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EDDY-CURRENT TESTING IN PRACTICE

J. W. Allen

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EDDY-CURRENT TESTING IN PRACTICE

John W. Allen

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EDDY-CURRENT TESTING IN PRACTICE

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EDDY-CURRENT TESTING IN PRACTICE

John W. Allen

ABSTRACT

The use of eddy-current testing methods is described as it applies to three major areas of effectiveness: the identification and sorting of metals according to their electrical conductivities and permeabilities; the measurement of the thickness of thin metal sections, or the thickness of cladding or shrouding of one metal on or around another; and the detection and evaluation of discontinuities and other conditions in metals relating to their quality. The basic principles of nondestructive testing with induced eddy currents are presented and discussed in detail, with particular regard to the effect of the several test parameters on the impedance of testing coils. Examples of effective eddy-current tests in use are presented, including the utilization of encircling coils for parts of cylindrical symmetry and probe coils which are applied to either plane or curved surfaces. The test systems are discussed with regard to the selection of test parameters, the attenuation of the induced eddy currents with depth, and the separation of the many variables which influence the tests.

INTRODUCTION

The uses of eddy-current techniques in the ever-expanding field of nondestructive testing divide into three general categories: (1) the measurement of conductivity or of a combination of conductivity and permeability: including identification of metals, sorting of metals according to their mechanical and thermal history, and the measurement of other metallurgical variables which affect the conductivity and permeability; (2) the measurement of the thickness of thin metal sections, the measurement of the cladding or shrouding thickness of one metal on or around another, and the measurement of the thickness of nonmetallic coatings on metals; and (3) the detection and evaluation of both surface and internal discontinuities and other conditions relating to metal quality.

Within these three general areas of effectiveness lie many nondestructive testing problems which are encountered daily in industry. It is the purpose of this paper to discuss the fundamental concepts which underlie the use of eddy-current methods in each of these three areas, to give a few examples of problems which have been solved by the use of eddy-current techniques, and to offer suggestions as to how some of the troublesome problems being encountered in eddy-current testing might be solved.

Since any intelligent discussion of the uses of eddy-current testing and of the various factors influencing the several types of eddy-current tests requires a fairly detailed understanding of the basic principles involved, a brief review of the fundamentals of electromagnetically induced currents is thought to be of value. Basically all of the testing methods which utilize induced currents consist of observing the change in the field of an exciting coil, or system of coils, produced by the currents induced within a metal part which is brought into the field of the coil. In general, there are two distinctly different effects on the field of the coil produced by the eddy-current flow:

1. The flow of the induced current through the metal part of finite resistivity produces a power loss which must be supplied by the exciting field, which in turn must be supplied by the exciting current. Thus, the impedance of the exciting coil, of necessity, must have a resistive component with a magnitude dependent upon the amount of power loss in the metal.
2. The flow of induced current produces a field in opposition to the exciting field, resulting in a net decrease in the field flux of the exciting coil. Therefore, the inductance of the coil (the ease with which the coil produces magnetic flux) is reduced by an amount dependent upon the quantity of the induced-current flow, and, accordingly, the reactive component of the impedance of the exciting coil is reduced.

Changes are thus produced in both the resistive and reactive components of the impedance of the coil according to the magnitude, phase, and distribution of the induced eddy currents.

If the exciting current is a single-frequency sinusoidal wave, which is usually the case, the impedance of the coil can be represented mathematically by a complex quantity whose real component is equal to the resistive component of the coil's impedance and whose imaginary component is equal to the reactive component of the coil's impedance. The impedance, therefore, may be plotted on the complex plane as a function of the various parameters of the test. Such a graph is usually designated as the impedance plane of the coil. Since the impedance of the coil always contains an inductive component in practical testing situations, the entire impedance contour is contained in the first quadrant of the complex plane.

The impedance plane of Fig. 1 (ORNL-LR-DWG 19109R) is illustrative of the impedance of a coil in proximity with a metal specimen as a function of the electrical conductivity of the specimen and the frequency of the exciting current. The impedance of the coil at any point on the curve is represented by a vector drawn from the origin to the point on the curve. This "impedance vector" is the vector sum of the resistive and reactive components of the coil's impedance at that point on the curve. The angle associated with the impedance vector is called the phase angle of the impedance, and is usually measured from the resistive axis.

Two fundamental facts concerning the impedance plane of Fig. 1 are noteworthy. First, the general shape and orientation of the curve are descriptive of the impedance of any coil in proximity with any metal specimen, regardless of the geometry of the coil and specimen or the properties of the specimen. The size and the exact shape of the curve are dependent upon the particular properties of any given system of coil and specimen. Also of importance concerning the impedance plane of Fig. 1 is that the conductivity of the metal and the frequency of the exciting current may be treated as a product in their effect on the impedance of the coil. As the conductivity-frequency product is increased from zero and becomes very large, the locus of the impedance vectors is the curve of Fig. 1. Although there are some minor cases in which the effects of changes in the conductivity and frequency are not identical, the error introduced by considering their effects identical will be small for purposes of practical eddy-current testing.

