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RECOGNIZING LIMITATIONS IN EDDY CURRENT TESTING

Connaissance des limitations
dans les essais par courant de Foucault

G. VAN DRUNEN and V.S. CECCO

Paper presented at "Quality Manufacturing Conference", Toronto, September 29 - October 1, 1981.

Chalk River Nuclear Laboratories

Laboratoires nucléaires de Chalk River

Chalk River, Ontario

November 1981 novembre

ATOMIC ENERGY OF CANADA LIMITED

RECOGNIZING LIMITATIONS IN
EDDY CURRENT TESTING

by

G. Van Drunen V.S. Cecco

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L'ENERGIE ATOMIQUE DU CANADA, LIMITEE

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G. Van Drunen V.S. Cecco

Résumé

Ce rapport concerne les limitations connues et les contraintes des essais non destructeurs par courant de Foucault. On estime qu'une évaluation incomplète des limitations des courants de Foucault a contribué à la faible utilisation et à la mauvaise application de cette technique. Le fait de bien connaître les limitations devrait mettre fin à ces deux situations. Certaines limitations, comme l'effet de peau, se rencontrent dans les méthodes d'essai électromagnétiques. Elles définissent le rôle de l'inspection par courant de Foucault dans le domaine des essais non destructeurs. D'autres limitations peuvent être surmontées grâce aux technologies disponibles, comme les sondes de surface pour détecter les fissures circonférentielles dans les tubes ou comme la saturation magnétique des alliages ferromagnétiques pour éliminer les effets de perméabilité.

Les variables responsables des limitations dans les essais par courant de Foucault sont passées en revue et lorsque des solutions de rechange existent elles sont indiquées. Les domaines où d'autres recherches et développements pourraient être effectués sont également indiqués.

*Rapport présenté à la Conférence sur les fabrications de qualité tenue à Toronto du 29 septembre au 1^{er} octobre 1981.

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RECOGNIZING LIMITATIONS IN
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ABSTRACT

This paper addresses known limitations and constraints in eddy current nondestructive testing. Incomplete appreciation for eddy current limitations is believed to have contributed to both under-utilization and misapplication of the technique. Neither situation need arise if known limitations are recognized. Some, such as the skin depth effect, are inherent to electromagnetic test methods and define the role of eddy current inspection in the field of nondestructive testing. Others can be overcome with available technology such as surface probes to find circumferential cracks in tubes and magnetic saturation of ferromagnetic alloys to eliminate permeability effects.

The variables responsible for limitations in eddy current testing are discussed and where alternative approaches exist, these are presented. Areas with potential for further research and development are also identified.

*Paper presented at "Quality Manufacturing Conference", Toronto, September 29 - October 1, 1981.

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1. INTRODUCTION

Numerous authors have emphasized the advantages of eddy current testing (ET) for solving nondestructive testing (NDT) problems; however, recurring comments and requests for information have demonstrated ET has been both under-utilized and misapplied. Under-utilization has come about through a lack of understanding of its capabilities or because past experience with the technique proved unsatisfactory. In some cases, unreliable test results from inspections attempted 10 or 15 years ago are used to justify no further application of the technology. Advances in understanding of basic eddy current principles, instrumentation and probe design over the past decade warrant expanding the use of ET into new areas as well as using it again in some situations where it proved inadequate previously. Misapplication of ET has occurred for a number of reasons including incomplete understanding of basic principles, absence of alternative NDT methods, and lack of emphasis on ET limitations by its proponents. This paper addresses the limitations of ET and qualitatively tries to explain the reasons for them. Methods available to overcome some limitations are also discussed.

That ET has limitations should come as no surprise; all NDT methods have them. Radiography (RT) will only detect cracks parallel to the radiation beam. The effectiveness of ultrasonic testing (UT) can be limited by rough or uneven surfaces, microstructural details and flaw orientation. In UT and RT one learns to minimize or circumvent these problems (e.g., multiple exposures in RT, different transducers in UT) or use a complementary NDT technique not subject to the same limitations. Similar solutions are often available to overcome limitations in ET.

It is believed an understanding of ET limitations can both expand its utilization and avoid misapplication. The main purpose of this paper is to provide those indirectly involved in ET with sufficient background to avoid obvious errors.

