Technical Letter Report:
Effect on Eddy Current Qualification of Varying Parameters in Examination Technique Specification Sheets

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Prepared by
S. Bakhtiar, D. S. Kupperman

Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

M. Stambaugh, NRC Project Manager

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Introduction

Eddy current (EC) testing is the primary nondestructive evaluation (NDE) technique for in-service inspection (ISI) of steam generator (SG) tubes. Because EC testing is a comparative NDE method, inspection reliability depends highly on the consistency of data acquisition parameters and calibrations. The quality of the data, which depends on both the test parameters used for the inspection and the condition of the SG tubes, is a critical issue for reliable ISI of SG tubes. Although data quality affects both detection and sizing of EC indications, it is of particular concern with regard to quantitative estimation of flaw size. Compromises in the setup of the instrumentation and the calibration procedures that are being used during ISI could affect the quality of NDE data and, in turn, the analysis results. Requirements for acceptable data acquisition parameters are documented in examination technique specification sheets (ETSSs) for ISI of SG tubes. For each particular probe (e.g., bobbin, rotating, and array), these ETSSs generally define the applicable test conditions, instrumentation setup (coil excitation frequencies, gain setting, cable length, sampling rate, probe speed, etc.) and calibration procedures required to achieve an adequate probability of detection (POD). With respect to sizing a degradation mechanism, additional specification or restrictions may be needed (when compared to the specifications for a technique qualified for detection). Even though a qualified technique may exist for detecting a degradation mechanism, this does not ensure that a technique exists for reliably sizing the degradation mechanism.

The degradation assessment (DA) document at a site 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 NDE examinations during an outage. The DA identifies site-validated NDE techniques to be used for an inspection. These site validated techniques rely on generically qualified techniques and their associated ETSSs. As part of this site validation, the site must demonstrate that the site specific technique is equivalent to (or more conservative than) the generically qualified technique. For each degradation mechanism, the DA identifies the appropriate ETSS validated for use at that particular site for that degradation mechanism. The DA document also provides the requirements for operator qualification and responsibilities, data acquisition procedures, calibration standards, and data analysis and reporting requirements. Inclusion of site-validated ETSSs into the DA document is done several months prior to the ISI. Techniques that have been qualified in accordance with Appendix H of the Electric Power Research Institute (EPRI) PWR Examination guidelines (i.e., generically qualified techniques) may be used when site-validated techniques are not available. In accord with the EPRI guidelines, when an NDE technique can not been site validated, adjusted POD values should be determined and documented. The document may be revised during the ISI in response to perceived deficiencies associated with an inspection technique selected previously for a particular damage mechanism.
Efforts are being made by the industry to define a suitable set of parameters that could be used to ascertain the appropriateness or quality of EC data. These parameters currently include limits based on the level of noise present in the EC inspection data measured over a region of interest adjacent to the potential flaw. More global parameters for the level of noise are also being evaluated. One such parameter is the signal-to-noise ratio (S/N). Because the initial detection of potential flaw signals during manual analysis of EC data is based on visual identification, defining acceptability in terms of a particular value or range of values for the S/N may be appropriate for the purpose of detection. However, for sizing of flaws, whether manual or automated, S/N has a much broader connotation. The quality of data that may be appropriate for the purpose of detection may not be acceptable for reliable estimation of the flaw size. Thus, more conservative requirements for data quality may be needed for reliable sizing of EC indications.

This report discusses the parameters addressed in an ETSS, which are commonly referred to as “essential variables,” and the effect of variations in their values on flaw detection. An essential variable is anything associated with the EC NDE technique including the procedure, equipment, acquisition and analysis hardware/software, and the electrical properties and dimensions of the material being examined, the modification of which could affect the results of the inspection. Variables such as the scanning method (i.e., manual or automatic) and mechanical fixtures used in the test setup that do not affect the inspection results are considered as non-essential variables. The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section V, states that when a parameter identified as an essential variable in a qualified procedure is different from the specified value, or outside the range of values specified in the procedure, the procedure shall be requalified. Both the Code and the EPRI guidelines provide only general guidance on acceptable methods for re-qualifying or demonstrating equivalency. This guidance typically does not involve a direct re-assessment of the POD or sizing ability when a technique is operated outside its originally qualified range rather it involves establishing “tolerance” values for specific parameters associated with an essential variable (e.g., when the frequency is outside the range specified in an ETSS, the alternate frequency is considered acceptable if it remains within 10% of the current density associated with the qualified frequency (i.e., a 10% tolerance band)). Specific examples of the use of this guidance on demonstration of equivalency are provided in this report. It should be noted that this report is not a review of the measures for demonstrating equivalency rather it is a reference that provides a general description of more commonly noted essential variables, their influence on detection, their acceptable range of variability based on industry guidelines and typical field conditions that may prompt further evaluation of an essential variable.

Implementation of an EC inspection technique for detection and characterization of a particular SG tube damage mechanism may only be ensued following site-validation of an applicable examination technique. The use of modified techniques (i.e., techniques that are used outside the range of values in the generically qualified ETSS) would involve evaluating and documenting the effects of these modifications on the performance indices (POD and sizing accuracy) as part of degradation assessment. This is usually done through a demonstration of equivalency. This demonstration may be made either experimentally or analytically. If the modified technique is shown to be operated within these tolerance values, then the technique is considered equivalent to the qualified technique. In general, the primary objective is to ensure
that any changes made to essential variables associated with the EC inspection equipment, techniques, and analysis methods result in PODs or sizing accuracy that are equivalent to or more conservative than those prescribed in the generically qualified technique. An example of a common performance constraint provided by the ASME Code on substitution of an essential variable that may be outside the qualified range is maintaining a S/N greater than 2. Very few systematic studies are available in the open literature addressing the equivalency issue. Therefore, the guidance given in the EPRI guidelines and here for the range of values that can be considered “acceptable” for demonstrating equivalency is based largely on expert judgment and experience.

EPRI guidelines refer to three categories of examination techniques that may be used for ISI of SG tubes. They consist of qualified, site-validated, and diagnostic techniques. Qualification, either generic or site-specific, of an EC inspection technique is based on meeting the minimum acceptance criteria specified in Appendix H of the EPRI guidelines. Site validation of an NDE technique includes demonstration of equivalency between the qualified and site-specific ETSS parameters. A generically qualified technique may be implemented following a documented review of the technique’s capability. Qualification is not required for NDE techniques that are used for diagnostic purposes only. A diagnostic technique may be implemented following a documented assessment of its capability to help characterize a site-specific damage mechanism. It is worth noting that the term “qualified” technique is commonly used not only to describe a technique qualified to Appendix H of the EPRI guidelines, but it is also used to describe a technique that has been demonstrated to be equivalent to the technique qualified to Appendix H.

In this report, inspection techniques using two types of eddy current probes are discussed. One is the bobbin probe, a high-speed non-contacting probe with two encircling coils that can be operated in differential or absolute mode. The bobbin probe is the primary EC probe used for the initial full-length examination of SG tubes. The other type is a low-speed but high-resolution probe, commonly referred to as motorized rotating probe coil (MRPC). The MRPC is commonly used for inspection of selected regions of the SG tube (e.g., tube sheet, support plates, and U-bend region) as well as for more detailed characterization of indications detected with the bobbin probe. A wide range of rotating probes with single and multiple coil configurations have been qualified and used for ISI applications. One common surface-riding rotating probe design in use today consists of three coils that are integrated into a single probe head: a differential cross wound coil (referred to as +Point™), an absolute mid-frequency pancake coil, and an absolute high-frequency pancake coil.