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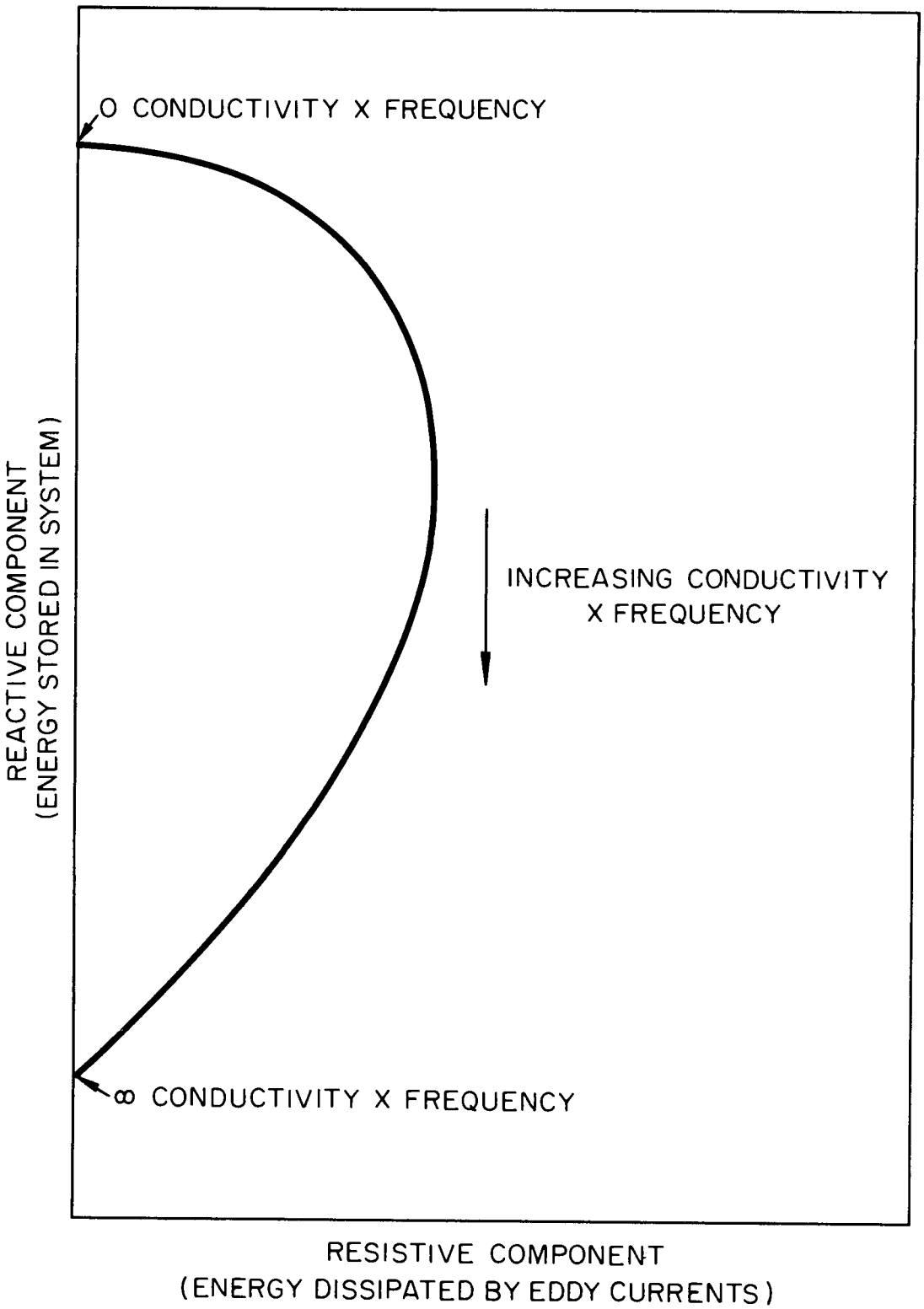

Fig. 1. Impedance of Coil in Presence of Increasing Conductivity X Frequency.

The exact nature of the alteration in the testing coil's impedance produced by the eddy currents in the metal specimen is a function of the frequency of the exciting current, the characteristics of the original field of the coil, the electrical conductivity and magnetic permeability of the part, its physical dimensions and location in the field, and the presence of discontinuities or "inhomogeneities" within the part. Since the mechanical and thermal history of the part influence its electrical conductivity and in some cases its magnetic permeability, they also become influencing factors. It is readily apparent that further discussion of the impedance of a testing coil must consider the particular geometry of the testing system and the particular properties of the metal specimen. Since the most common types of testing coils encountered in practice are those which encircle cylindrical objects (encircling or feed-through coils) and those which are placed on the surface of the part in the form of a probe, only these two types will be considered in this paper.

MEASUREMENT OF CONDUCTIVITY AND ASSOCIATED PARAMETERS

Encircling Coils

The simplest problem encountered in eddy-current testing is that of measuring changes in conductivity in a round, metal bar with an encircling coil. If the testing coil system consists of an exciting coil whose length is much greater than its diameter and a separate "pickup" coil situated near the longitudinal center of the exciting coil whose length is much less than its diameter (a system which is quite commonly encountered in practice), then the voltage which is induced into the pickup coil may be calculated by expanding Maxwell's electromagnetic equations into cylindrical co-ordinates. The calculations for this particular geometry can be made with considerable accuracy, although they are by no means exact. Caution should be exercised in extrapolating the results of such calculations to other encircling coil geometries. Since the voltage induced into the longitudinally short pickup coil is directly proportional to the impedance of the portion of the exciting coil to which it is coupled, it will be considered to be an impedance so that discussions of both double and single testing coil systems will be consistent. The equation which results from the calculation of the impedance of a coil encircling the solid bar is as follows:

$$\frac{R + j\omega L}{\omega L_o} = j(1-\nu) + \frac{2\nu^2 j + \frac{3}{2}}{\sqrt{f/f_c}} \quad \frac{J_1(j^{-\frac{1}{2}}\sqrt{f/f_c})}{J_o(j^{-\frac{1}{2}}\sqrt{f/f_c})},$$

in which R = resistive component of coil's impedance,

L = inductance of coil,

$\omega = 2\pi f$,

f = frequency,

ωL = reactive component of coil's impedance,

ωL_o = impedance of coil in absence of rod,

$\nu = D_p/D_c$,

D_p = dia of rod, (meters),

D_c = dia of coil, (meters),

$j = \sqrt{-1}$,

$f_c = \frac{2}{\pi \mu \gamma D_p^2}$,

$\mu = 4\pi \times 10^{-7}$(permeability of non-magnetic material),

γ = conductivity of rod (mhos/M),

and J_o, J_1 = Bessel functionsof the first kind and the zero and first order, respectively, for the arguments indicated in the equation.

