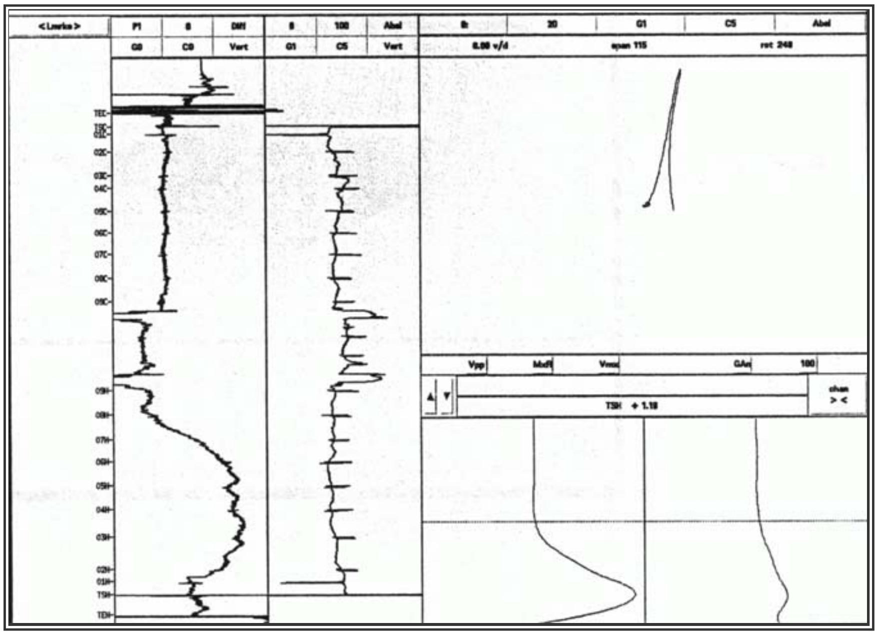


Figure 7. An indication detected with standard bobbin probe (top) and the same signal detected with a magnetically biased probe (bottom). The strip charts for the primary differential mix (400|100 kHz) and 200 kHz absolute channel show suppression of baseline noise associated with permeability variations with the magnetically biased probe.



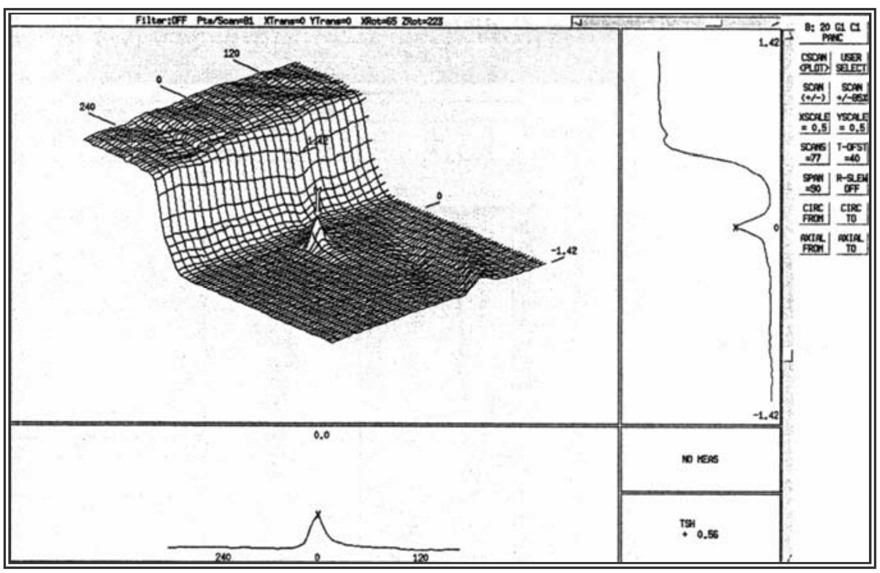


Figure 8. Bobbin coil signal (top) from a possible loose part (PLP) at the top of the tube sheet on the hot-leg side of a steam generator and a rotating probe signal (bottom) from a different loose part indication at the TTS on the hot-leg side.

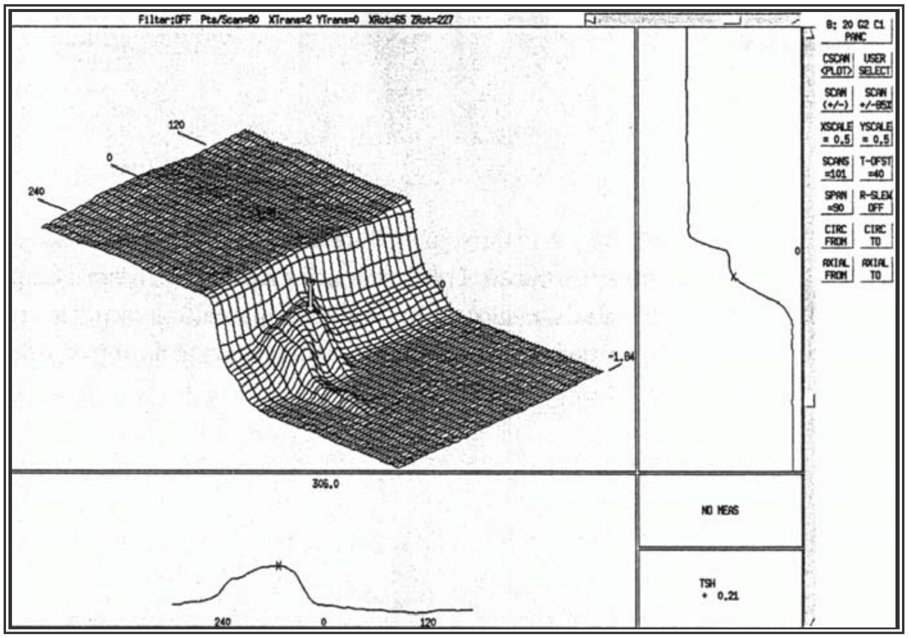
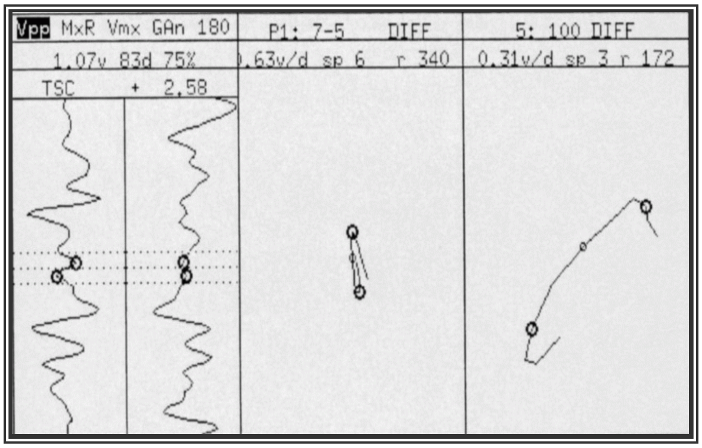
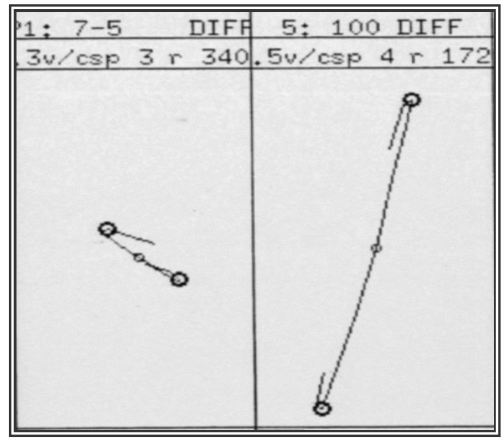


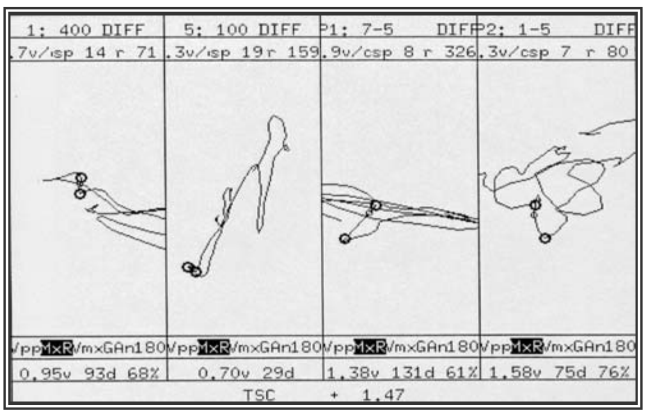
Figure 9. Isometric plot of rotating probe data from a mid-range pancake coil for signal associated with sludge at the top of the tube-sheet on the hot-leg side of an SG tube. The smooth increase in signal amplitude with no transition between the sludge and the TTS is characteristic of sludge deposit.



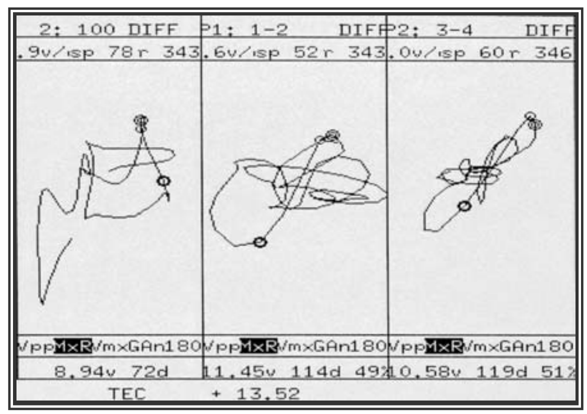
(a)



(b)



(c)



(d)

Figure 10. Detection and characterization of bobbin probe signals associated with copper deposits. The primary screening channel P1 is the 600|100 kHz mix channel (P1:7-5). The confirmation channels are 400|100 kHz TSP mix and an auxiliary 100 kHz differential channel. The signal in Figure 10(a) is reported in %TW, while the one in Figure 10(b) is identified as a copper residual. Figures 10(c) and 10(d) show two other examples of indications detected in the cold-leg side of the SG in the presence of copper deposits at the TTS and the crevice region within the tubesheet, respectively. The signals were detected with the screening differential mix channel and confirmed with the TSP mix and the auxiliary lower-frequency differential channel and are reported in %TW.

6 Characterization of Degradation Mechanisms

Analysis procedures for characterizing several degradation mechanisms based on EC inspection data are discussed in this section. Representative graphical displays produced by standard commercial software that is commonly used for analyzing EC inspection data are included to help better understand the decision-making process. As noted previously, characterization results are not based only on the fundamentals of electromagnetic testing and probe response to known forms of tubing discontinuities. They also rely heavily on the operator's knowledge of the plant design, operating history, potential damage mechanisms, and the location of signals along the SG tube as well as the tube's position within the bundle (i.e., the susceptibility of peripheral tubes to certain damage mechanisms that may not affect tubes located near the center of the bundle and vice versa).

6.1 Thinning, Wastage, Pitting, and Fretting Wear

Thinning is a generic term for corrosion degradation that results in a volumetric loss of tube material. Wastage is a common term for tube wall thinning that occurs at the TTS within the sludge pile and at the tube support structures (i.e., TSPs and AVBs). Cold-leg thinning is a special form of wastage that typically occurs at the lower elevation support plates and on the cold-leg tubes located at the periphery of the tube bundle (e.g., Model 51 SG). Pitting is another form of corrosion that occurs by dissolution of surface material, but the attack is more localized and often does not result in as large a volume of lost material as thinning. Fretting wear at AVBs, TSPs, and baffle plates (i.e., at the pre-heater section on the cold-leg side of Westinghouse Model D and E steam generators) is a mechanically induced form of tube wall degradation.

Fretting wear typically has a relatively predictable geometry. Corrosion-induced degradation typically has a non-uniform geometry. The magnitude of corrosion-induced volumetric wall loss can be estimated by data analysis techniques that do not rely on prior knowledge of the shape of an indication for estimation of flaw size.