**Background on Eddy Current Testing**

Eddy current (EC) testing of conducting materials is a relative measurement technique, unlike some NDE methods for which absolute-type measurements are possible. Calibration of data with respect to known signals on a reference standard tube is necessary to allow discrimination and quantitative characterization of consequential indications. Characterization of signals is based on the analysis of features of calibrated EC data obtained at multiple frequencies. This information can be used to differentiate flaws from artifacts. The
two most fundamental features are the variations with frequency of the signal amplitude and the phase information extracted from the impedance plane trajectory (i.e., lissajous pattern). Close proximity of defects to a wide range of internal and external artifacts can complicate interpretation of EC signals. Specially designed probes and software-based signal suppression methods are commonly employed to minimize the effect of interference from nearby artifacts.

In conventional EC data analysis of SG tubing, trained human analysts recognize flaw-induced signals and artifacts through selective application of a series of rules. In addition to well-defined rules for interpretation of signal behavior associated with common forms of tubing degradation, rules founded on experience and historical lessons learned in dealing with similar SG units are also applied. The complexity of the signal and the origin (inner or outer diameter) and location of indications within the SG are typical characteristics that are used to identify flaw types. Artifacts that can affect EC inspection data include probe response due to tube deformation or geometry change (e.g., dents, roll transitions, and U-bend ovalization), conducting and ferromagnetic deposits (e.g., sludge, magnetite, and copper deposits), and tube support structures (e.g., tube-sheet, support plates and anti-vibration bars). Although many of the artifacts by themselves may be considered inconsequential to tube integrity, it is still necessary to carefully analyze the EC inspection data in regions where such artifacts are present. Many of these sites have been shown to be more prone to certain forms of tube degradation. Two such examples are initiation of SCC as a result of residual stresses at deformed regions of the tube (e.g., dents and expansion transitions) and degradation (e.g., cracking) associated with excessive amount of deposits.

Eddy currents generated by a coil attenuate rapidly as a function of depth within the tube wall. For a conducting plate, the change in surface current density \( J_0 \) as a function of depth \( x \) inside the material can be written in its simplest form as

\[
J(x) = J_0 e^{(-1+j)\frac{x}{\delta}}
\]

in which \( \delta \) is the skin depth or the standard depth of penetration and is defined by

\[
\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}
\]

where \( f \) is the excitation frequency in Hz, \( \mu \) is the permeability of the medium in \( H/m \), and \( \sigma \) is the conductivity in \( S/m \). The real and imaginary parts of the exponent represent the attenuation and phase constant. For a non-ferromagnetic material (e.g., Alloy 600, 690, and 800) Eq. 2 simplifies to

\[
\delta = 1.98 \sqrt{\frac{\rho}{f}}
\]

where the unit of \( \delta \) is in inches, \( \rho \) (resistivity) is in \( \mu\Omega\cdot cm \), and \( f \) is in Hz.
In reference to Eq. 1, the change in current density and phase angle relative to its value at the surface is plotted in Fig. 1. The current density drops to $1/e$ ($\sim 37\%$) of its initial value at a depth of $1\delta$ from the surface. At depths $>3\delta$ the current density drops to $<5\%$ of its surface value, indicating significant loss of probe sensitivity to discontinuities beyond this depth. The change in phase lag relative to its value at the surface has a linear behavior as a function depth and is equal to 1 radian ($\sim 57.3^\circ$) at a depth of $1\delta$. The effective phase lag sensed by a probe on the surface is therefore twice (i.e., two way path length) the calculated value shown in Fig. 1 for a given depth.

The underlying assumption in Eq. 1 is that the conducting medium is infinitely thick. For a material with finite thickness, the decay in current density is no longer a simple exponential function. Therefore, for thin-wall tubing such as SG tubes, where the wall thickness becomes comparable to the standard depth of penetration, the accuracy of Eq. 1 will degrade at lower frequencies. This is because at longer wavelengths (i.e., lower frequencies) the medium no longer resembles an infinite half-space of conducting material and thus the effect of reflections at the interfaces (i.e., outside and inside surface of the tube) begins to more strongly influence the flow of currents. Finally, it should be noted that the above equations do not take into account the effect of EC coil geometry, which also plays an important role in selecting the optimum frequency for a particular test condition.

Figure 1. Relative current density (in percent of its value at the surface) and relative phase angle as a function of depth normalized with respect to the standard depth of penetration.
The exponential attenuation of induced current density within the tube wall makes the detection of outer diameter (OD) discontinuities, in general, more challenging than those originating from the inner diameter (ID) surface. The greater phase lag from OD indications, on the other hand, results in a greater degree of phase rotation in comparison to ID-initiated signals and thus provides a wider dynamic range that helps to better resolve the through-wall (TW) extent of a flaw. The angle and rotation of the impedance-plane signal trajectory as a function of frequency is commonly used to determine the flaw origin. For example, after adjustment of the phase angle at all test frequencies with respect to a TW flaw to a fixed value, a decrease in frequency results in indications of OD origin to exhibit a counter-clockwise rotation and those of ID origin to exhibit a clockwise rotation (although with smaller degree of rotation in comparison to OD indications) as the flaw depth increases. Because the characteristic depth of penetration is a function of frequency, data at lower frequencies can be used to more effectively distinguish OD-originated signals, and conversely, the higher frequencies are better suited for characterization of ID-initiated indications.

**Definition of Equivalency**

Electric Power Research Institute guidelines state that when qualifying a technique to the statistical requirements of Appendix H, the data set and parameters should be similar to the site-specific conditions.\(^2\) When the parameters for an inspection technique to be used at a site varies from those specified in the ETSS, the technique can be used only if it can be shown that the modified parameters are “equivalent” or more conservative than those specified by the qualified technique. A demonstration of such “equivalency” for site validation implies that with representative flaws and a statistically significant number of samples, the POD with the modified parameters meets or exceeds the Appendix H requirements (e.g., $\geq 80\%$ with 90% confidence). To demonstrate equivalency between two techniques, it is sufficient to demonstrate the equivalency of the modified parameter alone while keeping all other essential variables, unchanged (i.e., remaining within their qualified range). Techniques that use the same essential variables are considered equivalent.\(^2\)

The following example shows how equivalency might be demonstrated for a case in which specialized probes with the capability to induce high magnetic saturation (i.e., commonly referred to as mag-biased probes) are to be used for testing of tubes with unusually high levels of permeability variation. It should be noted that this is a hypothetical example (i.e., it should not be assumed that such an approach is adequate for demonstrating equivalency).