Note that in the above equation the impedance of the coil has been normalized to the inductive reactance of the coil in absence of the metal rod. A plot of the impedance variations described by the equation is shown in the impedance plane of Fig. 2 (ORNL-LR-DWG 14992A). The solid curves were generated by varying the f/f_c ratio for three different values of ν. The dashed curves indicate the change in impedance resulting from a change in the diameter of the rod (D_p) for the several values of f/f_c. These dashed-diameter curves are not straight lines because the quantity f_c varies inversely with the square of the rod diameter.

There are several facts of importance regarding the impedance plane of Fig. 2. First, it should be noted that as the diameter ratio, ν, is reduced from $\nu = 1$, which is the hypothetical case of equal rod and coil diameters, the size of the impedance curve decreases inversely with ν^2. Thus, the amount of impedance variation produced by a given change in conductivity will be reduced directly as the square of ν, and therefore, it is desirable to maintain the ν ratio as large

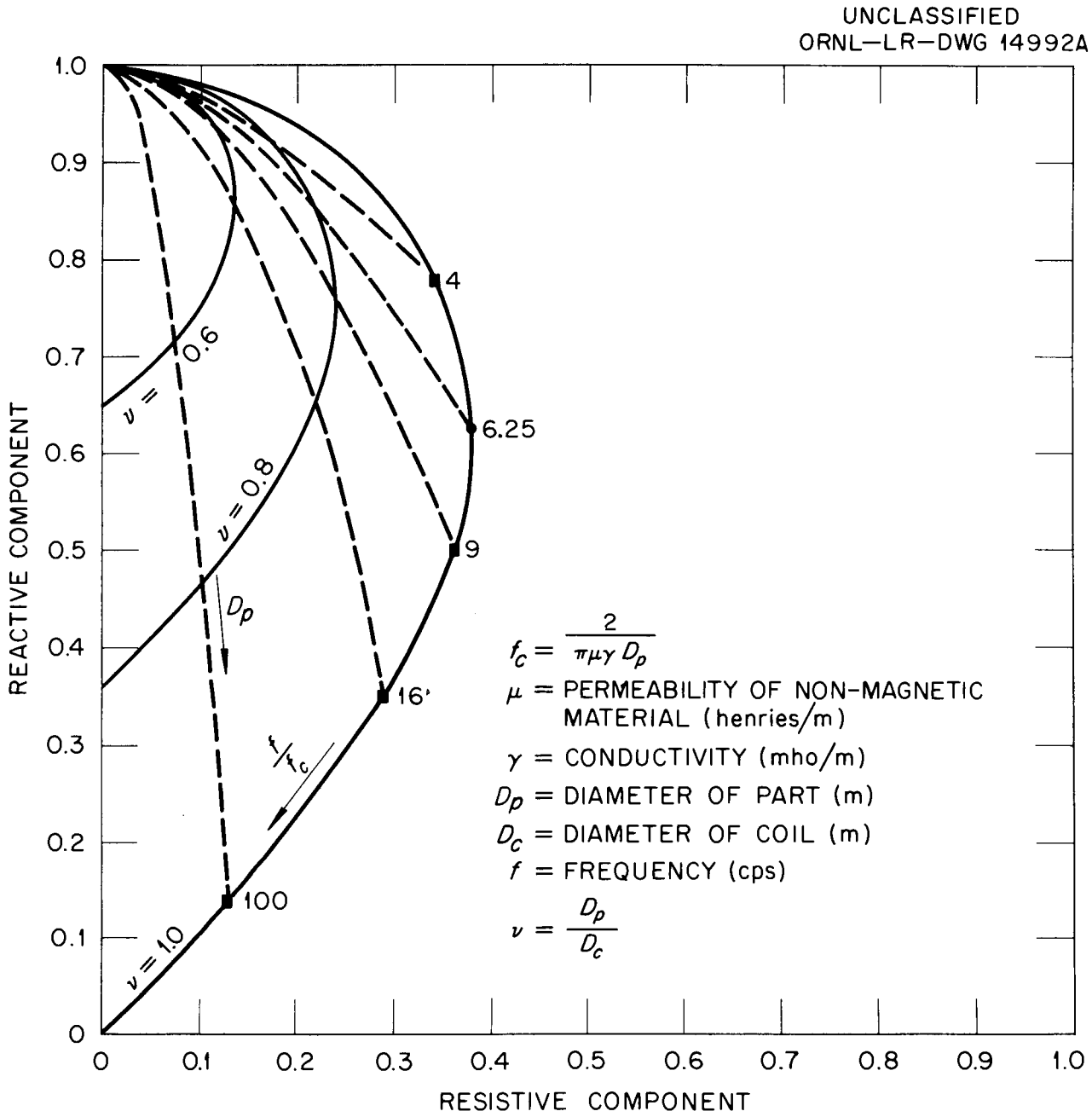

Fig. 2. Impedance Plane for Coil Encircling a Metal Rod.

as possible to achieve the best sensitivity. Variations in diameter and in f/f_c ratio produce impedance variations which, when measured from a given point on the impedance curve, occur at different phase angles: there is an angular displacement between the two effects. If phase-sensitive detectors are utilized the effects of varying diameter and of varying conductivity may be separated, which is advantageous in the high-speed monitoring of the conductivity of round bars in the presence of varying diameter. The phase angle between these effects, although always less than 45 deg, does not change appreciably for f/f_c ratios above 6.25. This means that a phase-sensitive instrument operating at a fixed frequency will allow diameter and conductivity effects to be separated effectively over a very large range of rod conductivities and diameters. The significance of the 6.25 value for f/f_c is that this is the condition for maximum sensitivity to changes in conductivity; that is, the rate of change of the impedance of the coil relative to the f/f_c ratio is a maximum at this point. The sensitivity to a small change in conductivity increases with the f/f_c ratio to the point $f/f_c = 6.25$, and then decreases toward zero as the f/f_c ratio is allowed to increase without limit.