This paper includes a brief review of ET fundamentals; for more detail the reader is referred to available literature(1,2). Emphasis is placed on in-service inspection for defects since this is the most complex area of ET. An appreciation for in-service inspection problems should also permit one to apply similar principles to manufacturing inspection. To the greatest extent possible, a non-rigorous

qualitative approach has been taken in order to minimize chances of the reader becoming lost in technical detail.

2. BASIC EDDY CURRENT BEHAVIOUR

2.1 Eddy Current Generation and Flow

Alternating current in a coil produces an alternating magnetic field oriented perpendicular to the current or parallel to the coil's axis. When this field intersects an electrical conductor, eddy currents are induced in it according to Faraday's and Ohm's Laws. The eddy currents flow normal to the magnetic field. The eddy currents, in turn, set up a magnetic field in opposition to the primary field causing partial cancellation. This decrease in magnetic flux through a coil causes a change in coil impedance. Eddy current testing consists of monitoring coil impedance changes. As an eddy current probe is brought close to a conductor both the resistive and inductive components of probe coil impedance are altered. When a probe passes over a defect the eddy current flow distorts resulting in a change in probe coil impedance.

2.2 Defect Detection

It is fundamental to ET that only those defects which in some way disturb or alter normal eddy current flow patterns are detectable. Since eddy currents flow parallel to coil windings, some types of defects can't be detected with all probe designs. Figures 1 and 2 schematically show eddy current flow with surface (pancake type) coils and circumferential (tube or bar) coils. Tube inspection with an internal circumferential coil results in a flow pattern similar to an external circumferential coil. Figures 1 and 2 also illustrate types of defects which can't be detected with the coil configurations shown because they don't impede eddy current flow. These are

- a) laminar defects in plates or tubes,
- b) circumferential cracks in tubes or bars,
- c) defects at the centre of solid bars or wire.

Theoretically, type (a) defects can be made detectable with a horseshoe probe design; however, the authors are unaware of any commercial probes made specifically for laminar defects. Similarly, one might induce eddy currents in the centre of a bar or wire with a surface probe. Such a test would have low defect sensitivity due to poor coupling and limited eddy

current penetration (Section 5.1). Type (b) defects can be made clearly detectable with surface probe designs, as discussed in Section 4.1.

Modern general purpose eddy current instruments combine a variable frequency excitation current source with an AC bridge to measure the small impedance changes due to defects. Probe coil(s) are located on adjacent arms of the bridge as shown in Figure 3(a). Bridge instruments normally use probes with two coils. If the probe has one test coil and one reference coil, it is an absolute probe, Figure 3(b). If both coils sense the material under test it is a differential probe, Figure 3(c).

Absolute probes respond to all variables which affect eddy current flow, such as resistivity, magnetic permeability, geometry of test material and defects. By contrast, differential probes compare adjacent material sections. A differential probe will only yield an out-of-balance (defect) signal when a difference in eddy current distribution exists under the adjacent coils. Surface probes are nearly always used in the absolute mode. For tube and bar testing both absolute and differential probes are commonly used.

Advantages and disadvantages of absolute and differential probes are summarized in Table I. The generally simpler signal interpretation with absolute probes and the possibility of missing long, gradual defects with differential probes prompts us to recommend absolute probes for general inspection use. Differential probes are recommended for those situations where their properties offer a decided advantage such as manufacturing inspection for localized defects. Until recently, eddy current testing in the U.S.A. was largely done with differential probes; however, recent publications(3,4) indicate American NDT personnel are increasingly recognizing the advantages of absolute probes.

2.3 Skin Depth and Phase Lag

Eddy currents induced by a changing magnetic field concentrate near the surface adjacent to the excitation coil. They decrease with increasing depth and the variation with depth depends on test frequency, electrical resistivity and magnetic permeability of the sample. Skin effect arises as follows: eddy currents flowing in the sample at any depth produce magnetic fields which oppose the primary field, thus

reducing magnetic flux and causing a decrease in current flow at greater depth. The result is an exponential decrease in eddy current density (J) with increasing depth as illustrated in Figure 4(a). For infinitely thick material, a standard depth of penetration (δ) is defined as the depth at which eddy current density (J_x) has dropped to $1/e$ or 36.8% of the surface density (J_0). It is given by the skin depth equation

$$\delta = 50 (\rho/\mu_r f)^{1/2} \text{ mm}$$

where ρ is resistivity in microhm-centimetres, f is test frequency in hertz and μ_r is the relative incremental magnetic permeability (dimensionless). Sensitivity to subsurface defects depends on eddy current density at that depth. Current density at 3δ below the surface is only 5% of the surface density; 3δ therefore represents the practical limit of defect detection.