Modified bobbin and rotating probes with strong rare-earth magnets are used to suppress probe response from atypically high level of permeability variations and thus allow small amplitude flaw signals to be detected. Since the probes have new designs (i.e., compared to the originally qualified probe designs), they have to be shown to be equivalent to probes qualified in accordance with the EPRI PWR Steam Generator Examination Guidelines, Appendix H, and more specifically per Supplement H1 pertaining to equipment characterization. Although the EPRI guidelines do not provide acceptance criteria for equivalency, generic tolerance values are provided for various parameters associated with the system performance either as
absolute quantities or as percent deviation from the nominal values. In this particular case, the generic
criterion of 10% tolerance associated with probe manufacturing quality parameters identified in the
Guidelines is used as an acceptance criterion of equivalency. That is, if the new probes’ response was
demonstrated to be within 10% of the comparable qualified probes, they would be deemed equivalent. In
situations where it is not possible to identify such a criterion, a general performance criterion based on S/N
may be used (e.g., S/N > 2:1).\(^4\) When a specialized probe is to be employed, equivalency would be
demonstrated for other relevant essential variables associated with characterization of that particular probe
design, such as effective scan field, fill-factor coefficient, depth coefficient, and phase-to-depth curve.

**Discussion of Essential Variables**

Three separate categories of essential variables are described in the PWR SG Examination Guidelines:
equipment, technique, and analysis variables. Equipment-related variables include EC inspection instrument,
probe and cable type. Technique-related variables include the operating frequency, drive voltage and gain,
excitation mode (absolute/differential), calibration methods pertaining to data acquisition, number of
channels, recording method, sample rate, and scan pattern. Finally, analysis-related variables include the
calibration method, data review requirements, reporting requirements, and instrument and computerized
system algorithms. A brief description of more commonly noted essential variables and their significance
regarding EC examination of SG tubes are provided below.

**Frequency**

The penetration depth of eddy currents into a conducting material is dictated, in part, by the excitation
frequency of the probe. Therefore, as an essential variable, frequency plays an important role in detecting and
sizing of flaws. For SG tube examination, the primary operating frequency is selected such that degradation
anywhere within the tube wall can be detected with reasonable sensitivity. The optimum frequency for a
particular application depends on several test parameters, including tube wall thickness, material properties,
and the origin and extent of potential degradations. For non-ferromagnetic thin-wall tubing, such as SG tubes,
the optimum test frequency (in Hz) can be calculated by using

\[
 f = \frac{K \cdot \rho}{t^2}
\]

where \(K\) is a parameter that is dependent on the test conditions (between ~5 and 10 for most ISI applications),
\(\rho\) is resistivity in \(\mu\Omega\cdot cm\), and \(t\) is the tube wall thickness in inches. As an example, for an SG tube with
resistivity of 100 \(\mu\Omega\cdot cm\) and wall thickness of 1.27 mm (0.05 in.), setting \(K\) equal to 5 in Eq. 4 would result
in a test frequency of 200 kHz, which is a frequency that provides good sensitivity for detection of indications
anywhere within the tube wall. Higher or lower values of \(K\) may be used in order to increase the sensitivity to
ID- or OD-originated indications, respectively. It is also worth noting that the optimum frequency for
detection proposes may be different from that for sizing. In reference to Eq. 4, the operating frequency is
linearly dependent on electrical resistivity and has an inverse square relationship with the tube wall thickness. Thus, for the same percentage of variation, the change in tube wall thickness will play a more important role in selecting the optimum test frequency than the change in material resistivity.

When the variation in the inspection frequency is outside the range recommended by ETSS, the technique then is requalified in accordance with Appendix H of the EPRI PWR Examination Guidelines, unless it can be demonstrated that the new test frequency will provide equivalent or better sensitivity than the qualified frequency. An analytical approach that might be used to demonstrate that the change in frequency will not degrade the detection sensitivity is to demonstrate using Eqs. 1-3 that the current density for the actual case is either increased over that determined by the qualified variables or that the decrease is acceptably small (e.g., ≤ 10%).

To demonstrate equivalency, EPRI guidelines recommend a tolerance on the frequency range that is based on the induced current density by the probe. They recommend that the frequency-equivalent current density should remain within 10% of the current density at the qualified test frequency. The relative current density, at a fixed depth equal to the thickness of tube wall, was calculated from Eq. 1 for tube wall thicknesses of 1.02 mm (0.04 in.) and 1.27 mm (0.05 in.) while keeping all other variables the same. A resistivity of 100 $\mu\Omega$-cm was used for this example, which is a typical value for SG alloy tubing. The results of these calculations are displayed in Fig. 2. The graph shows that to remain within 10% of the current density at the qualified test frequency, the acceptable frequency range is nonlinearly dependent on the tube wall thickness. The acceptable range is larger at higher frequencies and is also larger for tubes with smaller wall thickness. For example, for a tube with wall thickness of 1.02 mm (0.04 in.) and at qualified inspection frequency of 100 kHz, the 10% tolerance allows for variation in frequency from ~70 kHz to ~140 kHz. For the same tube at 300 kHz, this tolerance allows for variation in frequency from ~250 kHz to ~360 kHz. For the same qualified frequencies, the allowed variations for a tube with 1.27-mm (0.05-in.) wall thickness are ~80-130 kHz and ~260-350 kHz, respectively.

The operating characteristic (i.e., frequency response) of the probe, which is a design-dependent parameter, should be taken into account in selecting the optimum test frequency. This information is typically obtained from swept or stepped frequency measurements of the probe over the specified operating frequency range. In accordance with the EPRI guidelines, the manufacturing tolerance on a probe’s center frequency determined from its characteristic response (i.e., probe response as a function of frequency) is recommended to be <10% deviation from the design center frequency. This probe-related quality parameter should be distinguished from the tolerance on frequency associated with technique qualification discussed above.
Material Properties

Alloys 600, 690, and 800 possess virtually the same electrical properties (conductivity and permeability), and thus qualified techniques for any one of these tubing materials may be used for testing of the other two without modification. For such non-ferromagnetic materials, for tubes with the same nominal wall thickness, there is a linear relationship between frequency and electrical resistivity. Therefore, when the only essential variable being changed is the resistivity of the tube, to maintain the current density the frequency can be adjusted according to the following equation:

$$f_2 = f_1 \frac{\rho_2}{\rho_1}$$  \hspace{1cm} (5)

where the subscripts 1 and 2 denote the original and modified test variables.

Figure 3 shows the skin depth versus frequency for Alloys 600, 690, and 800. The skin depths here were calculated using Eq. 2 or 3 with resistivity being the only differing variable for the three alloy materials. The depth of penetration at 100 kHz is ~1.62 mm for Alloy 600, ~1.71 mm for Alloy 690 and ~1.58 mm for
Alloy 800. Because the resistivity of Alloy 600 (103 $\mu\Omega\cdot\text{cm}$), Alloy 690 (114.8 $\mu\Omega\cdot\text{cm}$), and Alloy 800 (98.9 $\mu\Omega\cdot\text{cm}$) are very similar, there is little difference between the depths of penetration of the alloys. Therefore, as an essential variable, resistivity is expected to have negligible effect on the selection of the optimum frequency for EC examination of these alloys.