Probe Coils

A testing coil system commonly used to measure conductivity, which is much more difficult to analyze than the encircling coil system, is the small surface probe coil. This type of coil system is very versatile since it may be applied to a great variety of shapes and sizes. The probe-coil arrangement usually consists of one or more coils whose axes are perpendicular to the metal surface such that the current-carrying wires composing the coil are approximately parallel to the metal surface. For practical testing purposes the use of more than one coil seldom produces an advantage over the single coil, and therefore, only the single-coil case will be considered.

There are a large number of interrelated variables which determine the impedance of a small probe coil in proximity with the metal surface and many of them do not lend themselves readily to analytical methods. Therefore, the empirical method is most effective in studying the parameters of an eddy-current probe-coil system. The empirical curves of Fig. 3 (ORNL-LR-DWG 30635) is typically descriptive of the effects of conductivity (γ), frequency (f), and relative permeability (μ_r) on

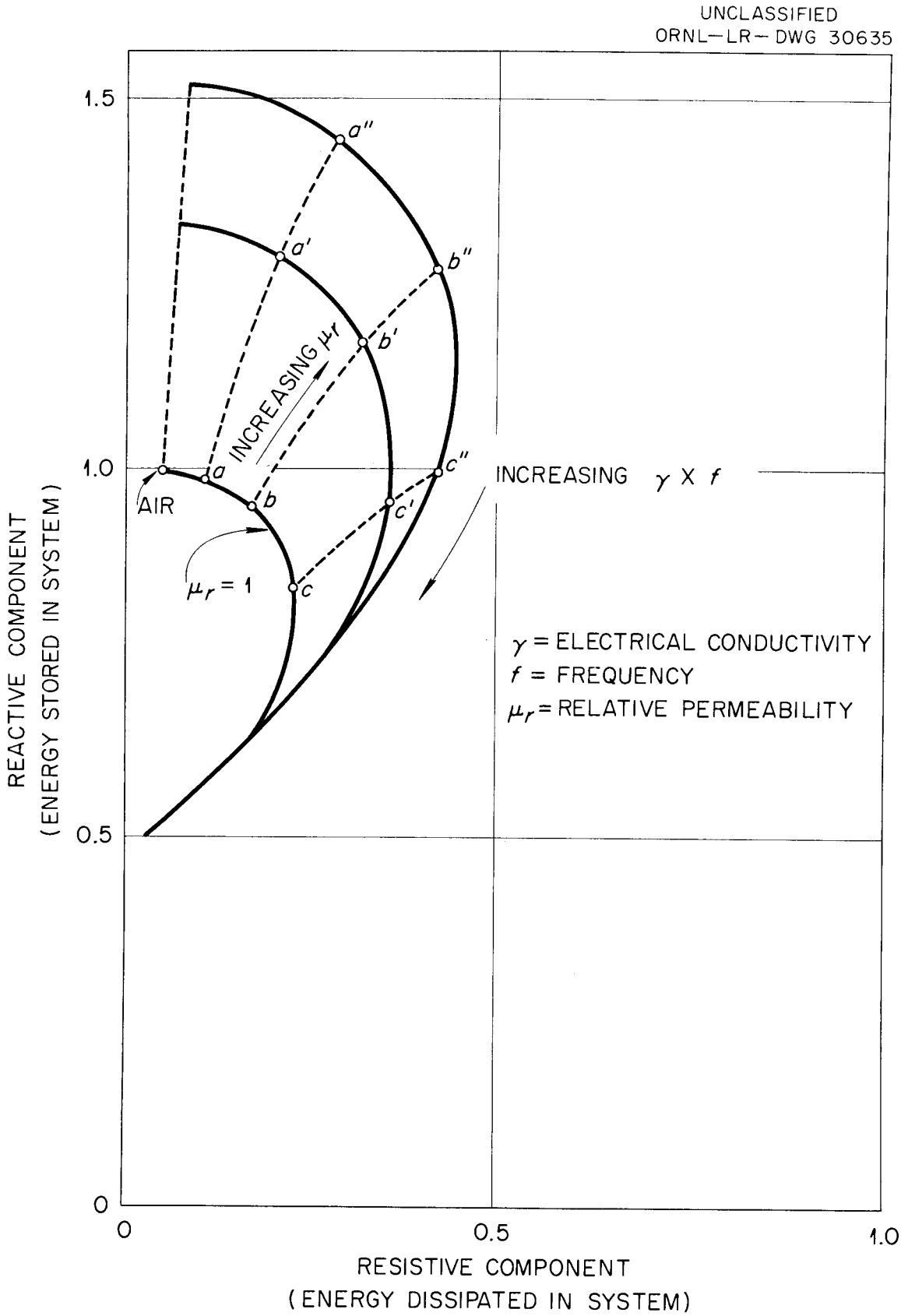

Fig. 3. Normalized Probe Coil Impedance Variations.

the impedance of a small probe on the surface of a very thick metal plate. It is evident that the shape and orientation of the curves of Fig. 3 are similar to those of Fig. 2 for the encircling-coil case except that the effects of relative permeability were neglected in Fig. 2. Note that for the probe coil also, the effect of conductivity and frequency may be considered as a product.

There are other features of the curves of Fig. 3 which are noteworthy. In the upper region of the graph there is a large phase separation between the impedance variations caused by permeability and conductivity changes. Thus phase detectors could be used to advantage in separating these effects. More important, however, is the fact that no ambiguity exists between conductivity (at a given frequency and permeability) and the resultant reactance, whereas the conductivity is double valued for each resistive component value. The unique relationship between conductivity and reactance has been used to advantage in developing a simple eddy-current instrument for rapid field identification of metals.