The skin depth equation is only strictly true for infinitely thick material and planar magnetic fields. For most materials and practical probe sizes, eddy currents are attenuated more than predicted by the skin depth equation (see Section 5.1). Using δ calculated from the above equation makes it a material/test parameter rather than a true measure of penetration.

The attenuation in eddy current density with depth due to skin depth effect means defects located at different depths below the surface will change probe impedance by different amounts. Large subsurface defects will yield similar signal amplitude to small surface defects. One can't therefore rely on signal amplitude to judge severity of defects. Older instruments with single channel output (meter or chart) only presented signal amplitude and were not reliable for determination of defect type and depth. This problem was overcome with the development of impedance plane instruments which portray both signal amplitude and phase.

Phase lag (β) in ET refers to the fact that subsurface eddy currents are not in phase but lag those at the surface. Phase lag increases linearly with depth as shown in Figure 4(b) for infinitely thick material. It is given by

$$\beta = x/\delta \text{ radians}$$

where x is depth below the surface and δ is skin depth. At one standard depth of penetration eddy currents lag surface currents by one radian (57°). Since phase lag is a function of skin depth it also varies with test frequency, resistivity and magnetic permeability.

2.4 Signal Analysis

Phase lag is of prime importance in ET since it permits estimation of defect type and depth. During ET many signal sources are possible since anything which affects sample resistivity or permeability will be detected as a change in probe coil impedance. Only some of these may be defects. Phase analysis allows one to decide which signals represent defects and which are irrelevant indications. Figure 5 shows common impedance plane eddy current signals encountered during in-service tube testing with internal probes. In this example, defect signals have phase angles, θ , between 0° and 90° . One can also determine defect type: 1) internal (ID) tube defects have small θ values; 2) external (OD) defects have θ near 90° ; and 3) through-wall defect signals fall between the two extremes. The phase angle of a particular defect is not a fixed quantity; it can be made to increase or decrease by increasing or decreasing test frequency (within limits).

Phase lag enables defect depth determination in spite of the uncertainties associated with signal amplitude discussed previously. Figure 6 shows impedance plane calibration defect signals from a Monel tube with OD defects; the tube was tested with an internal probe. As defect depth increases, signal amplitude increases but phase angle, θ , decreases. The deeper defects extend closer to the coil and therefore show less phase lag. Comparison of real OD defect signals with those in Figure 5 permits external defect depth in thin wall tubes to be estimated with an accuracy of $\pm 10\%$ of tube wall thickness. Depth of internal defects can be estimated to only $\pm 20\%$ because the phase (θ) rotation between shallow defects and through-wall defects is only about 30° , compared to 60° for external defects. Careful measurement of the angle θ (possible with differential probe signals) and a plot of θ against calibration defect depth might lead one to attempt depth estimation of greater accuracy. Uncertainties from one probe to the next as well as differences in geometry between real defects and calibration defects make such procedures questionable. Classification of defects into the following categories meets most in-service tube inspection requirements: less than 25%, 25 to 50%, 50 to 75% and greater than 75%.

A similar phase angle dependence on defect depth is shown for surface probes on flat plate in Figure 7. The deep crack signal phase angle is less than that of the subsurface void even though the crack extends deeper. This arises because both signal amplitude and phase angle represent an integrated response. The exponential decrease in eddy current density below the surface causes the top half of a crack to

contribute much more to the integrated signal than the bottom half. One requires calibration standards for each defect type.

Accurate estimation of surface defect depth in thick materials with surface probes is more difficult than in the case of thin wall tubes. It is doubtful that one could estimate such depths to better than $\pm 50\%$.