Because tube degradation associated with thinning is a volumetric wall loss, bobbin probe techniques are commonly employed for detection and sizing of this form of damage. One such technique that is commonly used for this application is described here. The primary screening channel for detection of cold-leg thinning is a mid-frequency differential channel (e.g., 200 kHz). Confirmation and sizing of a thinning signal are done by using the TSP mix [e.g., 400|100 kHz differential mix for tube wall thickness of 1.27 mm (0.05 in.)]. The flaw depth (i.e., sizing) is obtained from a phase-angle calibration curve that is established by using the drilled holes on an ASME reference standard tube. These holes have depths ranging from 20% to 100% TW.

Figure 11 shows a classic example of cold-leg thinning in a Westinghouse Model 51 steam generator. The thinning signal is from the first support plate on the cold-leg side of the SG. The multiple lissajous figures displayed in the lower panel of Figure 11 show a characteristic counterclockwise rotation of the OD-initiated flaw-like signal as a function of decreasing frequency. The large amplitude and relatively large phase angle (109 degrees at 400|100 kHz mix) of the signal suggest a volumetric OD indication. Figures 12 to 14 show more recent cases of cold-leg thinning that were detected with a bobbin probe and confirmed by a rotating probe technique. In all cases, the bobbin coil data suggest the presence of relatively shallow (large phase angle) volumetric indications representative of wastage/thinning-type wall loss. It is important once again to recognize that the characterization of the indications here, based on the analysis of bobbin probe data alone, was done in conjunction with the information available on the location of the indication and the operating history of the SG. The rotating probe results shown in the lower panels of Figures 12 to 14 can also help to confirm the bobbin probe results. Both the impedance plane pattern (i.e., the hook shape) and the isometric plot (i.e., the M shape in the circumferential direction) of the +Point™ data at the primary test frequency of 300 kHz suggest a localized volumetric wall loss (see also the results for a machined flaw in Figure 25). The estimated depth based on the phase angle values once again suggests the presence of relatively shallow degradation. Because of the directional sensitivity of the probe, it is expected that the signal from a volumetric indication will exhibit both an axial and a circumferential component.

Secondary-side pitting generally occurs between the TTS and the first TSP on the cold-leg side of the SG designs by Westinghouse and Combustion Engineering. The pits are often found in the sludge pile region above the TTS. Pits often have a reentrant shape, where the entrance to the cavity is smaller the body of the cavity, and can contain corrosion products.[5] The presence of large amounts of highly conducting deposits in such regions could drastically affect the detection and characterization of pitting-type damage. Because of the localized and volumetric nature of pitting damage, bobbin probe techniques may be used to detect and estimate the size of this form of tube damage. The primary test channel for detection of outer surface pitting is typically the primary differential mix (e.g., 400|100 kHz) that is established for suppression of TSP response. The confirmation channel is typically a high-frequency differential mix (e.g., 600|200 kHz or 600|100 kHz), established based on suppression of a copper ring placed on a calibration standard tube, to minimize the potential influence of copper deposits that may be present at that location. Once confirmed, the same channel may be used for estimating the depth of the pit based on the phase angle of the signal. It should be noted that the estimation of pit depth at such high frequencies can be unreliable for shallow indications.

Bobbin coil data for an indication characterized as pitting in the sludge pile region at the cold-leg side of an SG are shown in Figure 15. The bobbin probe signal at the primary mix channel (400|100 kHz differential) indicates the presence of a shallow volumetric flaw in the sludge pile region. The presence of this signal is confirmed by the auxiliary high-frequency copper mix (600|200 kHz differential) shown on the multiple lissajous panels in Figure 15. Although there is a poor correlation in this case between the lower frequency auxiliary channels (i.e., 200 kHz and 100 kHz differential), there is sufficient confirmation of pitting-type degradation based on the bobbin probe data and the known degradation history of the generator. In cases where the presence of a large number of closely spaced pits is suspected (i.e., multiple pits around the circumference at nearly the same axial location along the tube), bobbin probe data cannot be used to reliably estimate the size of the degradation. Supplementary examinations with rotating probes could help isolate an individual flaw and estimate its size. Once again, the volumetric nature of this type of degradation is expected to produce both an axial and circumferential component when directionally sensitive rotating probes are used.

Mechanical degradation of the tube wall, such as fretting wear caused by flow-induced vibrations, can be characterized, in general, more accurately than corrosion-induced damage. The degree and the geometry of damage depend on the shape of the support structure and its clearance to the tube. For example, the wear volume may have a rectangular or triangular cross section, may be on one or on opposite sides of the tube (i.e., one- or two-sided wear), and may have a uniform or tapered depth. When the geometry of the tube wall loss is predictable, machined flaws on calibration standard tubes can be used to help estimate more accurately the depth of fretting wear by means of bobbin probe techniques. In such cases, an amplitude-versus-depth calibration curve for a differential mix channel is created on the basis of signals from machined flaws to predict the depth of the damage. The vertical component of the signal, rather than its peak-to-peak value, is used for this purpose. When wear standards are not available, the depth may be more conservatively estimated by means of a conventional phase-angle calibration curve based on the flat bottom holes on the ASME standard tube.

Examples of characterizing fretting wear at support structures (i.e., TSP and AVB) with bobbin probe data are presented in Figures 16 and 17. Data from wear damage at a support plate in a turbine cooler are shown in Figure 16. Lower test frequencies are used in this case because of the higher electrical conductivity of the tubing material (90% Cu-10% Ni) in comparison to Alloy 600 tubing. The detection channel is the primary differential frequency. The large amplitude and large phase angle of the signal once again are indicative of shallow OD-initiated volumetric wall loss. Confirmation here is done with the primary TSP differential mix channel. Confirmation also includes verification that the signal rotates counterclockwise as the frequency decreases over all auxiliary test frequencies, as illustrated in the multiple lissajous plots in the lower panel of Figure 16. In this particular case the degradation depth was conservatively estimated with the phase-angle calibration curve from the primary TSP mix channel.

Figure 17 shows a two-point amplitude calibration curve for sizing of single-sided wear based on machined flaws on a reference standard tube. The SG tubes in this case are 304L stainless steel with 1.65-mm (0.065-in.) wall thickness. The use of lower test frequencies in this case is based primarily on the larger thickness of the tube wall and, to a lesser degree, based on the slightly higher conductivity of the 304L tube material in comparison to the Alloy 600 tubing. Data from the indication are identified as fretting wear at an AVB in the U-bend region. The detection channel is the primary differential mix for suppression of TSP response. The confirmation channel is the differential base frequency. The signal amplitude and phase from the detection channel once again suggest a volumetric OD indication at the second AVB. Observation of the auxiliary differential channels showed proper rotation of the OD-originated signal. The lack of AVB signal in the base frequencies in this case indicates the lack of contact between the AVB and the tube. The degradation depth was estimated from the sizing channel by using a previously established amplitude calibration curve. The sizing channel in this case is the TSP suppression mix, with the measurements made by using the maximum vertical component of the signal.

Characterization of signals associated with loose parts was discussed earlier in this report. Contact between the tube and a loose part can result in wearing of the tube. The extent of damage by a loose part can vary significantly based on the flow conditions and the location inside the SG as well as the general characteristics of the loose part (i.e., size, geometry, and material properties). Electrically conducting or ferromagnetic loose parts in contact with the tube's outer surface can produce measurable EC signals even at intermediate test frequencies. Characterization of composite signals (i.e., loose part in conjunction with tube wear) in such cases could pose a challenge to inspection techniques using bobbin probes. In addition, close proximity of indications to support structures and tube dimensional changes such as the TTS can be an additional complicating factor. Implementation of complementary NDE techniques in such cases could help improve the reliability of inspection results.

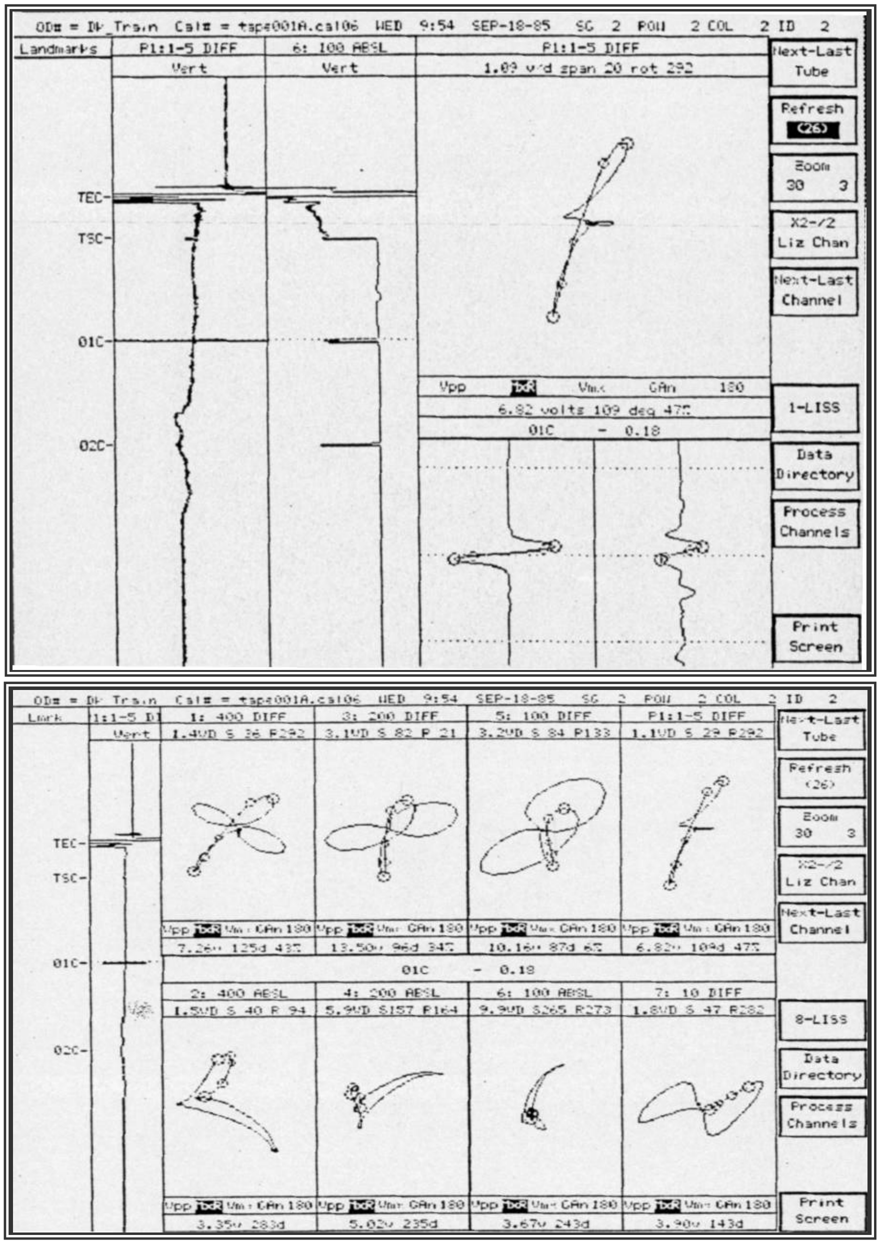


Figure 11. Cold-leg thinning detected and sized by bobbin-probe inspection technique. Also displayed are the multiple lissajous patterns showing confirmation of the signal at the primary and auxiliary test frequencies as well as the 400|100 kHz mix process channel (P1).