The Metal Identification Meter is a small, portable, field survey instrument with a small-surface probe coil which can be used to identify metals according to their electrical conductivity and magnetic permeability. A photograph of the instrument and the associated probe is shown in Fig. 4 (Y-26220). The instrument is seen to contain only one variable control and an indicating meter. In operation the probe is placed on the surface of the unidentified metal, and the tuning dial is turned until the meter reads a maximum (no particular significance is attached to the actual meter reading). The setting of the tuning dial for maximum meter response is a measure of the conductivity and permeability of the unknown metal. Signals due to variations in lift-off[1] are eliminated for all practical purposes by the spring action of the probe holder which ensures positive contact between the face of the probe and the metal specimen: successive applications of the probe to a particular metal surface will result in precisely the same reading each time.

The operation of this instrument is diagrammed in Fig. 5 (ORNL-LR-DWG 30293). The probe coil is the primary frequency-determining element in a transistor

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[1] Lift-off is defined as the spacing between the probe coil and the metal surface.

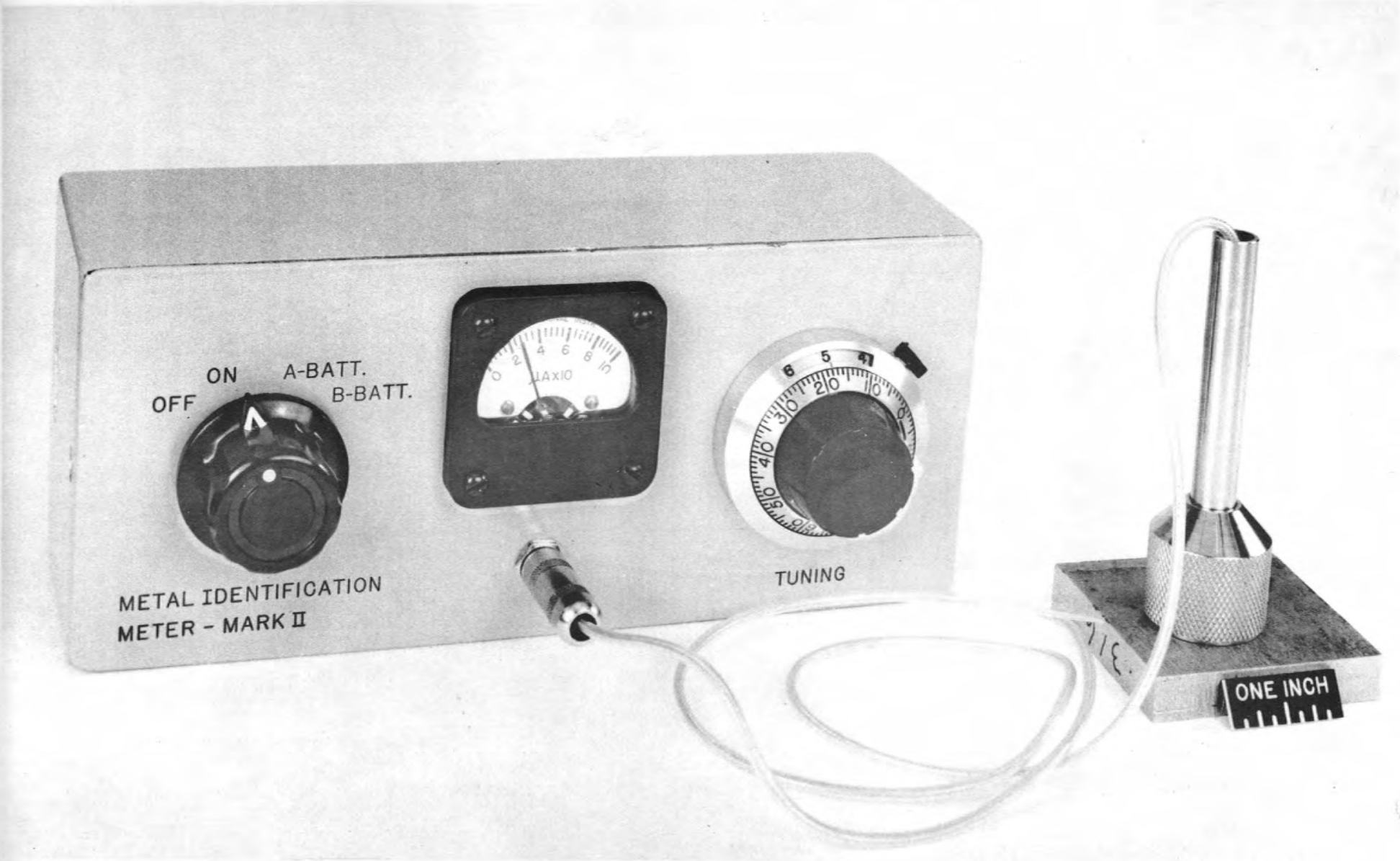

Fig. 4. (Y-26220) Metal Identification Meter and Probe.