Although the small variations in electrical resistivity due to alloy composition do not affect the system response, manufacturing processes and service-related conditions could produce variations in material properties that could influence the adjustment of essential variables for site-specific validation of an inspection technique. Processes such as cold working (e.g., pilgering) and heat treatment could add considerably to the level of eddy current noise and lead to a dramatic reduction in inspection reliability and thus are taken into consideration in selecting of a site-qualified inspection technique. The primary essential variable to monitor in this case is the level of noise that may be generated under these conditions. Changes in tube material properties associated with permeability variations are of particular concern to the ISI of SG tubing. Permeability variations can affect both the operating characteristics and the level of noise, thus leading to significant reduction in the quality of EC inspection data. The presence of conducting and magnetic deposits may also be interpreted as an effective change in tube material properties. Generically qualified EC examination techniques are available that can help minimize the effect of material property variations on EC inspection results. Such specialized techniques can be used for site-specific applications when it can be demonstrated that the quality of data is equivalent, to or better than that specified by the

![Graph of calculated standard depth of penetration as a function of frequency for Alloys 600, Alloy 690, and Alloy 800.](image)

*Figure 3. Calculated standard depth of penetration as a function of frequency for Alloys 600, Alloy 690, and Alloy 800.*
associated ETSS. The signal-to-noise ratio is one of the main essential variables to monitor when such specialized techniques are implemented.

Eddy current inspection techniques based on magnetic saturation of the tube wall are typically employed to suppress the probe response from permeability variations. These specialized techniques use magnetically biased bobbin and surface probes. Because of differences in probe design and operating mode (i.e., absolute versus differential), variations in material properties could affect the response of the two types of probe differently. For example, for some heats of tubing material, a relative rotation of phase angle as large as 90° has been observed between the responses of mag-biased and non-mag-biased pancake coils to the same indication. Such differences in phase angle rotation are not observed for the +Point™ probe, which is a differentially wound coil. Recalibration of the phase angle for the pancake probe can help minimize the effect of phase rotation due to material property changes associated with heat treatment of the tube. Thus, when switching from a non-mag-biased to a mag-biased probe during field inspections, it is important to ensure that proper recalibration procedures are in place. Failure to recalibrate properly could lead to misinterpretation of the eddy current signals, particularly for probes operating in the absolute mode. The 2001 ASME Boiler and Pressure Vessel Code Section V, Article 8, states that, if the calibration standard material is heat treated differently from the tubing to be examined, then the standard can be used if the response from the discontinuities in the standard are demonstrated to be equivalent to potential flaws in the tubes. As discussed in the ASME Code, the acceptability of the calibration standard in such cases may be demonstrated based on the S/N value. The S/N could be determined by measuring the EC baseline noise level and the signal from a known machined flaw in the reference tube. The discussion here suggests that it is also important to examine differences in rotation of the phase angle.

Tube Wall Thickness

Equation 4 shows that for thin-wall tubing, the primary test frequency is inversely proportional to the square of the tube wall thickness. Therefore, as an essential variable, wall thickness is a critical parameter in determining the operating frequency, which governs the penetration depth and thus the ability to detect SG tubing flaws. For typical field inspections employing bobbin probes, equivalent techniques use scaling factors based on tube wall thicknesses for the adjustment of test frequencies. This adjustment is not always implemented for rotating probe examinations for reasons discussed below. In general, small variations (<5%) in the nominal tube wall thickness are not expected to significantly affect the ability to detect signals from consequential indications at the primary test frequency.

Based on the results of calculations presented earlier, in an SG tube with 1.27-mm (0.050-in.) wall thickness, the skin depth is 1.32 mm (0.052 in.) at 150 kHz, 0.81 mm (0.032 in.) at 400 kHz, and 0.6 mm (0.024 in.) at about 600 kHz. In the middle frequency range (i.e., ~200-300 kHz), flaws near both the ID and OD surface may be detected with acceptable sensitivity. Above this range the probe loses its sensitivity to shallow OD defects. Lack of sensitivity to OD discontinuities, in turn, renders higher frequencies more useful for detection and characterization of signals from shallow ID indications.
When the change in wall thickness is the only essential variable of concern, the operating frequency for examination of non-ferromagnetic tubes may be calculated from:

\[ f_2 = f_1 \left( \frac{t_1}{t_2} \right)^2 \quad (6) \]

where the subscripts 1 and 2 denote the original and the modified variables. As calculated from the above equation, the primary and auxiliary frequencies of 400 kHz, 200 kHz, and 100 kHz that are used for the inspection of Alloy 600 tube with 0.05-in. (1.27-mm) wall thickness will scale up to 540 kHz, 270 kHz, and 135 kHz, respectively, for a tube with a 0.043-in. (1.1-mm) nominal wall thickness. Alternatively, a similar approach to that described earlier for selection of test frequencies can be used. In both cases, the scaling of frequency is based on keeping constant the ratio of the depth of penetration to the tube wall thickness.

Although adjustment of the frequency is required by ETSS documents for bobbin coil examinations, the scaling of frequency is not always implemented for rotating probe examinations. For rotating probe examinations, the same coil design is typically used for tubing with nominal wall thicknesses of 1.1 mm (0.043 in.) to 1.27 mm (0.05 in.), because sensitivity of rotating probes is acceptable over a relatively wide range of tube wall thicknesses. The operating characteristic of such probes is strongly dependent on the coil design, and the selection of the excitation frequencies can be based on the probe’s optimum response over a range of tube wall thicknesses. Site-specific ETSSs may prescribe a different set of qualified test frequencies when the nominal tube wall thickness is outside of the range where the detection sensitivity is acceptable.

**Tube Diameter**

The fill factor, which is an indicator of the strength of field coupling between the coil and the tube, is defined for bobbin-type probes as

\[ FF = \left( \frac{\bar{D}_{\text{coil}}}{D_{\text{tube}}} \right)^2 \quad (7) \]

where the numerator is the average diameter of the coil, and the denominator is the inner tube diameter. Variations in the SG tube diameter change the fill factor for bobbin probes and can produce lift-off for surface probes. These variations can, in turn, strongly affect the sensitivity of the probe. An analogous condition is when the changing parameter is the probe diameter. Because the field intensity drops sharply with an increase in distance between the probe and the test piece (the tube in the case), the response due to probe displacement associated with abrupt change in tube diameter can be large enough to mask potential flaw signals. Changes in SG tube diameter are typically associated with tube-sheet expansion, including the expansion transition, ovalization at small-radius U-bends, and denting. The probe head assembly and centering mechanism are selected to match the tubing diameter and thus help limit the effect of probe wobble.
Field conditions, such as unusual tube deformations that can hinder probe movement, could result in selecting a smaller diameter probe that may need to be operated outside the qualified range of the essential variables.

From a practical standpoint, the fill factor cannot be measured directly for typical ISI applications. Therefore, the EPRI guidelines require that the probe amplitude response to a 100% TW flaw be measured over the fill factor range that is expected to be encountered under field conditions. The drop in the magnitude of the signal (peak-to-peak voltage) from largest to the smallest fill factor should not exceed ~40% of the peak value (i.e., highest voltage measured at the smallest fill factor). The same tolerance on the magnitude of the signal also holds for surface probes for which the effect of probe lift-off is measured over the expected range (i.e., smallest to the largest lift-off). Variation in probe lift-off under laboratory conditions is commonly simulated by placing layers of non-conducting sheet of known thickness between the coil and the test piece. Although a 40% drop in peak signal may not significantly affect the detection of consequential indications, it could result in underestimation of flaw size based on the signal amplitude. It is, therefore, important in such cases to closely monitor the integrity of the probe and guiding mechanism to ensure reliability of the inspection results. Regions of the SG with an excessive degree of tube deformation are generally examined more closely. The S/N (i.e., >2) can be used as an effective means to measure the influence of probe displacement on the quality of EC inspection data.