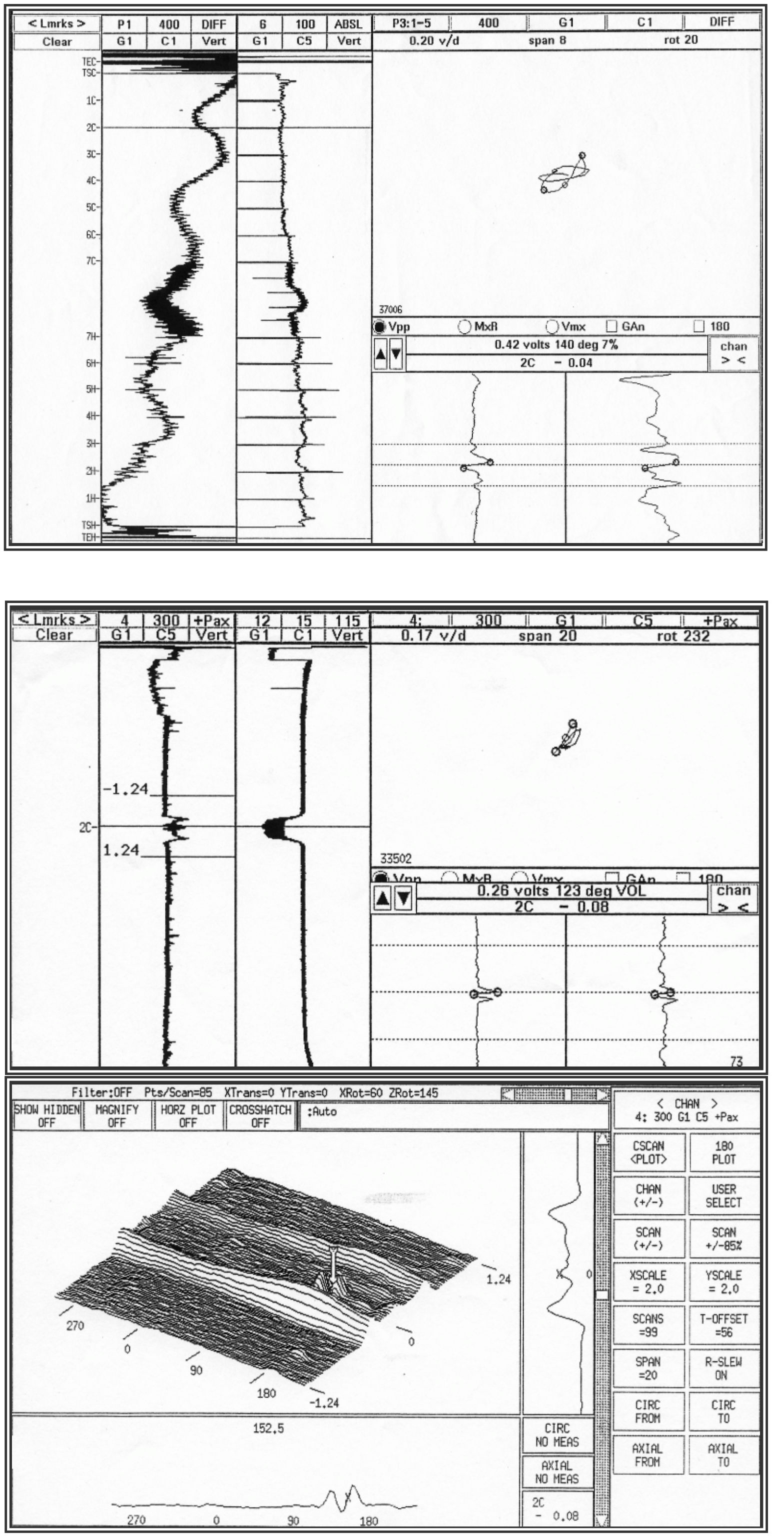


Figure 12. Bobbin (top) and rotating probe (bottom) data for an indication characterized as thinning at the second support plate on the cold-leg side of an SG. Eddy current inspection data from both probes suggest the presence of a shallow OD volumetric indication.

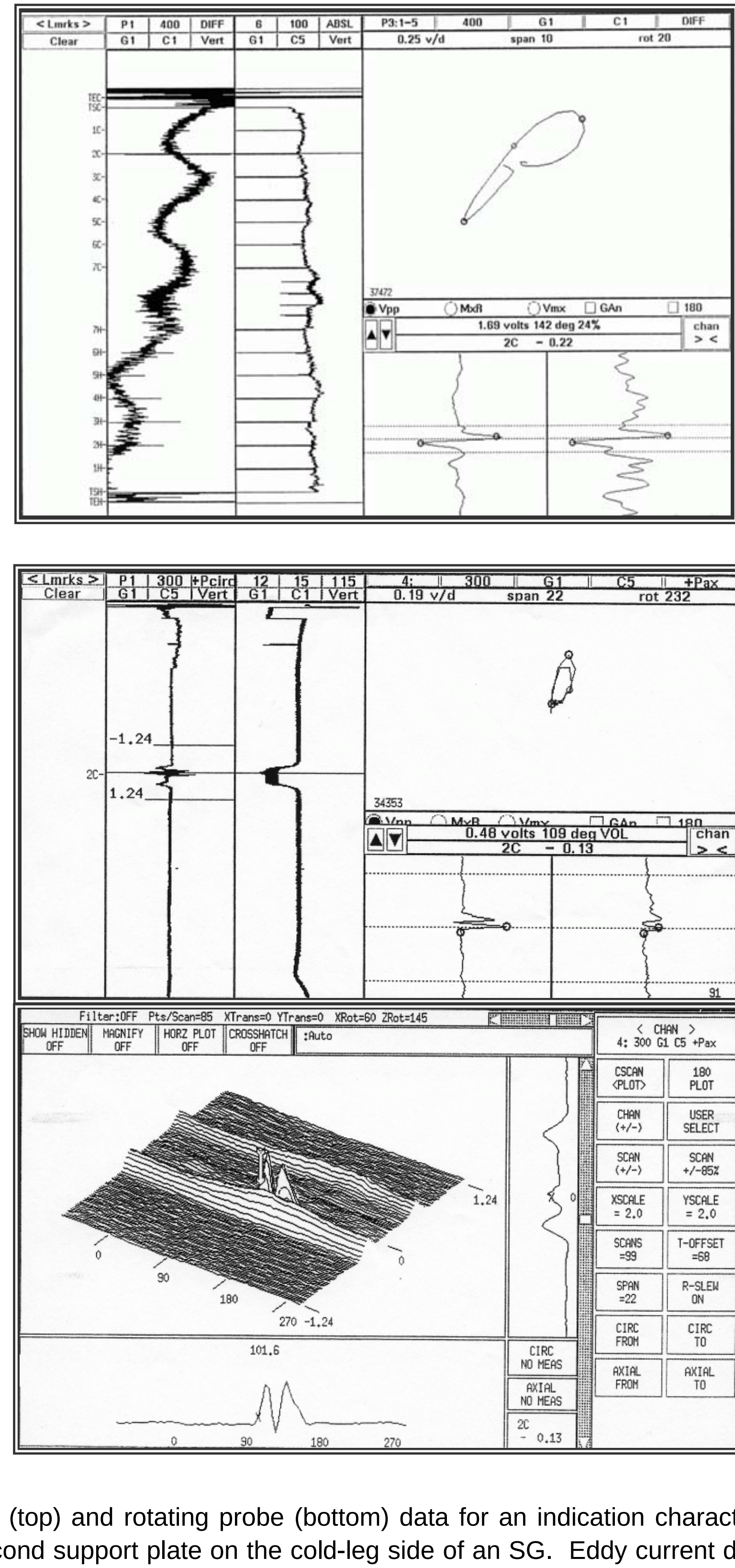


Figure 13. Bobbin (top) and rotating probe (bottom) data for an indication characterized as thinning at the second support plate on the cold-leg side of an SG. Eddy current data from both probes suggest the presence of a relatively shallow OD volumetric indication.

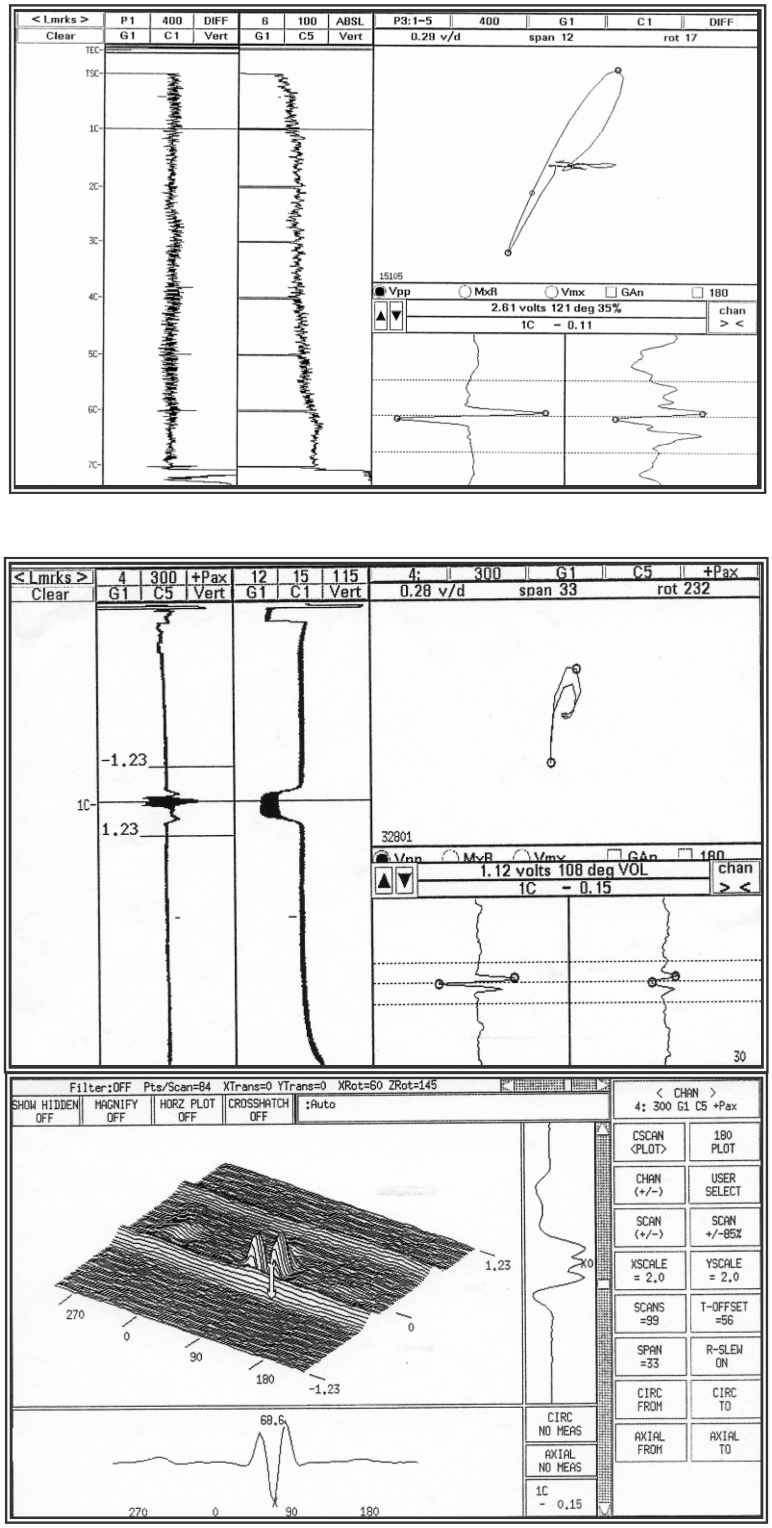


Figure 14. Bobbin (top) and rotating probe (bottom) data for an indication characterized as thinning at the first support plate on the cold-leg side of an SG. Eddy current data from both probes suggest the presence of a relatively shallow OD volumetric indication.