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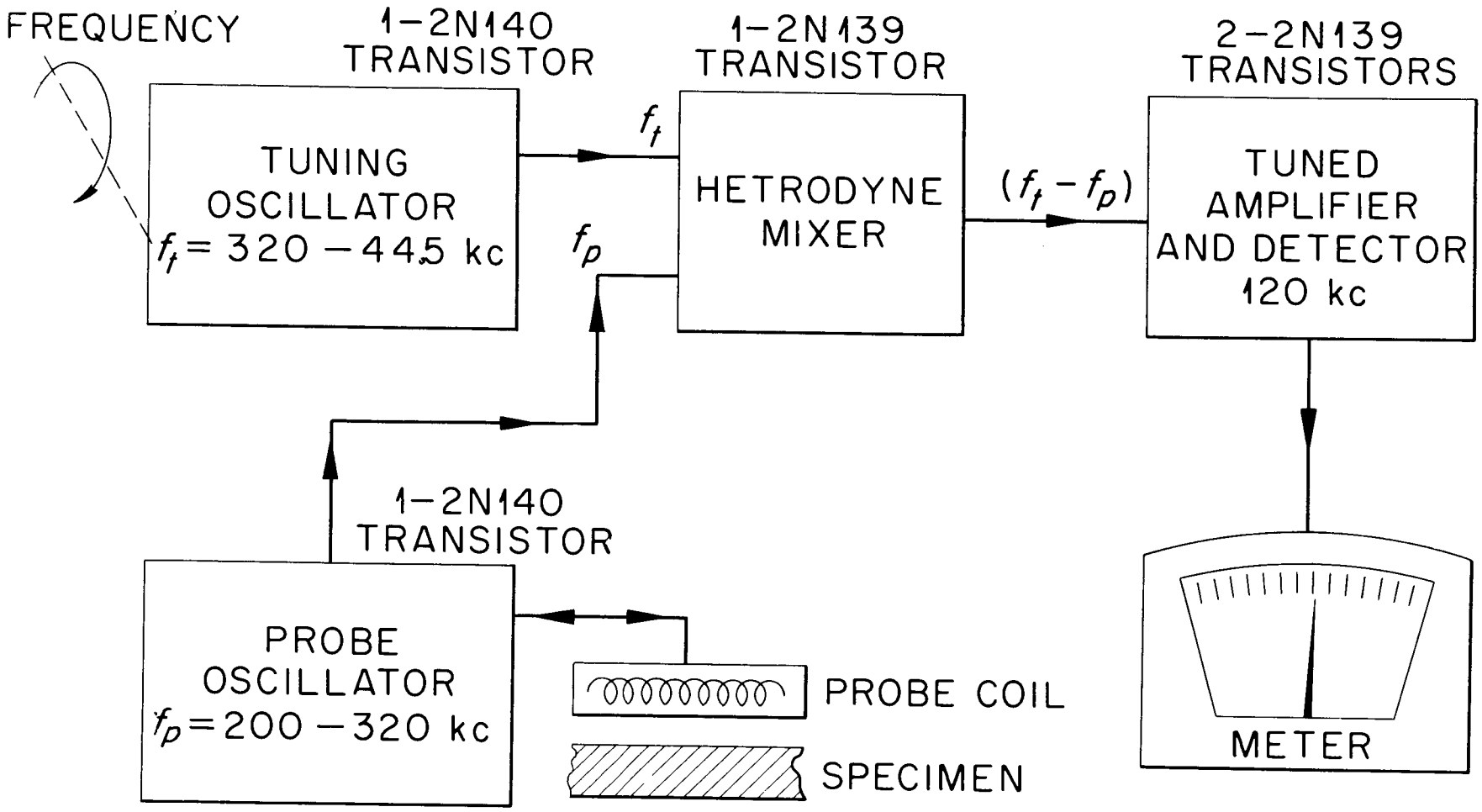

Fig. 5. Block Diagram of Metal Identification Meter. Mark II.

oscillator. The frequency of the probe oscillator varies from 200 kc to 320 kc as the reactance of the probe varies according to the conductivity and permeability of the metal specimen. A variable-frequency oscillator may be varied from 320 kc to 445 kc with the tuning dial, and its output is heterodyned with that of the probe oscillator. Thus, if the setting of the tuning dial is fixed, the difference frequency varies in accordance with the conductivity and permeability of the metal; conversely, if the difference frequency is to be maintained constant, the calibration dial must be varied in accordance with the conductivity and permeability of the metal. The indicating portion of the instrument consists of a sharply tuned amplifier whose output is indicated by the meter. The amplifiers are tuned to a pre-selected frequency of 120 kc, and the output measuring circuitry, of which the meter is a part, is so constructed that if the difference frequency is varied slightly from 120 kc either by turning the tuning dial or changing the conductivity or permeability of the metal, the meter reading will drop markedly from the maximum value; further removal of the difference frequency from the pre-selected value will result in the output-meter reading dropping promptly to zero.

A typical calibration curve of the Metal Identification Meter for non-magnetic metals is shown in Fig. 6 (ORNL-LR-DWG 30294). The calibration curve is a plot of instrument-dial setting versus conductivity of metal specimens in per cent IACS (International Annealed Copper Standard), and indicates the broad range of conductivity over which the instrument operates. All ferromagnetic materials indicate at dial settings of greater than 700, and therefore, are readily identified as such. The response curves shown in Fig. 7 (ORNL-LR-DWG 30634) are indicative of the manner in which the instrument can be used for rapid identification of metals. These curves represent the meter response to conductivity for tuning-dial settings of 495, 545, and 565 which correspond, respectively, to the conductivity of samples of a common austenitic stainless steel, Inconel, and a common Hastelloy alloy. It is evident that if the instrument were calibrated on any one of these three metals, it would not respond to the other two. It should be noted that the response curve, although having very steeply sloped sides, is relatively flat near the peak, such that in the normally encountered variation of conductivity due to chemical composition and thermal and mechanical history, the meter response will not decrease appreciably from the maximum reading.