Very shallow defects in surfaces adjacent to test coils cause problems with both surface and tube probes. This arises because such defects have a phase angle of nearly 0° . Unfortunately, probe wobble (coupling variations) gives identical signals and though signal amplitude may be large, it's often difficult to discriminate between very shallow defects and probe wobble.

3. PRACTICAL CONSIDERATIONS

3.1 Calibration Standards

Eddy current testing is not an absolute science; one can't specify a probe, test frequency and instrument settings and proceed with a test. Variations between "identical" probes and instruments as well as the numerous test material variables which affect probe impedance make such an approach impractical. To overcome this problem calibration standards are required. Standards should duplicate test material in geometry as well as electrical and magnetic properties. Calibration defects can generally be simple. EDM notches or machined slits are used to simulate cracks; internal and external machined grooves and drilled holes are adequate to simulate most types of manufacturing and service related tube defects.

3.2 Testing Speed

General purpose eddy current instruments have no lower limit on probe speed; they can indicate probe impedance with the probe at rest. Maximum probe speed is limited by probe coil size as well as the frequency response of the eddy current instrument and recording equipment. In general, signal distortion becomes severe above 0.5 m/s. For reliable signal analysis a speed of 0.25 m/s should not be exceeded. Some manufacturing inspection systems operate much faster than 0.25 m/s. This only becomes feasible if any abnormality is grounds for rejection.

3.3 Codes and Standards

A number of North American specifications on eddy current testing exist. ASTM standards include:

- ASTM E-215, aluminum alloy tubing;
- ASTM E-243, copper and copper alloy tubing;
- ASTM E-426, stainless steel tubing;
- ASTM E-571, nickel alloy tubing;
- ASTM E-309, ferromagnetic rods, wires and tubes;
- ASTM E-376, coating thickness measurement;
- ASTM E-566, sorting magnetic alloys;
- ASTM E-690, in-service inspection of heat exchanger tubes.

These are of limited use in specifying in-service inspection procedures. They emphasize equipment set-up procedures rather than defect detectability limits or defect characterization. Most are oriented toward manufacturing inspection and many test requirements are left to be agreed upon between the supplier and the customer.

In-service inspection of nonmagnetic steam generator tubing is covered in more detail by the ASME Boiler and Pressure Vessel Code(5). However, the test frequency specified may lead to confusing results in some test situations(4,6).

In summary, existing specifications and standards only supply broad guidelines in choosing test parameters. Establishing reliable ET procedures requires knowledge of the technique.

3.4 Choice of Test Frequency

Frequency is often the only test variable over which an inspector exercises any control. It should be apparent from Section 2.3 that frequency should be low enough when inspecting for defects to ensure eddy current flow in the complete volume to be inspected. As a general rule one should use a test frequency which makes the maximum thickness of material to be inspected about one standard depth of penetration. Lower frequencies might give deeper penetration but would yield reduced sensitivity and poor discrimination between surface and subsurface defects. Higher frequencies would make subsurface defects undetectable.

Two empirically derived relations have been found useful for defect inspection. Tube testing at the frequency

$$f_{90} = 3 \rho/t^2 \text{ kHz}$$

provides 90° phase separation between ID and OD defects as in Figure 5; ρ is tube material resistivity in microhm-centimetres and t is tube wall thickness in millimetres.

This frequency also allows clear discrimination between defects and other signal sources such as probe wobble, support plates, etc. A similar relation for surface probes on thin sheet material is

$$f = 1.6 \rho / t^2 \text{ kHz}$$

which provides 90° phase separation between lift-off (probe/material spacing) and thickness variations.

Eddy current tests for features other than defects normally require test frequencies tailored to the particular inspection. Measurement of tube dimensions (ID or OD) or coating thickness on flat surfaces require high frequencies. Measurement of support plate position or external tube deposits in heat exchangers require a low test frequency to minimize signal contribution from the intervening tube wall.

3.5 Material Condition

Material factors such as surface roughness and alloy uniformity can affect eddy current test sensitivity.

Surface condition is of concern because it limits surface defect detectability. As shown in Section 2.4, signals from shallow flaws in the surface adjacent to the test coil consist primarily of a lift-off or fill-factor indication. Rough surfaces yield very similar signals resulting in poor sensitivity to shallow surface defects. Die chatter and pilger noise on internal tubing surfaces lead to comparable problems; shallow internal defects can be obscured by such periodic tube "noise".