Data Acquisition Variables

A typical ETSS specifies the minimum values for digitization rate (samples per second) and sampling rate (samples per inch) as well as the maximum value for probe axial speed (inches per second) and rotational speed in rotations per minute (rpm). The minimum sampling rate in the axial direction for the bobbin probe and in the axial and circumferential directions for rotating probes is set such that the probe response from the smallest detectable flaws can be acquired with sufficient spatial resolution. An insufficient number of samples will always result in loss of information. Minimum acceptable sampling rates are provided in Appendix H. These are typically around 30 samples per inch for bobbin and rotating probes (i.e., in both the axial and circumferential direction). Lowering the sample rate below the prescribed values will result in degradation of the signal. Higher sampling rates can be used when necessary to better resolve closely spaced signals.

An ETSS for a bobbin probe typically specifies a minimum sampling rate of 30 samples per inch and a minimum digitization rate of 400 samples per second for a 12 in./s maximum axial probe speed. Thus, data are collected every ~0.03 inches (0.75 mm) in the axial direction. When a higher probe speed is permitted by the ETSS, the minimum sample rate requirement is met by a proportional increase in the minimum digitization rate. For a typical rotating probe at 300 rpm and a sampling rate of 30 samples per inch circumferentially and 25 per inch axially, a data point is collected about every 4 degrees or every 0.1 in. (2.5 mm) circumferentially and every 0.04 in. (1 mm) axially. Thus, the spatial resolution is on the order of millimeters (also a probe-dependent parameter). For a given sampling rate, smaller diameter coils are expected to provide better spatial resolution than larger diameter coils. Spatial resolution is a function of
both frequency and coil geometry (size and coil separation). In special circumstances, it may be necessary to increase the sampling rate (in the axial or circumferential direction) to better resolve flaws for engineering assessments. Such an increase in the data acquisition sampling rate in general may be implemented without re-qualification of the technique. Use of sample rate below the minimum prescribed by the associated ETSS will require re-qualification or an engineering argument to demonstrate equivalency.

The ETSS for rotating probe examinations specifies the maximum allowable rotational speed to achieve the expected POD and sizing accuracy. The rpm value prescribed for a rotating probe is set so that the minimum sample rate requirements are met for a given probe axial speed and instrument digitization rate. Higher rotational speeds can also lead to dynamic effects that can be different in different locations in the steam generator. Thus, a rotational speed that is acceptable for the inspection of free-span regions may not be acceptable in the U-bend region of the SG. As an essential variable, the average rotational speed over the inspected length of a tube is maintained within the acceptable limits (i.e., ±25% of the average speed). The rpm specified in an ETSS would be considered as the maximum allowable value for a given sampling rate. For rotational speeds higher than those specified by the ETSS, equivalency should be demonstrated under site-specific conditions. The process includes employment of appropriate samples that simulate flaws in specific regions of tubing (e.g., free-span, roll transition, U-bend, dented regions, etc.). A demonstration of the detectability of flaw signals may be based either on direct measurement of S/N using the modified technique or by comparing the level of noise between the qualified and modified technique to adjust the POD curve.

Rotating probe data were collected and analyzed at Argonne National Laboratory to show the equivalency between free-span data acquired at 900 rpm [traversing the tube at 0.5 in./s (12.7 mm/s)] and 300 rpm [at 0.1 in./s (2.54 mm/s)] using the same probe. Figure 4 shows the lissajous plots for a laboratory-grown flaw that was inspected with a +Point™ coil at 300 and 900 rpm. The signals are nearly indistinguishable with regard to their amplitude and phase angle. In the free-span region of the tube, comparable results have also been observed for other frequencies and coils. However, in other sections of the steam generator such as the tube-sheet and U-bend regions, a change in the rotational speed could result in unacceptable change in the quality of signals because of a potential increase in the level of noise that is associated with excessive probe wobble.

As previously mentioned, increasing the spatial resolution by using a higher sample rate could provide, in certain cases, critical additional information about the degradation morphology. A notable application is for improved characterization of ligamented cracks. The ligaments provide a conducting path for the flow of eddy currents, thus reducing the EC signal strength, which could result, in turn, in significant underestimation of the flaw size. The presence of ligaments along a crack could result in NDE data that leads to a significant underestimation of tube failure pressure. If the signal from an indication suggests the possibility of ligaments being present, acquiring EC inspection data at higher spatial resolution could improve sizing results. Higher spatial resolution in this case would be achieved by increasing the data acquisition sample rate.
The gain setting is another essential variable that is defined by the ETSS for a particular technique. In accordance with the EPRI guidelines, the gain setting is adjusted such that the magnitude of the largest expected signal, typically from the deepest flaw, produces a response that is 80% of full scale. This helps to ensure that the largest signals will not be saturated. This gain setting also provides reasonable assurance that the limiting flaws are detectable. Observation of the probe response from the largest manufactured flaw in the calibration standard tube is, in general, a good indicator of proper setting of the gain.

**Data Analysis Variables**

Site-specific data analysis guidelines provide explicit information regarding applicable data analysis procedures such as calibration setups and data evaluation procedures. These guidelines make recommendations on the primary and auxiliary frequencies/channels for analyzing data in various regions of the SG tubing, settings for display of data in strip chart and lissajous formats, amplitude and phase angle calibrations, implementation of calibration curves for sizing, and data quality requirements. A brief description of selected essential variables associated with analysis of EC inspection data and their influence on the analysis results is presented here.
Analysis guidelines specify the primary and auxiliary frequencies that are qualified for a particular examination technique. Frequency selection and the associated tolerances for demonstrating equivalency were discussed earlier in this report. For each qualified technique, the associated ETSS also specifies the process channels. For example, the primary (process) channel for typical bobbin probe inspection technique is based on mixing of two frequencies such as a 400|100 kHz mix or a 550|130 kHz mix for tubes with 0.05-in. (1.27-mm) and 0.043-in. (1.09-mm) wall thickness, respectively. Any deviation from the recommended frequencies beyond the acceptable tolerances specified by the EPRI guidelines is followed by site-specific demonstration of the technique’s performance.

The minimum span setting associated with manual analysis of EC inspection data is intended to optimize visual detection of the smallest relevant indication. As an example of span setting, the recommended value for the +Point™ coil specified in ETSS 20510.1 (circumferential primary-water SCC at expansion transition) is five divisions for a 40% ID circumferential notch. Adjustment of the span setting on the analysis screen to a value that is considerably outside the prescribed range could lead to missing of consequential signals during the initial review of the data. Errors on the order of 10% in span setting should not adversely affect the ability to detect signals from significant flaws. For more detailed examination of signals over a particular region of the tube, however, the span setting may need to be temporarily adjusted.