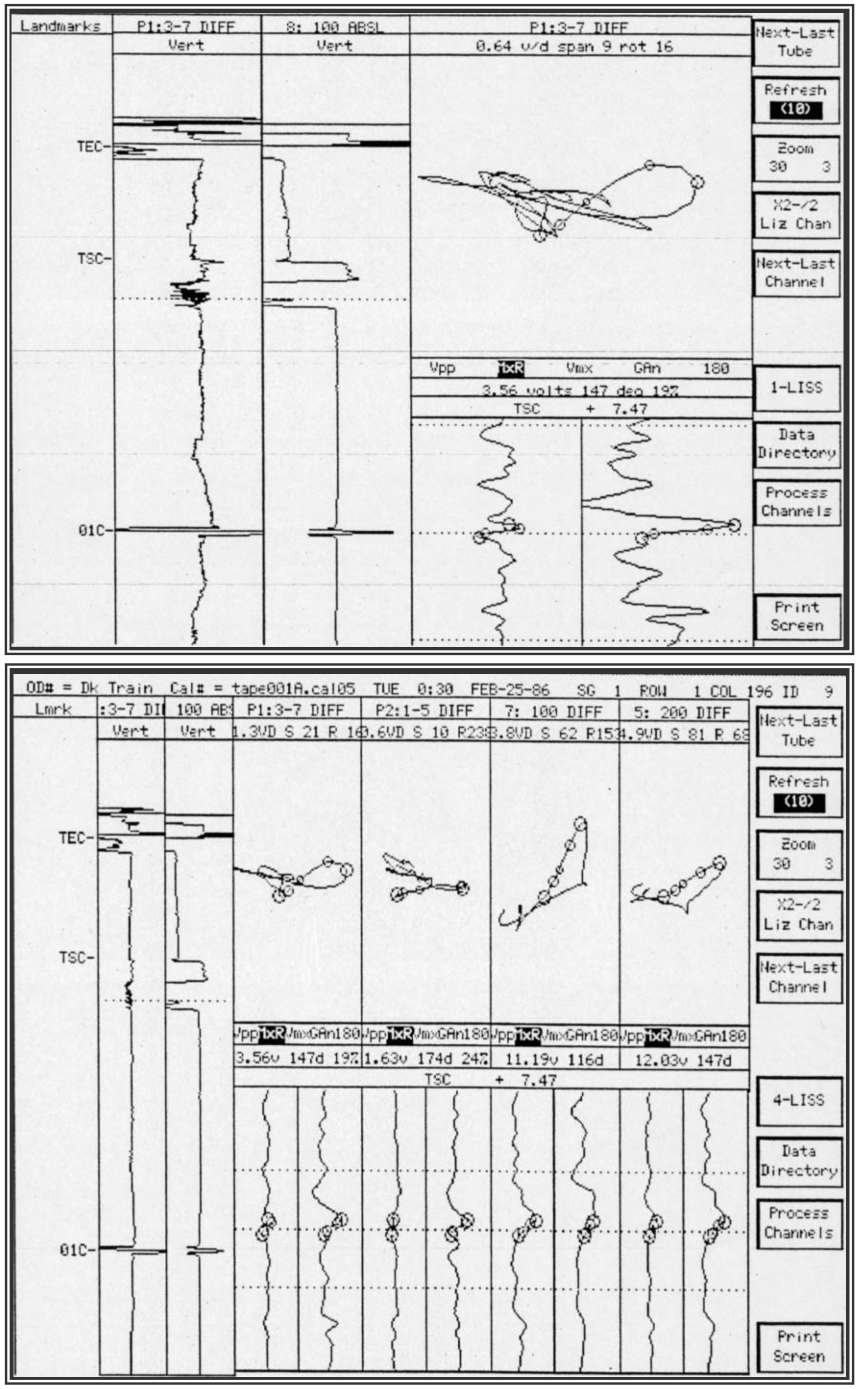


Figure 15. Bobbin coil data from indication characterized as pitting in the sludge pile region at the cold-leg side of an SG. The primary test channel is the 400|100 kHz (P1:3-7) differential TSP mix. The confirmation channel is the differential 600|200 kHz (P2:1-5) copper suppression mix. The same channel is used to estimate the pit depth based on the phase angle of the signal (i.e., depth-vs.-phase calibration curve).

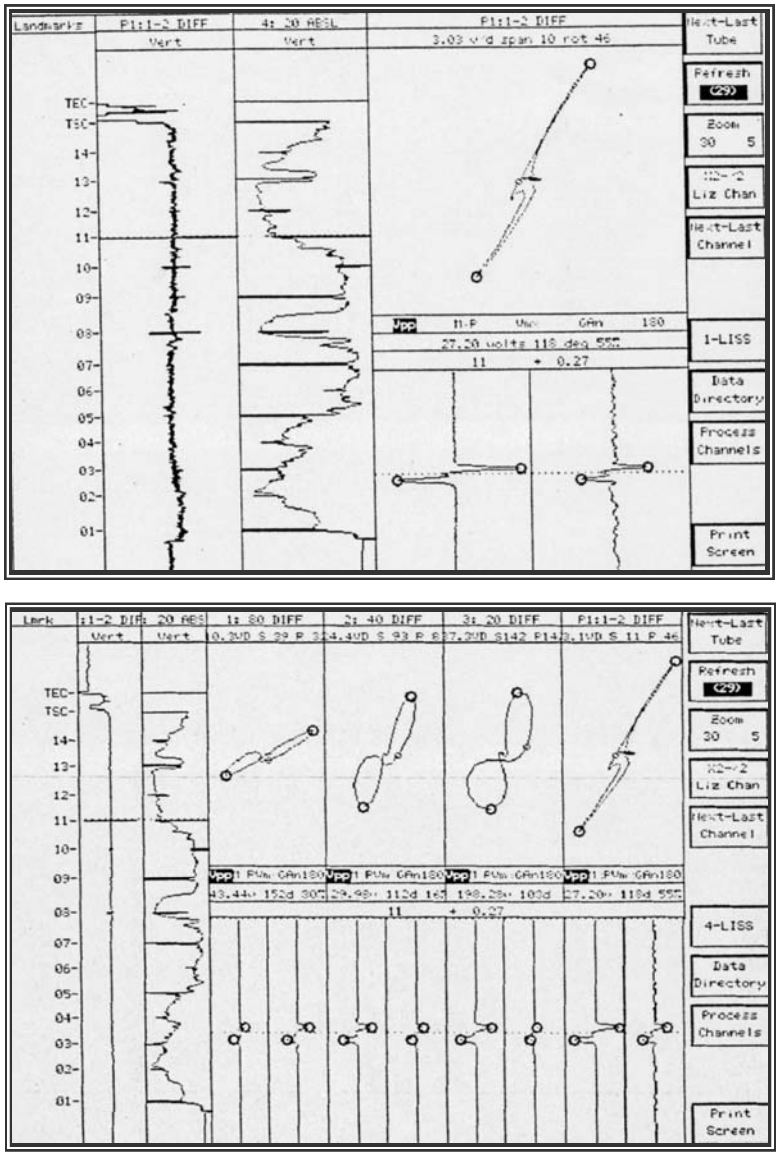
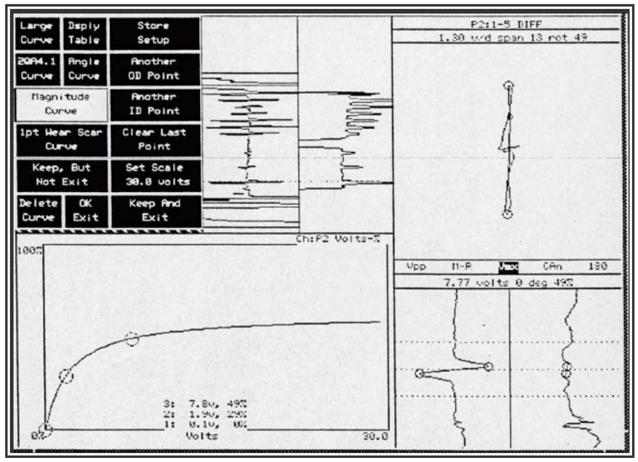
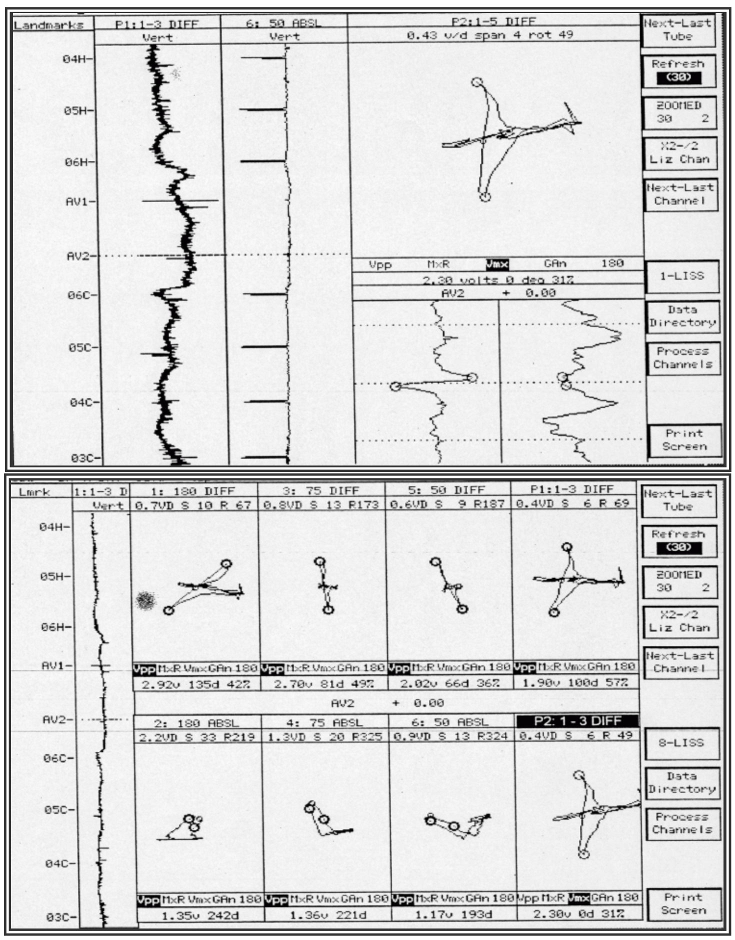


Figure 16. Bobbin probe data from an indication characterized as wear at a support plate intersection in a turbine cooler. The detection channel is the primary differential frequency. The confirmation channel is the primary TSP differential mix. The degradation depth was estimated on the basis of a phase-angle calibration curve from the primary TSP mix channel.



(a)



(b)

Figure 17. (a) Two-point amplitude calibration curve for sizing of single-sided wear and (b) data from indication identified as fretting wear at AVB in the U-bend region. The detection channel is the primary differential TSP mix. The confirmation channel is the differential base frequency. The sizing channel is the TSP suppression mix, with the measurements made by using the maximum vertical component of the signal.

6.2 Characterization of Cracking

Volumetric wall loss, which is either corrosion induced or the result of mechanical damage, is generally detectable with bobbin probes even when the loss is relatively shallow (< 10% TW). In contrast, tube degradation mechanisms that essentially do not result in loss of material, such as IGA and SCC, pose a much greater challenge to NDE techniques. For EC inspections, the presence of networks of electrically conducting paths in IGA and contact across crack faces of SCC or fatigue cracks can significantly reduce the probe response compared to that from the electro-discharge machined notches in a calibration standard or other such attempts to simulate cracking. The significant underestimation of the size of deep but tight cracks by EC inspection techniques is a good example of the kind of problem that can arise from the loss of signal. The relatively small probe response to cracks means that the interference from various discontinuities (including support structures, conducting deposits, and geometrical variations) could result in reduced S/N and thus further complicate the detection and characterization of tube wall cracking. Additional complexities in characterizing such indications may arise when different forms of degradation occur in combinations (e.g., volumetric damage in conjunction with crack-like indications).