Alloy uniformity is normally not of concern in new wrought materials. However, wrought alloys can change during service, either in composition (e.g., oxygen contamination of reactive metals such as titanium and zirconium) or by changes in heat treat condition (e.g., overaging of aluminum alloys). Such mechanisms can cause resistivity variations which will affect eddy current response. Castings and welds often have alloy segregation which can lead to both resistivity and magnetic permeability variations. Any changes in magnetic or electrical properties influence eddy current response. At best, such variations cause reduced signal to noise leading to lower defect sensitivity. In the extreme, they could be mistaken for serious defects. Reference (2) discusses test procedures required to discriminate between real defect signals and anomalous indications.

4. LIMITATIONS IN TUBE TESTING

4.1 Circumferential Cracks

Tubes and bars under 50 mm diameter are normally tested with circumferential coil probes which induce eddy current flow around the tube circumference. A major limitation of such probes is their inability to detect circumferential cracks as explained in Section 2.2. Special probe designs are used to detect circumferential cracks. Three such probe designs are shown in Figure 8. Of these, the spring loaded, single coil design (Figure 8(a)) has proven suitable for in-service heat exchanger inspections(6,7). Its advantages include good sensitivity to small defects and simple signal interpretation. Its main disadvantage lies in the need for helical or multiple pass scanning to achieve complete circumferential coverage. This problem can be overcome to a large extent by limiting inspection to defect-prone areas such as near tubesheets and under support plates in heat exchangers. Development of automated mechanical scanning systems hold promise for increased use of this type of probe.

4.2

Magnetic Materials

Magnetic materials present special problems in eddy current testing. Real defect signals are normally indistinguishable from those due to normal permeability variations. Factors which may influence permeability include

- minor alloy composition differences,
- variations in heat treatment,
- degree of cold work,
- presence of residual stresses,
- temperature variations.

The skin depth equation of Section 2.2 shows a change in permeability will vary δ . Defect signal interpretation was also shown to rely on eddy current phase lag. If δ varies, so will phase lag, and defect characterization on the basis of phase angle is not feasible even if one can separate defect and permeability signals. This is a second major reason why magnetic materials are generally considered uninspectable by ET. Permeability values can range from 50 to several hundred in engineering materials. This reduces penetration drastically compared to nonmagnetic materials. One can offset the effects of permeability by reducing test frequency but the inability to discriminate between defects and random permeability variations remains.

The best remedy for ET of magnetic materials is by magnetic saturation in the vicinity of the probe. Incremental relative permeability becomes 1.0 in saturated material, then magnetic alloys behave like nonmagnetic ones for ET purposes. Saturation is easily achieved during manufacturing inspections either with external (air or water cooled) electromagnets or with large permanent magnets. In-service inspection is considerably more difficult because saturating fields have to be introduced from the inside of tubes. This limits the range of materials that can be inspected and is an area where further research seems warranted.

To date, permanent magnet probes have been developed(8) which can saturate Monel 400 tubing. Monel saturates at a flux density of less than 0.3 T (3000 gauss). Applied research work in progress indicates permanent magnet probes can be designed for materials requiring flux densities up to perhaps 1.0 T. Saturation of strongly magnetic alloys such as ferritic stainless steels (1.5 to 1.8 T) and carbon steel (2.1 to 2.2 T) with permanent magnets remains an unsolved problem at present. Pulsed DC saturation instruments also hold promise for stronger magnetic alloys, though disadvantages exist in terms of probe coil design complexity and reduced scanning speed.

4.3 Supporting Structures in Heat Exchangers

Tubesheets and tube supports in heat exchangers can present problems during in-service testing. Both tend to be defect prone areas and one is often faced with extracting defect signal components from complex combined signals. In nonmagnetic tubes with ferromagnetic supports this problem is minimal. Defect and support signals are vectorially additive and since magnetic support signals are usually small, serious defects can easily be detected with absolute probes, see Figure 9(d). Nonmagnetic tubes with nonmagnetic supports are a more serious complication; the signals are large and no longer vectorially additive as illustrated in Figure 9(c). In this case a 50% deep fretting wear groove could be difficult to detect under the brass support plate. A surface probe design such as in Figure 8(a) provides improved test sensitivity as shown for the same defect in Figure 10. (The same probe has proven useful for defects near tubesheets where there is an additional complication due to the tube expansion signal). The procedure used is to inspect each tube with a conventional probe for general defects, then re-inspect for fretting wear at support plates with a surface probe. Where in-service ET of heat exchanger tubes is contemplated at the design stage, use of ferromagnetic support plates is recommended. If corrosion considerations preclude carbon steel, a ferritic stainless steel should be considered.