Proper adjustment of the phase angle plays an important role in detection and sizing of EC indications. The phase alignment at each test frequency is set in accordance with the ETSS before review of the inspection data. As an example, the phase angle setting for the +Point™ specified in ETSS 20510.1 (circumferential primary-water SCC at expansion transition) is 15 degrees for a 40% ID circumferential notch. As an essential variable, inconsistent phase alignment could produce rotation of the impedance plane trajectory outside the flaw plane or inconsistent signal behavior as a function of frequency, and hence result in mischaracterization of signals. An incorrect setting could lead to missing a flaw signal as a result of possible reduction in the vertical component of the signal that is monitored during the initial data reviewing process. Improper setting of the phase angle at the calibration stage can also have a profound effect on estimation of flaw depth. Because of the smaller dynamic range of phase angle for ID-originated signals, any deviation from the prescribed phase setting for calibration purposes is more likely to affect the estimation of the depth of ID indications. Errors on the order of 3° in phase setting based on machined flaws in a calibration standard tube are generally acceptable.

Consistency of the inspection results depends heavily on proper scaling of EC data. Normalization of signal amplitude (voltage setting) based on artificial flaws in a calibration standard tube serves both to assess the extent of tubing degradation and to compare the results from previous inspections. Normalization also permits comparison and use of NDE information from different sources. This can help toward development of more effective ISI solutions through integration and evaluation of data from various databases. For a bobbin probe the signal amplitude from four 20% TW OD holes on the ASME calibration standard is set to 4v at 400 kHz or 2.75v on the 400-100 kHz mix channel. Consistent scaling of signal amplitude is of particular importance to plants that implement voltage-based repair criteria at tube support plates. To obtain consistent
Calibration standards are the primary means for determining the response of the EC inspection system, which is a critical factor with regard to inspection reliability. In-line calibration standards such as ASME and electro-discharge machined (EDM) notch standards are used during data acquisition to ensure accuracy and consistency of the examination technique’s variables. The choice of calibration standards depends on the site-specific inspection technique that is being employed to detect and characterize a particular type of degradation. When a “qualified” sizing technique (e.g., amplitude-based sizing of wear scars) is implemented, it is important that the calibration standard have adequate number and range of artificial flaws for establishing the calibration curves. Machined flaws with shallow depths may be used for characterization of large volumetric degradations (e.g., mechanically induced wall loss) that are typically detected with bobbin probes. The measured flaw depths are expected to be known to within approximately 5% of the actual depth to assure acceptable consistency of the analysis results. Site-specific applications, such as voltage-based repair criteria at support plates using bobbin probes, require further consistency of the calibration standards, which is typically achieved by comparing each calibration standard with a reference standard (“mother standard”). Consistent calibrations are also important for both historical comparisons at a given site and comparisons of data from different sources.

The quality of EC inspection data is evaluated based on the level of noise present in the data from a particular site. Eddy current noise can have a significant impact on the detection and sizing of SG tube defects. Noise can add either constructively or destructively to the EC signal. Noise levels that may not significantly affect detection can have a profound effect on sizing results. An estimate of the minimum noise level can generally be established by using data from unflawed sections of tubing at representative locations in the SG. Such measurements are useful for the purpose of general data quality assessment. However, detection probability and sizing are strongly affected by local noise levels in the vicinity of the degradation. For site-specific applications, noise level associated with SG tubing conditions typically associated with degradation such as deposits, dents, expansion transitions and U-bends can be measured and compared with the available values for a particular technique to demonstrate its capability for achieving an acceptable POD. In work done at Argonne using the ANL/NRC SG mock-up, the maximum S/N, in terms of vertical component of EC data, at which a flaw was missed was slightly above 2 for bobbin probe inspection of free-span and TSP regions. A S/N above 2 resulted in detection of flaws at the 90% confidence level for the database used in that study. Treating the noise in rotating probe data in a similar manner as for the bobbin probe may not always provide a conservative measure of the influence of noise. Reference 2 provides more detailed information on the measurement of EC noise level and its effect on detection probability.
The level of noise in some cases can be significantly reduced by applying appropriate frequency and spatial domain filtering schemes. For ISI applications, digital filters are often used as screening tools and for diagnostic purposes only. This is done to minimize variability, which could be introduced by the filtering process, in reporting of the data and to prevent potential suppression of flaw signals. Knowledge about the plant’s history, location along the tube, characteristic response, and distribution of indications always plays an important role in discriminating signals from artifacts.\textsuperscript{1} This information may be used on a site-specific basis to implement more effective noise suppression schemes that can help improve the capability of a technique to detect difficult flaws.

**Equipment Variables**

Equipment variables such as instrument type, probe type, and cable length and type are specified by the ETSS. As with all other essential variables, equivalency would be demonstrated following any change of equipment or software outside the qualified range, prescribed by the site-qualified technique. Upgrades associated with qualified data acquisition and analysis software do not generally need to be requalified. EPRI guidelines also provide general requirements for all of the variables associated with the examination system, including equipment variables. Changes in cable length are frequently encountered during field inspections. The EC probe and cable can be considered as parts of a resonant circuit. The cable resistance and capacitance are dependent on its length, which, in turn, can affect the system response. Any change in cable length can influence the characteristic response of the EC probe and thus degrade its performance. Using an arbitrary length of extension cable could adversely affect the quality of data and, in effect, the probability of detection for a particular inspection technique. The EPRI guidelines recommend two possible approaches for determining the effect of cable length modification on the system response. The first method is based on swept or stepped measurement of the frequency response with the modified cable length and comparison of the results with those from a qualified technique. The difference between the two center frequencies should be less than 10%. The second approach is based on comparison of the probe response from the same indication (e.g., artificial flaw in a reference standard tube) between the modified and the qualified method. The difference in amplitude response between the two should again be less than 10%. The 10% criterion on variation of amplitude response would be considered reasonable in view of realistic tolerances on controlling the quality of manufacturing parameters.
Summary

The effect of varying more commonly noted essential variables such as frequency, tube wall thickness and material properties as well as variables associated with the acquisition and analysis of eddy current inspection data was discussed in this report. A brief discussion was initially provided on the basic principles of EC electromagnetic testing. Followed by a discussion on equivalency, several examples on how equivalency could be demonstrated for particular field applications were presented. Short discussions were presented on several common essential variables, and when applicable, analytical calculations were presented to support assessing equivalency for a technique operated outside the specified limits on the generically qualified ETSS. Limited experimental test cases were also provided on the effect of essential variables on EC inspection results based on data acquired at ANL. A listing of common essential variables discussed in the text and the effect of their variation are summarized in Table 1 of Appendix A. With regard to the table, it is worth noting that it is not always possible to provide a fixed tolerance as the criteria for acceptability of certain essential variables. In such cases one may refer to the discussion and equations provided in the text in order to help determine the bounding values for those variables.
References


Table 1. Listing of some common essential variables and summary of the effect of their variation on qualification of ETSS parameters.