Site-specific data analysis guidelines for production analysts typically require that they determine certain pieces of information from the EC inspection data. This includes information regarding the location, size (i.e., signal amplitude, phase, and spatial extent), orientation (i.e., axial, circumferential, or volumetric from rotating probe examinations), number (i.e., single or multiple), and OD/ID origin of an indication. This information is not necessarily sufficient to completely characterize a particular form of degradation, and a more detailed characterization may be carried out by the resolution and lead review teams or as part of engineering assessments (i.e., CMOAs). The decision-making process for characterizing IGA/SCC-type tube degradation either alone or in combination with other forms of damage is discussed below. Once again, it must be noted that in addition to EC signal characteristics, the plant operating history and past experience from similar SGs play a critical role in reliable characterization of damage mechanisms based on NDE data.

6.2.1 Intergranular Attack

Detection and characterization of pure volumetric IGA pose a major challenge to all EC inspection techniques. Relatively little volume loss of material occurs with this kind of attack, and the grain boundaries are attacked but not fully separated. This situation is particularly true when the depth of attack on the outside surface of the tube is relatively shallow. Pure IGA shows up as a low amplitude variation of the baseline trace, indicative of a small change in material conductivity. Because of the volumetric nature of IGA, EC probes operating in the differential mode could underestimate the extent of tube degradation from IGA. Furthermore, as a result of the complexity and low amplitude of signals associated with shallow IGA, phase angle information often cannot be used to reliably estimate the flaw size. Field-induced IGA often becomes detectable only when either a significant volume of the tube wall is affected, or more commonly when it appears in combination with SCC (i.e., separated grain boundaries). For pure IGA, the amplitude of the probe response is expected to be proportional to the volume of the degraded material. Site-specific guidelines often set an amplitude threshold for reporting of tube wall degradation associated with IGA.

An example of IGA degradation at the tube-sheet expansion transition region detected with a rotating probe is shown in Figure 18.[6] Figure 18(a) shows an isometric plot of data collected with the +Point™ coil. The probe response shows a relatively smooth signal extending more than 180° around the circumference of the tube. The signal was present predominantly on the axial channel. The axial length of the indication was determined from the number of hits in the axial direction. The low amplitude of the signal in combination with the relatively large extent is suggestive of IGA. The metallographic data shown in Figure 18(b) revealed a series of closely spaced and predominantly axially oriented and deep IGA areas, which could not be resolved by the rotating probe as separate defects. The degradation depth based on the phase angle data underestimated the maximum depth. This discrepancy can be attributed primarily to the complexity of the IGA morphology, as discussed above.

6.2.2 Stress Corrosion Cracking

As stated earlier, EC data analysis for ISI of SG tubing may not always provide sufficient information to uniquely correlate an indication with a particular form of damage mechanism. Instead, the primary intent is to provide a conservative estimate of the extent of tube wall degradation and a general categorization of the flaw type. For example, even an indication detected with a rotating probe on the outside surface of the tube on the hot-leg side of an SG with Alloy 600 tubing that appears to be volumetric based on EC data analysis may be characterized as outside-diameter stress corrosion cracking (ODSCC). This decision would be based on prior experience showing no major occurrences of OD volumetric degradation at TSP intersections on the hot-leg side of operating steam generators, except at dented regions of the tube. On the other hand, EC indications with similar characteristics that are detected on the cold-leg side of the unit may be characterized as volumetric degradation.

Although bobbin probes are used to detect and estimate the size of SCCs, such probes are not qualified for detection of cracking that is primarily circumferential in orientation. Therefore, plants usually employ rotating probe inspection techniques for those regions of the SG that could be prone to circumferential cracking, such as the TTS, small radius U-bends, dents, and dings. Rotating probes are also employed for selective reexamination of indications that cannot be resolved based on analysis of bobbin probe data. Conservatism is often practiced in making a call with bobbin probes. Because cracking is considered to be a more aggressive form of tube wall degradation than most volumetric-type damage, an indication may be attributed to SCC based only on detection of a signal from the primary test frequency, regardless of confirmatory signals or proper phase angle rotation at auxiliary test frequencies.

Figure 19 shows an example of an indication from the sludge pile at the TTS on the hot-leg side of an SG. This signal was identified by bobbin probe examination and attributed to ODSCC degradation. The signal was detected from the 400-kHz primary screening channel for the 1.27-mm (0.05-in.) tube wall thickness. The sharp transient response in the OD flaw plane and the location of the signal along the tube are all indicative of cracking that originated from the outside surface of the tube. Confirmation was based on the differential TSP suppression mix (i.e., 400|100 kHz) and proper rotation of the signal at the auxiliary test frequencies. The flaw depth was estimated from the primary differential mix channel based on a pre-established phase-angle (phase-versus-depth) calibration curve for drilled holes on an ASME reference standard.

Figure 20 shows a signal identified as ODSCC and detected with a bobbin probe at a high elevation support plate in a once-through steam generator (OTSG). The damage mechanism in this case is IGA/SCC. The signal was detected from the differential TSP suppression mix channel of 600|200 kHz used for 0.889-mm (0.035-in.) tube wall thickness. Once again, the sharp transient response in the OD flaw plane suggests that the cracking originated from the outside surface of the tube. Confirmation was based on the differential base frequency (i.e., 400 kHz) and proper rotation of the signal at auxiliary test frequencies. The flaw depth was estimated from the primary differential mix channel by using a phase-versus-depth calibration curve.

6.2.3 Identification of Fatigue Cracks

Stresses produced by tube vibration could result in fatigue cracks. High-cycle fatigue cracks have been found in both recirculating SGs and in OTSGs. In OTSGs, fatigue cracks have been found primarily at the highest elevation support plate. In recirculating SGs, fatigue cracks have been found at the upper edge of high elevation TSPs on the cold-leg side. High-cycle fatigue cracks could propagate very quickly. Because of the circumferential orientation of the fatigue cracks, bobbin probes are insensitive to circumferential cracking and thus are not qualified for detection of circumferentially oriented indications. Bobbin probes may only detect fatigue cracking when the crack opening either grows wide or when the crack has an axial component (i.e., not perfectly circumferential). Although rotating probes are much better suited for detection of fatigue cracks, such cracks are still expected to pose a major challenge when tight. Figure 21 is an example of a bobbin probe signal from a high-cycle fatigue crack. The crack was detected after it had grown significantly through the wall and had a major axial component. The indication was detected by the differential screening channel of 400 kHz. It was confirmed and sized with the differential TSP suppression mix of 600|200 kHz.

6.3 Characterization of Closely Spaced Flaws

Because bobbin probes provide an integrated measurement at each axial position along the tube, inspection techniques that employ bobbin probes may only be used to resolve indications that are axially separated. Figure 22 shows an example of multiple but axially separated SCC signals that were detected by a bobbin probe. The indications were located inside the crevice region of a tube that was not expanded for the full axial extent of the tubesheet (i.e., a partial depth tube expansion).

Separation of closely spaced indications along the axial direction, as well as separation of multiple indications with similar axial positions located around the tube's circumference, requires use of rotating probes whose small surface coils provide high spatial resolution. The resolution of such surface coils is limited by the size of the coil, which defines the coil coverage. For example, the high-frequency 2.0-mm (0.08-in.) pancake coil on a conventional three-coil rotating probe can clearly resolve indications that are within ~6.4 mm (0.25 in.) of each other. More closely spaced indications will produce a convoluted probe response without a return to baseline in between the peaks from individual indications. Examples of single and multiple indications detected with a rotating probe are shown in Figure 23.

6.4 Characterization of Complex Flaws

The capability of EC inspection techniques to detect and identify crack-like indications that occur in combination with volumetric tube deformation or wall loss depends on the probe type and complexity of the flaws. As noted previously, bobbin probes provide a single measurement at each axial position along the tube axis. Consequently, crack-like indications that may occur in combination with a volumetric degradation may only be resolved if part of the crack extends outside the zone affected by the volumetric degradation or, in extreme cases, when the probe response from the crack is significantly larger.

6.4.1 Identification of SCC in Dents

Identification of dents based on the bobbin probe response was discussed earlier in this report. Crack-like indications may be detected in the presence of localized tube deformations, such as dents and expansion transitions, when the crack signal does not overlap with the peak of the probe response from the dent (i.e., at the edge of the dent). Figure 24 shows an example of a flaw-like indication at a dented support intersection. Because the flaw signal in this case extends outside the dented region, bobbin probe data from that part of the flaw signal may be isolated and measured. Initial detection of flaws in dented regions is based on the shape of the dent signal. In comparison to Figure 4, which shows the probe response from just a dented region is flat, the composite signal in Figure 24 shows a lissajous pattern with an open lobe, which suggests an indication in the dented region. The detection channel once again is the primary differential TSP suppression mix (400|100 kHz). The confirmation is made by examining the signal amplitude and phase response at all auxiliary test frequencies. Although unreliable, due to the influence of a dent, the flaw size was reported from the primary mix channel. As stated earlier, the indication may be more accurately characterized by employing rotating probe techniques.

6.4.2 Characterization of SCC in a Volumetric Flaw

As in the case of dents, volumetric indications associated with tube wall loss induce a strong signal when examined with bobbin probes. Therefore, inspection techniques that employ bobbin probes cannot be used to resolve cracking that occurs in combination with volumetric tube wall loss, such as thinning or wastage. Inspection techniques that employ high-resolution rotating or array probes are the best candidates for detection of cracking that may be embedded within or at the same axial elevation of a volumetric wall loss indication. However, the capability of these probes to reliably detect and characterize composite embedded flaws has not yet been demonstrated. Laboratory studies are under way to help identify the optimum high-resolution EC inspection techniques for this application.

Figure 25 shows EC data collected with the +Point™ coil of a three-coil rotating probe from a tube specimen with a volumetric flaw and machined axial and circumferential flaws.[†] Because of the directional sensitivity of the coil, all three indications are correctly identified by the probe. As shown earlier, the volumetric flaw displays a hook-shaped circumferential lissajous pattern with an M-shaped amplitude trace in the circumferential cross section. Figure 26 shows data collected with the same probe on a pair of specimens with laboratory-produced volumetric wall loss. Once again similar patterns can be observed for the +Point™ response to volumetric flaws. Figure 27 shows rotating probe data from the same specimens after circumferential SCC was induced at the bottom of the volumetric flaws. Analysis of the rotating probe data for these test cases indicated that, although the amplitude of the negative component of the signal increased after inducing the SCC, the composite probe response still displayed a primarily circumferential feature of the volumetric indication. The complexity of field-induced degradations is expected to further complicate the analysis process, thus reducing the reliability of applying such empirical rules for detection of cracks in the presence of volumetric wall loss. Similar studies conducted at the Atomic Energy of Canada, Ltd. (AECL) using an X-probe have shown improved performance over the +Point™ probe for characterizing cracks embedded in volumetric defects. In this case, an empirical rule based on the ratio of the circumferential-to-axial channel was used to detect the presence of SCC. Nevertheless, the detection and characterization of SCC indications in the presence of volumetric defects pose a challenge for all EC inspection techniques.

[†] Through personal communication with Laura Obrutsky, Atomic Energy of Canada Limited.

7 Summary and Conclusion

This report gives an overview of conventional EC examination techniques and the associated ISI data analysis procedures used for characterization of various forms of SG tube degradation. It covers the following topics:

- Generic procedures for the analysis of data acquired with conventional EC probes. In particular, characterization of volumetric indications is discussed in detail.

- Conventional EC inspection techniques employing bobbin and rotating probes.