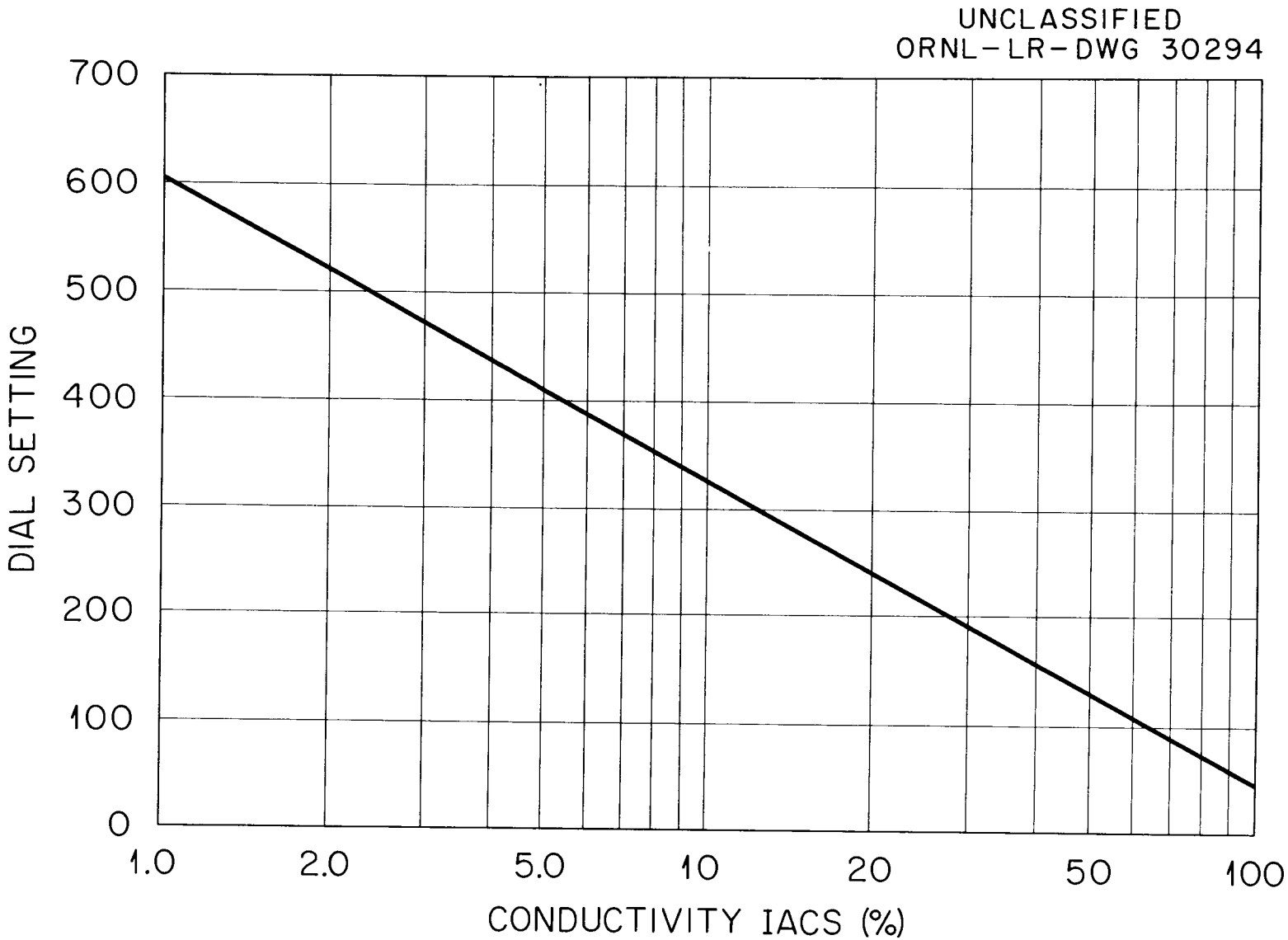

Fig. 6. Typical Calibration Curve Metal Identification Meter-Mark II.