Ferromagnetic tube materials represent a different set of circumstances. In this case magnetic supports can "steal" magnetic flux intended for tube saturation. The result is a tube not completely saturated under supports which yields large permeability signals and makes the tube uninspectable in this defect-prone area. For weakly magnetic alloys such as Monel 400 this is not usually a serious problem. Present saturation probes provide sufficient magnetic flux to keep such tubes saturated under carbon steel. For more strongly magnetic alloys such as 3Re60, E-Brite 26-1 and carbon steel it may never be possible to achieve complete saturation under magnetic supports. In this case, nonmagnetic support materials are a better choice in spite of the problems outlined above.

5. LIMITATIONS IN SURFACE PROBE TESTING

5.1 Penetration

Eddy current testing with surface probes is a very effective technique for surface defects but often exhibits limited sensitivity to even quite shallow subsurface defects. This situation arises because eddy current penetration under surface probes is influenced strongly by factors related to probe coil diameter in addition to penetration limitations due to skin depth. The probe diameter effect is usually more important than skin depth. A similar problem does not arise with tube probes because of inherent differences in probe/material coupling geometry. Figure 11 schematically shows the reason for the difference. In tube testing (Figure 11(b)) cross section comparable to tube wall thickness results in magnetic field penetration (and hence eddy current flow) through the entire tube wall; this geometry provides adequate sensitivity for most defects which occur in tubes.

In the case of surface probes (Figure 11(a)), it is not coil cross section but coil diameter (D_o) which largely controls penetration. The magnetic field in a thick material under a surface probe penetrates to a depth of about one quarter the coil diameter ($D_o/4$). One can decrease penetration to less than $D_o/4$ by raising test frequency but lowering frequency will not increase penetration appreciably. The only solution is to increase probe diameter; however, as diameter is increased sensitivity to short defects decreases because the ratio, defect volume/inspected volume, becomes smaller. One reaches a point where a further increase in coil diameter would result in significant surface and subsurface defects going undetected.

The above explains why complete volumetric inspection of material thicker than about 4 mm is not considered practical with present ET technology. Complete volumetric inspection of thicker materials may become possible with special probes; this area deserves research and development effort. Despite these limitations there is a place for ET in inspecting thick sections for surface defects. It can provide complementary depth information when uncertainties arise with other NDT methods such as UT and RT.

5.2 Magnetic Materials With Surface Probes

Surface probe testing also requires magnetic saturation to eliminate "permeability noise" and to permit predictable defect depth estimation. Saturation for surface probes is generally more difficult than for conventional tube testing. Axial magnetization is required for tubes, the tube wall provides an ideal low reluctance (preferred) return path for magnetic flux. In the case of surface probes one desires magnetization parallel to the coil axis, perpendicular to the test material surface. Most arrangements to achieve this involve passing flux through long (high reluctance) air paths. It may well happen that some materials which can be saturated completely with tube probes can't be magnetized sufficiently for surface probe testing.

6. SUMMARY

1. Only defects which disrupt eddy current flow will indicate their presence by a test coil impedance change (laminar defects and defects at centre of cylinders are not detectable).
2. In general, absolute eddy current probes offer advantages over differential probes.
3. Reliable defect characterization requires impedance plane phase analysis, this normally permits defect depth estimation to an accuracy of $\pm 10\%$ for OD defects in tubes, $\pm 20\%$ for ID tube defects and $\pm 50\%$ for surface defects in thick materials tested with surface probes.
4. Shallow surface defects present problems in detectability because their signals will be similar to probe wobble.
5. Calibration standards which duplicate test material in geometry as well as electrical and magnetic properties are required for initial instrument adjustment and subsequent defect signal analysis.