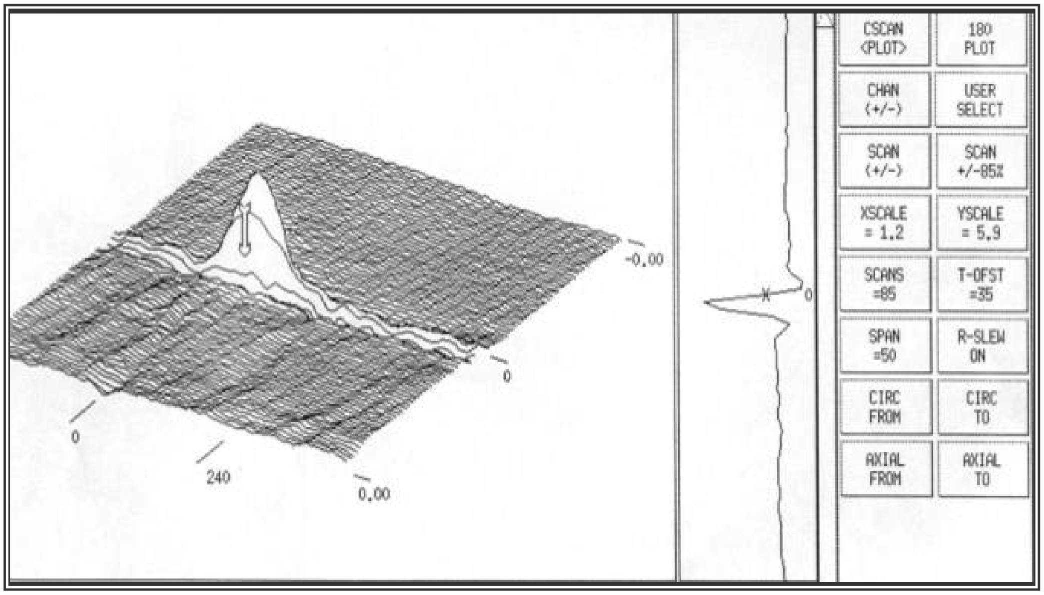
- The information in DA documents for providing a common framework for controlling the quality of ISI results. This information includes site-specific guidelines regarding the inspection plan, operating history, the qualifications and responsibilities of analysts, plant design specifications, qualified data acquisition and analysis procedures, and reporting requirements. The importance of updated SSPDs in familiarizing analysts with the history of the SGs at a particular site is noted.

- General procedures for the analysis of multifrequency EC inspection data, including general signal characteristics that are used to distinguish between “chronic” (i.e., tube degradation or damage mechanisms that are not expected to change significantly between successive outages) and “acute” (i.e., more aggressive tube degradation mechanisms such as certain types of SCC) forms of damage mechanisms. Examples of flow diagrams or decision trees are provided which help the analyst focus on the areas of interest at a particular plant and thus help increase the likelihood of detecting the degradation of concern.

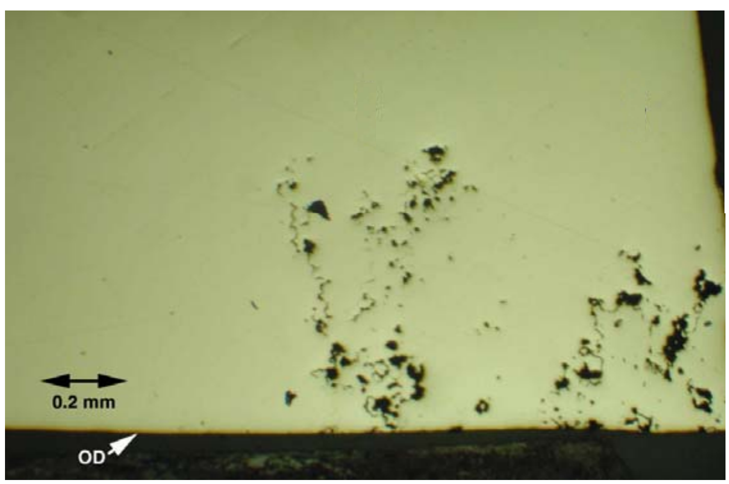
- The characterization of non-degradation discontinuities such as dents, dings, manufacturing burnish marks, loose parts, and various types of deposits.

- The detection and characterization of common forms of tubing damage or degradation. This discussion summarizes EC data analysis procedures for detection and characterization of volumetric (i.e., thinning, wastage, and wear) and planar (e.g., SCC and IGA) degradation. Some key signal features (spatial characteristics and frequency response) that may be used to identify volumetric and crack-like indications are also mentioned. Eddy current techniques for characterization of complex and closely spaced flaws are also briefly discussed.

The report emphasizes that the characterization results are not based only on the fundamentals of electromagnetic testing. They also rely heavily on the operator’s knowledge of the plant design, operating history, potential damage mechanisms, and the location of signals along the SG tube as well as the tube’s position within the bundle. Numerous graphical examples are provided to aid the description of data analysis processes for identification and characterization of various types of flaw indications.



(a)



(b)

Figure 18. (a) Isometric plot of +Point data from extensive IGA degradation at TTS and (b) destructive examination image for a cross section perpendicular to the tube axis and 0.5 mm (0.02 in.) below TTS. Axially oriented IGA is observed extending from the OD to depths of 65% TW.

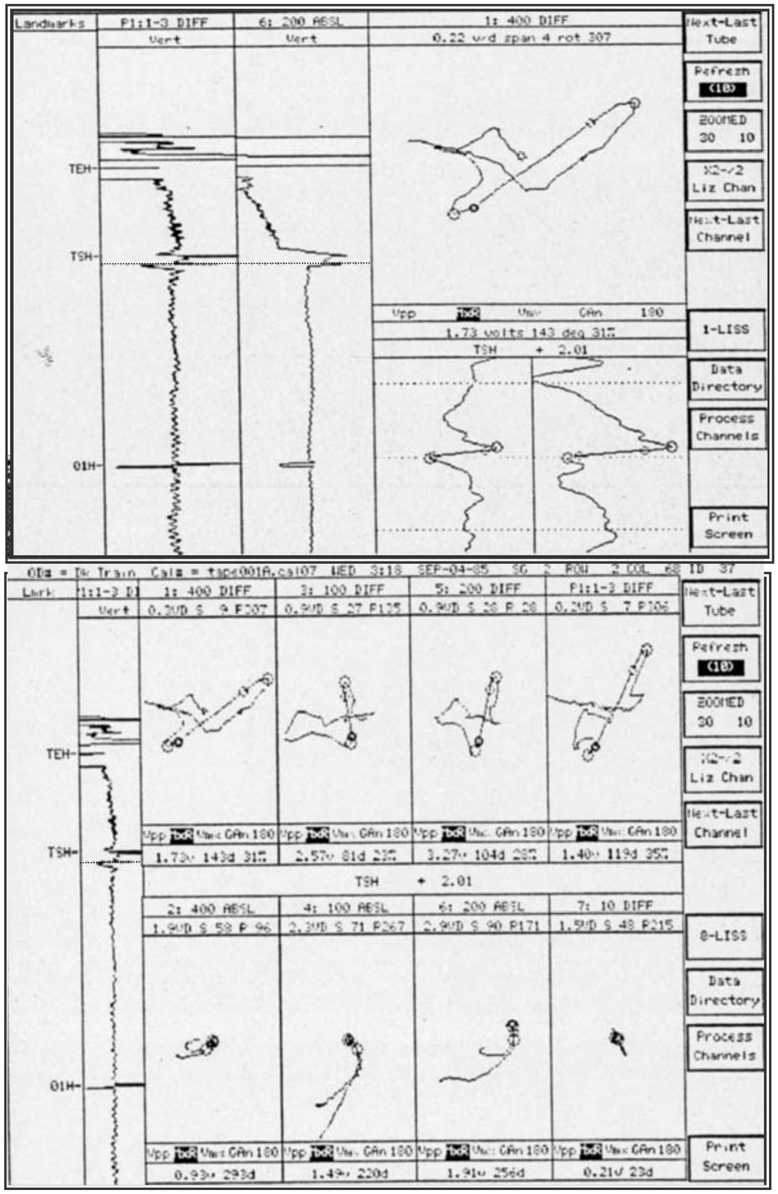


Figure 19. Bobbin probe data for an indication at the TTS sludge pile region identified as ODSCC degradation. Detection was made by using the differential base frequency. Confirmation was made with the differential TSP suppression mix and proper rotation of the signal at auxiliary frequencies. The flaw depth was estimated from the primary differential mix channel.

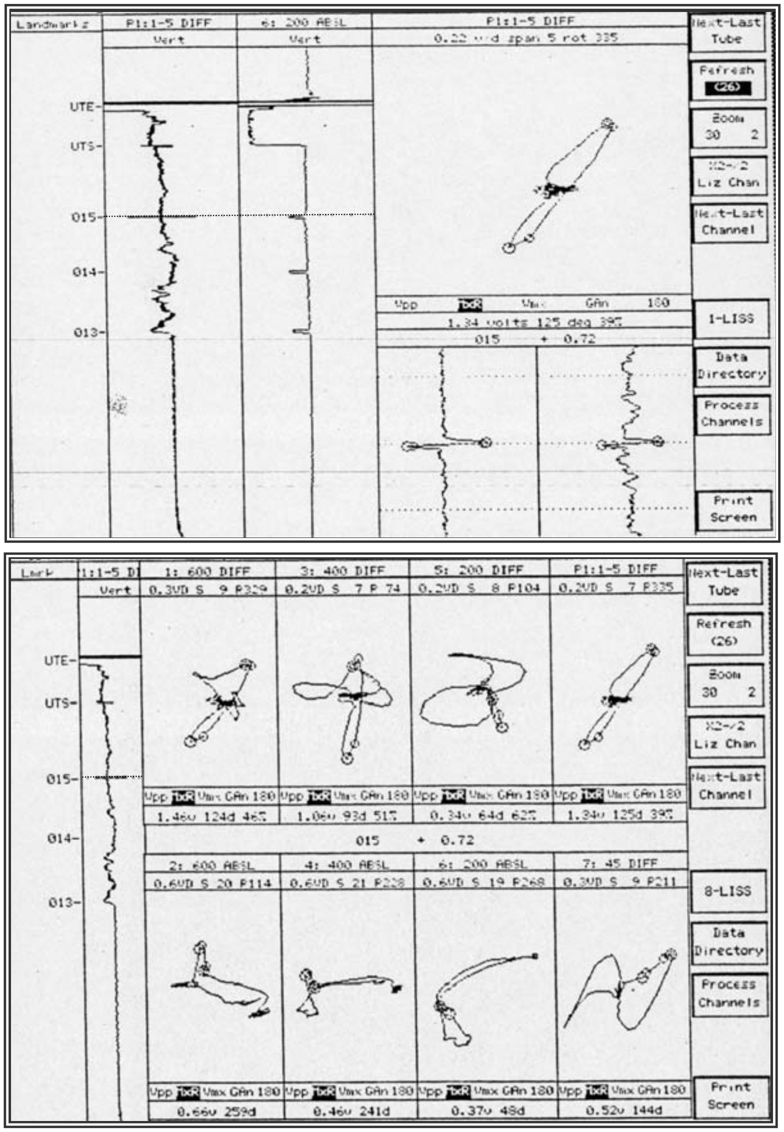


Figure 20. Bobbin probe data from an indication at the fifteenth support plate in an OTSG identified as ODSCC/IGA. The signal was detected from the differential TSP suppression mix of 600|200 kHz for 0.889-mm (0.035-in.) tube wall thickness. Confirmation was based on a differential channel of 400 kHz and proper rotation of the signal at auxiliary test frequencies. Flaw depth was reported from the primary differential mix channel using a phase-versus-depth calibration curve.