<table>
<thead>
<tr>
<th>ETSS parameter (Text reference)</th>
<th>Importance</th>
<th>Probe type</th>
<th>Effect of variation of ETSS parameter on detection</th>
<th>Degradation type, origin (OD/ID), and location</th>
<th>Conditions that may prompt further evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Pg. 3, 4, 7-9, 11, 15)</td>
<td>H</td>
<td>BC and RPC</td>
<td>An ETSS specifies the frequencies for an inspection technique. Failure to use the proper frequency could lead to flaws being missed and sized incorrectly. Acceptable variation is based on frequency-equivalent current density (see Eq. 1) being within 10% of the current density at the qualified test frequency. For non-ferromagnetic thin-wall tubing, the optimum test frequency (Hz) can be calculated from Eq. 4 (refer to discussion in text for details). Detection probability will be reduced if frequency is outside the range qualified for a given wall thickness. Increasing frequency generally improves detection of shallow ID flaws. Use of proper frequencies and process channels are particularly important for locations such as the TSP, TS and U-bends. Applies to all forms of degradation, but is expected to more strongly affect the detection of OD-originated indications.</td>
<td>Any time the test frequencies deviate from those specified in the site-validated technique. Frequency-equivalent current density can be used to determine acceptability of frequency variations.</td>
<td></td>
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<tr>
<td>Material (Pg. 3-4, 6-10)</td>
<td>L</td>
<td>BC and RPC</td>
<td>Negligible difference between the electrical properties of non-ferromagnetic tubing materials such as Alloy 600, Alloy 690, and Alloy 800. Equivalency is demonstrated for different heat treatments. Probe response from support structures (e.g., TSP TS, AVB, etc.) can vary significantly depending on their type and material properties. Dependent primarily on plant’s operating history and active damage mechanism.</td>
<td>When in-generator noise level in the region of interest (based on sampling) is found to be higher than the available values in the ETSS. When tube material or manufacturing process is different from that used for technique qualification.</td>
<td></td>
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<tr>
<td>Wall Thickness (Pg. 4, 7-8, 10-11, 15)</td>
<td>H</td>
<td>BC and RPC</td>
<td>Variation in wall thickness can significantly affect EC probe response. Tube wall thickness is expected to be as close as possible to the nominal values and the calibration standard tube. Variation &lt;5% in general is acceptable. The wall thickness variations are expected to conform to qualified limits placed on the operating frequency that is referred to in this table (also see Eq. 6). At a given frequency, the Strength of OD flaw signal decreases with increasing thickness. Less significant effect with increasing wall thickness on detection of shallow ID flaws. Expanded and repaired regions are of particular importance. Applies to all types of degradation. The detection of large volumetric flaws could be less affected by variations of wall thickness.</td>
<td>When variation of wall thickness does not conform to the bounding frequency range.</td>
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<tr>
<td>Tube Diameter (Pg. 11-12)</td>
<td>H</td>
<td>BC</td>
<td>Variation of tube diameter can affect the fill-factor and probe centering, which in turn can degrade the sensitivity of bobbin probes (reduces S/N). Probe diameter is selected in accordance with the manufacturer’s specifications for a particular tube ID dimension. EPRI guidelines require that the drop in the magnitude of the signal from largest to the smallest fill factor should not exceed ~40% of the peak value. Same effect on rotating probe inspections. Detection capability with surface-riding probes is less affected by small variations of the tube diameter.</td>
<td>Critical to use qualified probes for a given SG location particularly when tube geometry variations are present (e.g., TTS, dented locations, and U-Bends). Use of smaller diameter probes may be needed when probe movement is hindered by tube deformation.</td>
<td>When probe wobble associated with tube diameter changes and geometry deformations result in unusually high level of noise (i.e., above qualification values provided in the ETSS).</td>
</tr>
<tr>
<td>Fill Factor and lift-off (Pg. 6, 11-12)</td>
<td>H</td>
<td>BC and RPC</td>
<td>A reduction in fill factor for BC or an increase in lift-off for RPC can affect the probe sensitivity for detecting flaws. Important in regions where larger tube geometry variations are present (e.g., expanded and U-bend regions). Specialized rotating probes are used for inspection of small radius U-bends. Affects the sensitivity for detecting all flaws types.</td>
<td>See comments regarding tube diameter variations. Routine monitoring of probe wear, a major contributor to this type of noise, is important.</td>
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<td>Sampling Rate (Pg. 1, 6, 12-14)</td>
<td>H</td>
<td>BC and RPC</td>
<td>A failure to meet the minimum requirements could lead to decreased spatial resolution and reduced ability to detect and characterize indications. Increasing the sample rate above the minimum value specified by ETSS could improve data quality. If the sampling rate is below that specified in the ETSS, it would be appropriate to judge whether the inspection results are invalid.</td>
<td>Applies to all locations in the SG. A failure to meet the minimum requirements will lead to decreased spatial resolution and reduced ability to detect and characterize flaws, particularly crack-like indications.</td>
<td>When sampling rate is below the minimum value specified by ETSS.</td>
</tr>
<tr>
<td>RPM (Pg. 12-14)</td>
<td>M</td>
<td>RPC</td>
<td>Failure to operate below maximum RPM for a given sampling rate requirement will lead to decreased spatial resolution and reduced ability to detect and characterize indications. Reduction of probe RPM typically improves data quality. Demonstration of equivalency is performed when an RPM value higher than that specified in the ETSS is to be implemented.</td>
<td>Lower RPM could improve data quality, particularly when tube geometry changes and abrupt deformations are encountered.</td>
<td>When RPM exceeds the maximum value allowed, in view of the requirements on axial speed and sampling rate.</td>
</tr>
<tr>
<td>Axial Speed (Pg. 2, 12-14)</td>
<td>M</td>
<td>BC and RPC</td>
<td>Failure to meet the maximum allowable speed for a given sampling rate will lead to decreased spatial resolution and reduced ability to detect characterize indications. Reduction of probe speed typically improves data quality. Axial speed above the maximum value specified in the ETSS may be implemented when equivalency can be demonstrated.</td>
<td>Lower probe speeds typically improves data quality particularly when tube geometry changes and abrupt deformations are encountered.</td>
<td>When axial speed exceeds maximum allowed or the average speed is &gt;25% over the extent of tube examined.</td>
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<tr>
<td>ETSS parameter (Text reference)</td>
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<td>Probe type</td>
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<tr>
<td>Span Setting (Pg. 15)</td>
<td>M</td>
<td>BC and RPC</td>
<td>Significant deviation from the prescribed span settings provided in the data analysis guidelines can lead to missing or misinterpretation of indications during visual screening of the EC inspection data. Variation &lt;25% is acceptable.</td>
<td>Span setting should be set so that minimum detectable OD/ID flaw would be visible on the screen.</td>
<td>When smallest flaws on calibration standard are not visually discernible on the analysis screen.</td>
</tr>
<tr>
<td>Phase Alignment (Pg. 4-6, 10, 15)</td>
<td>H</td>
<td>BC and RPC</td>
<td>Different phase settings are defined for the calibration of data collected with bobbin and rotating probes. It is critical to have consistent phase settings for both detection and sizing. Variation &lt;3 degrees of that specified in the site-qualified procedure is acceptable for phase angle calibrations.</td>
<td>Deviation from the specified values could result in missing of shallow indications or misinterpretation of consequential signals. Complex forms of degradation can produce inconsistent phase angle response, which can lead to incorrect characterization of EC indications. Interpretation of probe response based on phase angle alone may not be reliable in such cases.</td>
<td>When phase settings are not consistent with the site-qualified analysis procedure.</td>
</tr>
<tr>
<td>Gain Setting (Pg. 1, 6, 14)</td>
<td>M</td>
<td>BC and RPC</td>
<td>Improper gain setting can lead to saturation of signals and general loss of data quality. Calibration of instrumentation within the past year helps to verify the consistency of gain setting.</td>
<td></td>
<td>When instrumentation has not been calibrated within the past year. When the gain setting causes saturation of large signals or reduced sensitivity to smallest detectable flaw in the calibration standard tube.</td>
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<td>ETSS parameter (Text reference)</td>
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<tr>
<td>Noise (Pg. 1, 9-10, 13, 16-17)</td>
<td>H</td>
<td>BC and RPC</td>
<td>Variation of EC noise level during ISI of SG tubing will have a profound effect on detection and sizing as a direct result of its influence on S/N. The noise level for data quality assessment can be established by using sampled data from unflawed sections of SG tubing. Acceptability of noise level associated with the test conditions (e.g., electronic instrumentation, tube denting, deposits, tube geometry variations, etc.) can be demonstrated by comparison of measurements from a particular region with those available from ETSS. A S/N &gt; 2 generally ensures detection of critical flaws with an acceptable level of confidence during field inspection.</td>
<td>Sources of noise can be of both ID and OD origin. Noise can affect detection and characterization of all forms of degradation.</td>
<td>When the measured noise level in a particular region of SG is greater than the documented ETSS values for the site-qualified technique.</td>
</tr>
<tr>
<td>Manufacturer/ Equipment model and Version of Software (Pg. 2, 6, 8, 17)</td>
<td>H</td>
<td>BC and RPC</td>
<td>Equivalency&lt;sup&gt;(a)&lt;/sup&gt; is demonstrated for any change of equipment or software from those specified by ETSS. Upgrades for qualified software do not generally require site-specific qualification.</td>
<td></td>
<td>When special equipment and software is being used for the first time. Availability of proper documentation on qualification and calibration of instrumentation for review prior to ISI.</td>
</tr>
<tr>
<td>Probe Type (Pg. 1-3, 6, 8, 10-14, 16-17)</td>
<td>H</td>
<td>BC and RPC</td>
<td>Significant effect on detection and sizing. Equivalency&lt;sup&gt;(a)&lt;/sup&gt; is demonstrated for any change from that defined in the site-qualified technique.</td>
<td>Complementary inspections with specialized probes/ techniques could be performed to improve POD for particular forms of degradation. Critical to use qualified probes that provide optimum S/N for a particular form of degradation.</td>
<td>When probes other than those specified in the site-qualified technique are used.</td>
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<tr>
<td>ETSS parameter (Text reference)</td>
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<td>Probe type</td>
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<tr>
<td>Cable Length (Pg. 1, 6, 17)</td>
<td>H</td>
<td>BC and RPC</td>
<td>The resistance and capacitance of the cable changes with length and could affect the operating characteristics of the probe and in turn the system response. Proper length cables are used in accordance with manufacturer’s specifications. Performance demonstration can be based either on a) variation of &lt;10% in center frequency using swept/stepped-frequency measurement of the probe response, or b) variation of &lt;10% in amplitude response from machined flaws in a calibration standard tube, between the modified and the qualified procedure.</td>
<td></td>
<td>When extension cables are used.</td>
</tr>
<tr>
<td>Analysis Channels/Variables</td>
<td>M</td>
<td>BC and RPC</td>
<td>Analysis channels are specified by the site-qualified procedure. Channels different from those specified in the ETSS may be used for reporting of indications when equivalency&lt;sup&gt;a&lt;/sup&gt; can be demonstrated.</td>
<td></td>
<td>When channels not specified in the site-qualified ETSS are used for analysis.</td>
</tr>
<tr>
<td>Filters (Pg. 17)</td>
<td>M</td>
<td>BC and RPC</td>
<td>Filters are generally not used during field analysis because of the potential inconsistency among analysts and to prevent potential suppression of flaw signals. For engineering assessment filters can be helpful in detecting difficult flaws.</td>
<td></td>
<td>When the use of filters on channels that are used for reporting are not specified by the site-qualified technique.</td>
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<td>ETSS parameter (Text reference)</td>
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<td>Calibration Standard (Pg. 1, 3, 10, 14-16)</td>
<td>H</td>
<td>BC and RPC</td>
<td>Types and sizes of artificial flaws in calibration standard tubes are specified by ASME codes(^{(b)}). Artificial flaw depths are generally known to within 0.003 in. (0.08 mm) and all other dimensions are accurate to within 0.010 in. (0.25 mm). Better consistency could be achieved by comparing the calibration standards with a reference standard. In accordance with the ASME codes(^{(b)}), if the calibration standard material is heat treated differently from the tubing to be examined, it can be used if signal responses from discontinuities in the standard are demonstrated to be equivalent.</td>
<td>Calibration standards commonly have OD/ID machined flaws as small as 20%TW. Shallower flaws may be used for characterization of large volumetric degradations. The standard contains the type of flaws and geometrical discontinuities (e.g., expansions, dents, support structures) that are representative of those present in the field. To simulate potential forms of degradation in a particular SG, machined flaws could be present in combination with geometrical discontinuities.</td>
<td>When calibration standard tube does not contain the entire range of artificial discontinuities specified by the site-qualified technique.</td>
</tr>
</tbody>
</table>