6. With presently available eddy current and recording instrumentation, probe speeds faster than about 0.25 m/s may lead to excessive signal distortion.
7. Existing industrial codes and standards do not provide the information required to specify detailed in-service inspection procedures.
8. Each particular eddy current test has an optimum test frequency. A frequency chosen to accomplish everything in a single pass will generally be a compromise.
9. Rough or irregular surfaces make it difficult to detect shallow surface defects.
10. Variations in material composition can lead to reduced defect detectability or anomalous eddy current indications.
11. Special probe designs are required to detect circumferential cracks in tubes and bars.
12. Ferromagnetic materials need to be magnetically saturated for reliable eddy current testing.
13. Nonmagnetic heat exchanger tubes with magnetic tube support plates provide the simplest eddy current test situation for detecting defects under supports. Nonmagnetic tube support plates may require special probes for reliable defect detection.
14. Magnetic tube materials may be difficult or impossible to saturate especially under ferromagnetic support plates. In this case nonmagnetic supports would improve inspectability.
15. Saturation of magnetic materials for surface probe testing is generally more difficult than for circumferential tube probes.
16. For complete volumetric eddy current inspection one is limited to material thicknesses of about 4 mm.
17. Eddy current penetration under surface probes is limited by probe coil diameter in addition to the skin depth effect.

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TABLE I
COMPARISON OF ABSOLUTE AND DIFFERENTIAL PROBES

A B S O L U T E P R O B E S

ADVANTAGES

- respond to both sudden and gradual changes in properties and dimensions
- combined signals are usually easy to separate (simple interpretation)
- show total length of defects

DISADVANTAGES

- prone to drift from temperature instability
- more sensitive to probe wobble than a differential probe

D I F F E R E N T I A L P R O B E S

ADVANTAGES

- not sensitive to gradual changes in properties or dimensions
- immune to drift from temperature changes
- less sensitive to probe wobble than an absolute probe

DISADVANTAGES

- not sensitive to gradual changes (may miss long gradual defects entirely)
- will only detect ends of long defects
- may yield signals difficult to interpret

EDDY CURRENTS FLOW PARALLEL TO COIL WINDINGS
- POOR SENSITIVITY TO LAMINATIONS

ZERO SENSITIVITY
AT CENTRE OF COIL

LOW SENSITIVITY
PARALLEL TO WINDINGS

MAXIMUM SENSITIVITY
ACROSS WINDINGS

FIGURE 1: Eddy Current Flow Under Surface Probe Coils

FIGURE 2: Eddy Current Flow Under Encircling Coils

FIGURE 3: (a) Location of Probe Coils in an AC Bridge Circuit.
 (b) Absolute and (c) Differential Probes for Internal Tube Testing.

FIGURE 4: Skin Depth and Phase Lag in Thick Materials. (J_x is Eddy Current Density at Depth x Below the Surface, J_0 is Density at Surface.)

FIGURE 5: Eddy Current Impedance Plane Signals from a Typical Calibration Tube for In-service Inspection. Tube Material is Inconel 600, 12.7 mm OD x 1.1 mm Wall; 250 kHz Test Frequency

FIGURE 6: Impedance Plane Eddy Current Signals from a Tube with External Calibration Defects Ranging in Depth from 35% to 90% of Tube Wall Thickness. Tube Material is Monel 400, 12.7 mm OD x 1.2 mm Wall; 100 kHz Test Frequency

FIGURE 7: Impedance Plane Eddy Current Signals from a Thick Aluminum Plate Tested with Surface Probes at 50 kHz

FIGURE 8: Probes for Detecting Circumferential Cracks in Heat Exchanger Tubes. (a) Spring Loaded Surface Probe (b) Zig-zag Probe (c) Multiple Surface Coil Probe

FIGURE 9: Comparison of Defect Signals at Magnetic and Nonmagnetic Tube Supports. (Tube Material is Nonmagnetic).

FIGURE 10: Testing for Fretting Wear Under a Nonmagnetic Tube Support with an Internal Surface Probe. (Compare with Figure 9 Results.)

FIGURE 11: Schematic Illustration of Magnetic Fields Around
(a) Surface and (b) Tube Eddy Current Probe Coils

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