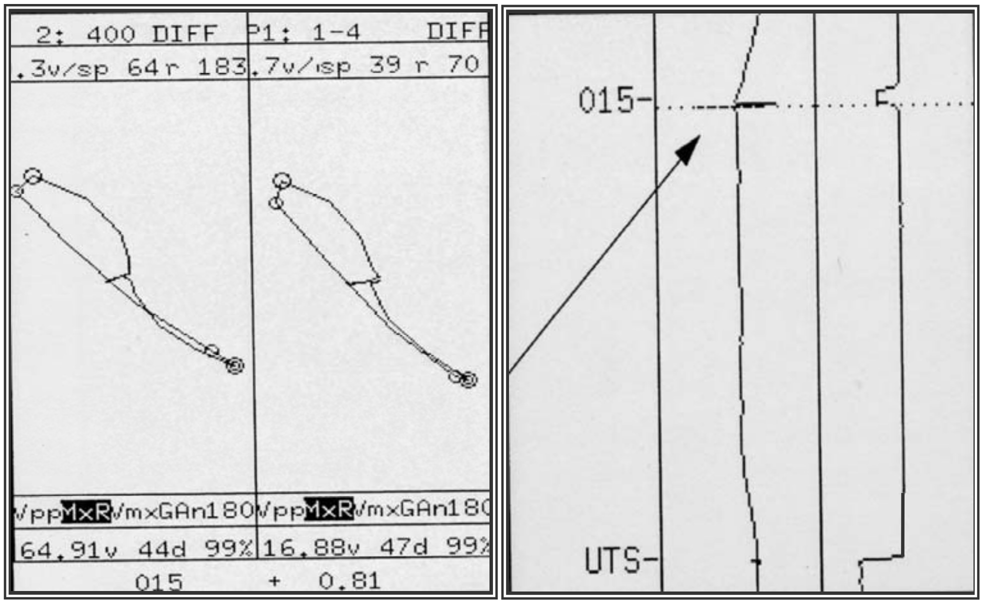


Figure 21. High-cycle fatigue crack detected with bobbin probe in an OTSG unit. The degradation was located at the highest elevation support plate having a significant through-wall depth and with a major axial component. The flaw was detected by the differential channel of 400 kHz. It was confirmed and sized with the differential TSP suppression mix of 600|200 kHz.

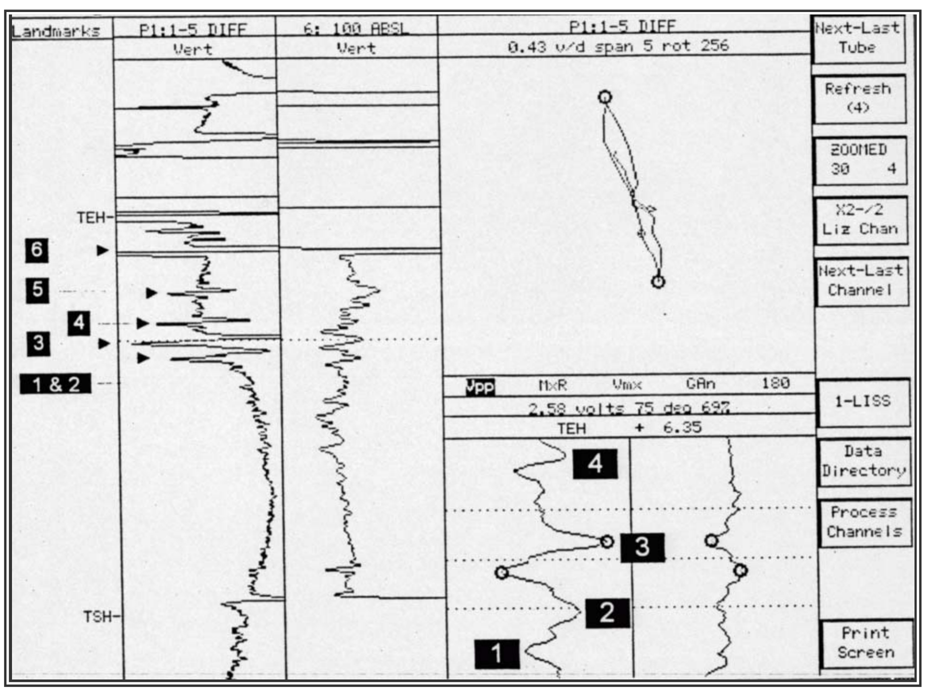


Figure 22. Example of multiple but axially separated SCC indications detected inside the crevice region of a tube that was not expanded for the full axial extent of the tubesheet. The numbers in the black boxes denote the multiple cracks.

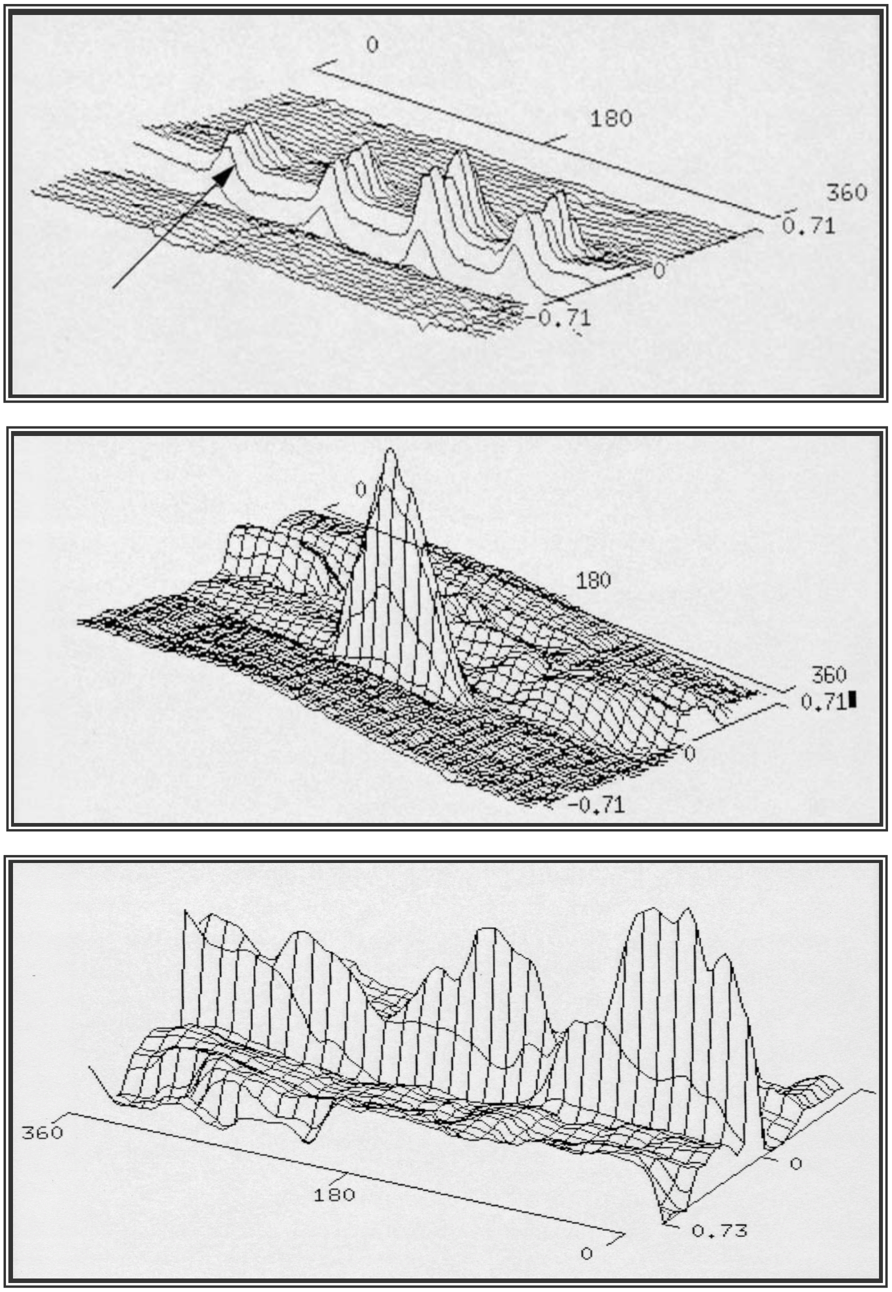


Figure 23. Isometric plot of data collected with a rotating probe showing (top) multiple axial PWSCC, (middle) single circumferential PWSCC, and (bottom) multiple circumferential ODSCC indications at the TS expansion transition region.

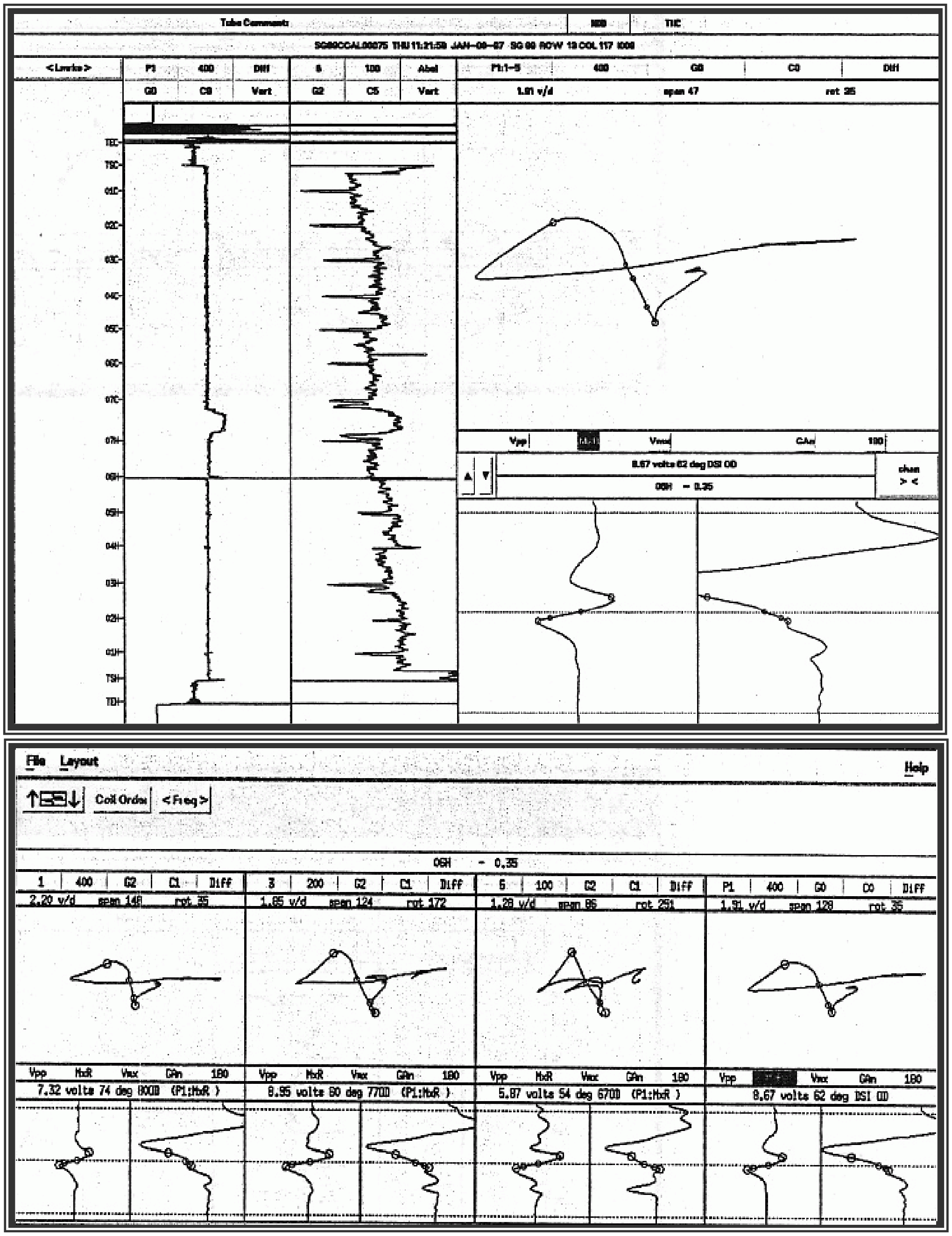


Figure 24. Bobbin probe data used to detect an indication in a dented TSP intersection. The detection channel is a differential TSP suppression mix of 400|100 kHz. Confirmation was made by observing the signal at auxiliary differential channels (200 kHz and 100 kHz). The indication was reported from the primary mix channel.