| Procedure Qualification\(^{(c)}\) (Pg. 1-2, 5-13, 15-17) | H | BC and RPC | When a procedure qualification is specified, a change of requirement for an essential variable from the specified value, or range of values, may be made through re-qualification of the written procedure. Where a range is specified for an essential variable, the bounding values of the range are qualified by demonstration. | | When the technique to be used has not been qualified for that particular site. |

H: highly important  
M: moderately important  
L: relatively low importance  
BC: bobbin coil  
RPC: rotating probe coil

\(^{(a)}\) Equivalency between two techniques implies that the same essential variables are used for both techniques. To demonstrate equivalency between two techniques, it is sufficient to demonstrate the equivalency of the bounding values of the varying essential parameter alone while keeping all other variables unchanged (i.e., remaining within their qualified range).

\(^{(b)}\) 2004 ASME Boiler and Pressure Vessel Code Section V, Article 8, II-860.2 Calibration Standards: Calibration standards shall be manufactured from a tubing of the same material specification, same heat treatment, and same nominal size as that to be examined in the vessel. This section also states that if the calibration standard material is heat treated differently from the tubing to be examined, it can be used if signal responses from discontinuities in the standard are demonstrated to be equivalent in both the calibration standard and tubing of the same heat treatment as the tubing to be examined.

\(^{(c)}\) 2004 ASME Boiler and Pressure Vessel Code Section V, Article 8, T-823.2: When procedure qualification is specified, a change of a requirement in Table T-823 identified as an essential variable from the specified value, or range of values, shall require requalification of the written procedure. Where a range is specified for an essential variable, the bounding values of the range shall be qualified by demonstration.