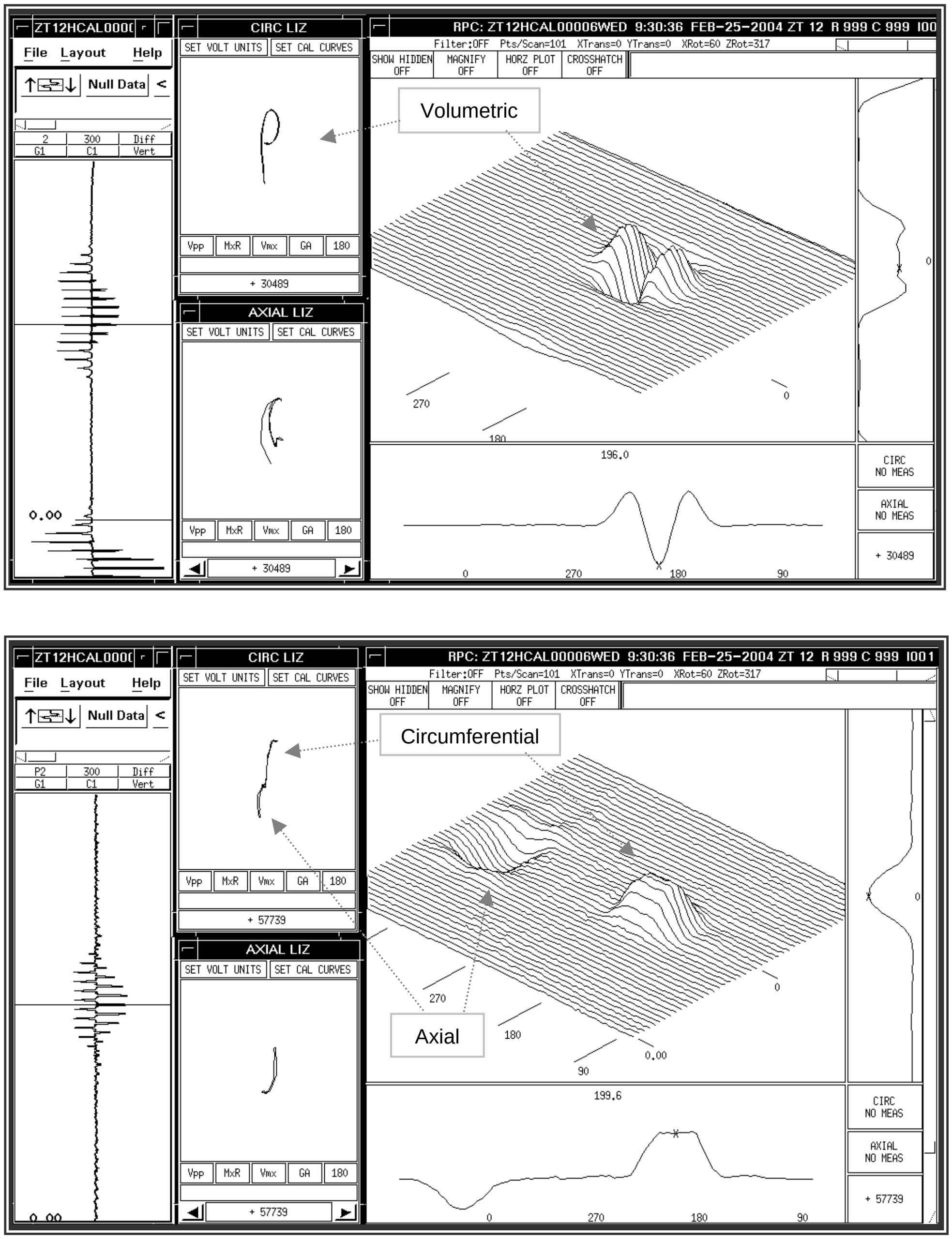


Figure 25. Data collected with a +Point™ probe from a calibration reference tube with volumetric (top panel) and directional (axial and circumferential) machined flaws (bottom panel).

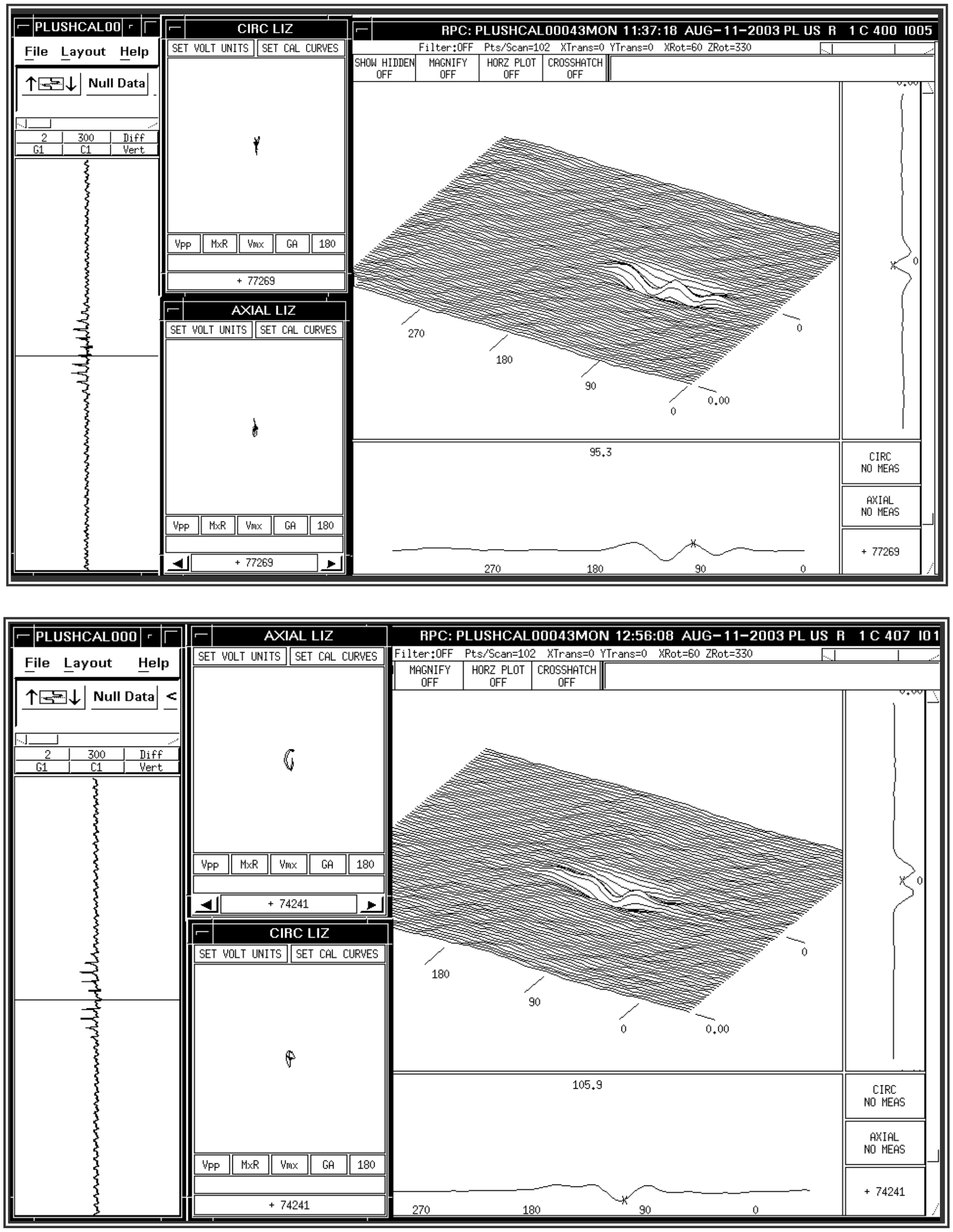


Figure 26. Data collected with a +Point™ probe from two tube specimens with laboratory-produced volumetric flaws.

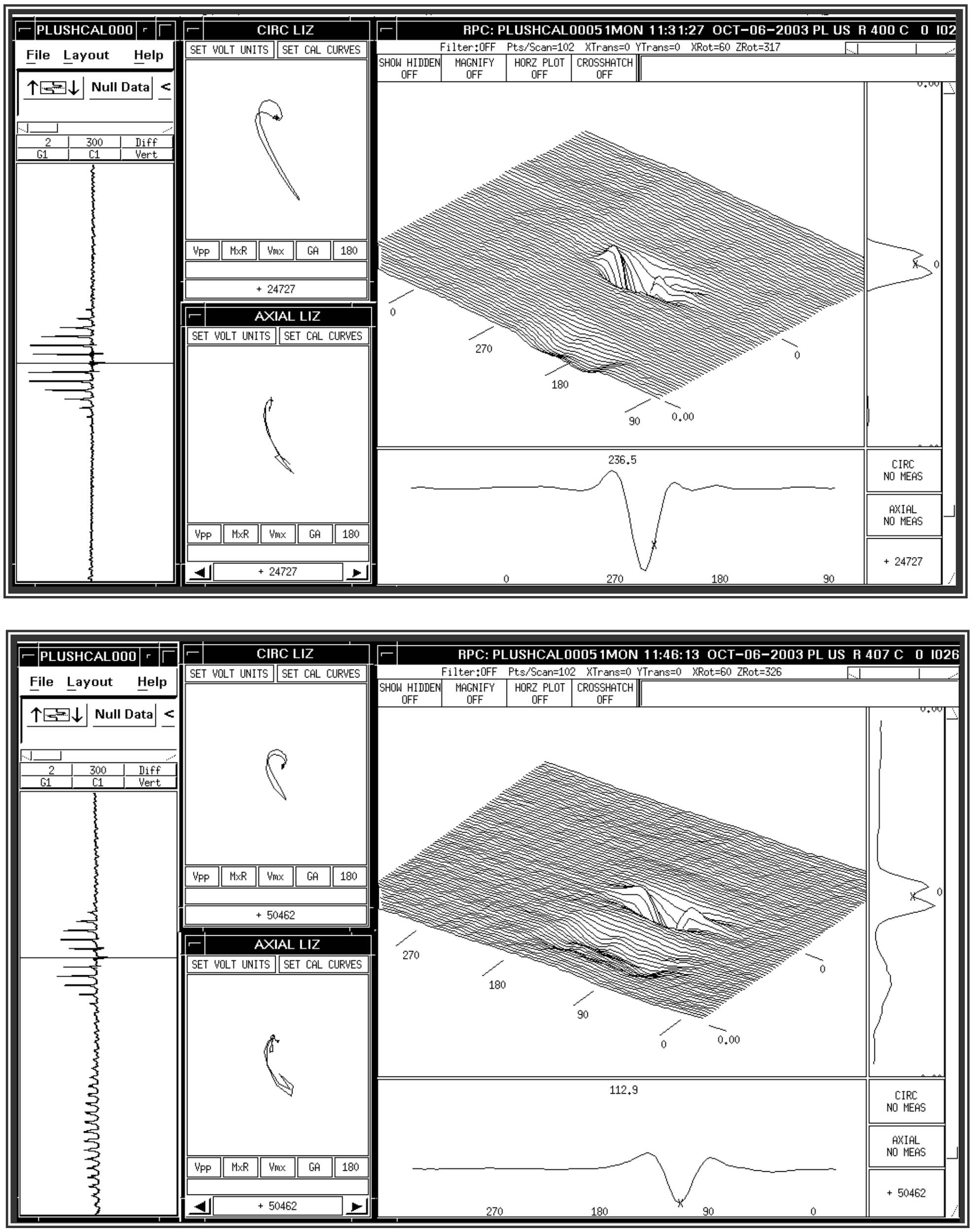


Figure 27. Data collected with a +Point™ probe from the same two specimens shown in Figure 26 after SCC was induced at the bottom of volumetric flaws.

8 References

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