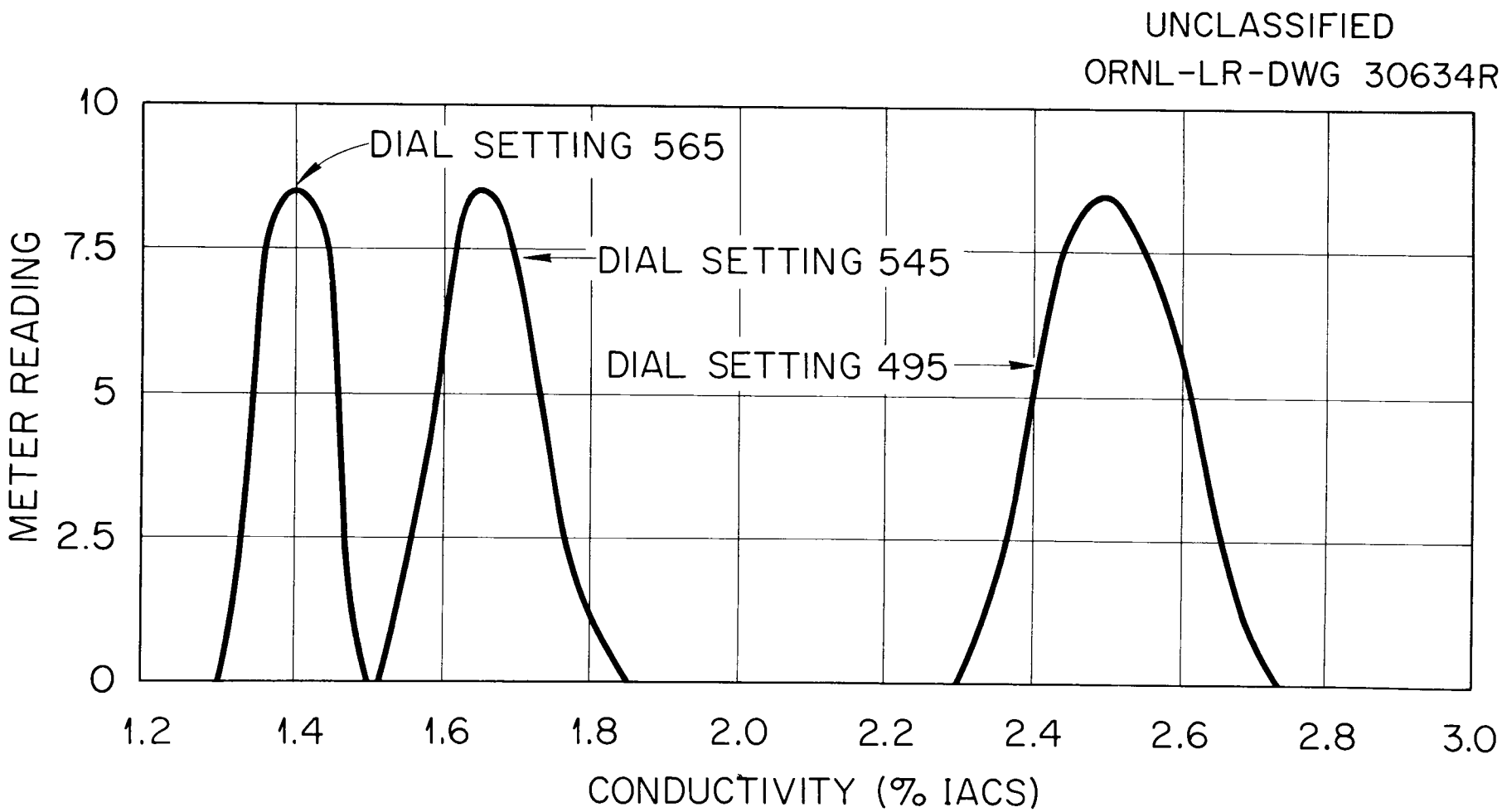

Fig. 7. Response of Metal Identification Meter Mark II to Conductivity Changes as a Function of Tuning Dial Setting.

The measurement of conductivity by the eddy-current method (or any other method) cannot establish a unique identification of a metal in an unlimited system of metals since this property varies with differences in chemical composition and in mechanical and thermal history. It is entirely possible that two alloys may have entirely different chemical compositions and yet possess exactly the same electrical conductivity. If the choice of alloys is limited, however, eddy-current conductivity measurements can be employed to reliably sort or identify the alloys of the system. A particularly troublesome situation is encountered when it is desired to sort or identify the particular members of alloy families, in that even though their nominal values of conductivity are different, slight variations in their chemical composition or in their mechanical and thermal condition may cause their range of conductivities to overlap. A classic example of this situation is that of the common austenitic stainless steels. It is generally impossible, for instance, to separate type 316 stainless steel from type 347 stainless steel since the ranges of their electrical conductivity overlap. If, however, only one chemical composition of each of the alloys is present, and if all of the pieces of each alloy have been given the same mechanical and thermal treatment, it is not only possible, but usually very easy to separate them.

The advantages of speed and economy which the eddy-current method exhibits for the identification of metals make it very attractive in situations in which it is possible to establish unique identifications. In spite of this effectiveness, however, there are several troublesome conditions peculiar to eddy-current conductivity-measuring techniques which can produce erroneous measurements and identifications. For the benefit of the inexperienced, a few of the pit-falls will be listed:

1. If the thickness of the metal specimen under surveillance does not appear infinitely thick to the testing coil, erroneous measurements will result, since the test will become sensitive to thickness changes in addition to conductivity-permeability changes. The thickness of metal which will appear infinite to the probe coil is a function of the frequency, the conductivity, and permeability of the metal, and the geometry of the coil. This thickness may be easily determined experimentally for a particular metal, probe, and

frequency by simply increasing the thickness of the metal specimen in steps until an increase of thickness does not change the indicated value of the conductivity. Identifications may be made on samples of finite thickness, of course, if the thickness is held constant and an appropriate calibration is made.

2. The application of eddy-current probes to curved surfaces can sometimes produce erroneous results by the introduction of lift-off between the probe and metal surface. The magnitude of the problem is determined by the radius of curvature of the metal surface and the size and geometry of the probe coil. Identifications on curved surfaces can best be accomplished by utilizing a reference standard of known identity having the same radius of curvature as that of the part being investigated.
3. The presence of non-conductive coatings, i.e., paint, scale, etc., may produce erroneous results by the introduction of lift-off, and therefore, should be removed before interrogation is attempted. It should be noted that the use of steel-wire brushes to remove coatings from non-ferromagnetic material sometimes leaves imbedded deposits of steel on the metal surface which will introduce serious errors to the measurement.

MEASUREMENT OF THICKNESS

Eddy-current techniques inherently lend themselves to the measurement of thickness of thin metallic sections, the thickness of cladding or shrouding of one metal on or around another, and the thickness of non-metallic coatings on a metal. Thickness measurements with eddy-current techniques are somewhat more difficult than are conductivity measurements because of the addition of the thickness variables into a measuring system already containing several variables. In the measurement of the thickness of a metallic cladding on another metal, the conductivity of the additional metal becomes another variable. It is readily apparent that if a system is encountered in which several of the many parameters of the measurement vary simultaneously, the separate measurement of the variable of interest borders on the impossible and certainly becomes impractical. In other situations many of the parameters can be controlled or inherently do not vary, and the measurement of one variable such as thickness become practical.

In principle, the detection of thickness changes with induced eddy currents is relatively straightforward. Since the currents which are induced into the metal part are produced by the alternating field of a coil which is external to the metal, it is fundamental that the induced currents will continuously decrease in amplitude and delay in phase as a function of the depth below the surface. The impedance of the coil is determined by the integrated effect of all of the induced eddy currents at their respective depths and phases. As the thickness of a part varies, the amplitude and phase of the eddy currents flowing on the surface of the part opposite to the coil varies. Thus, the impedance of the eddy-current coil varies with the thickness, and a measure of the change of the coil's impedance is a measure of the change in thickness.

Encircling Coils

A clearer and more detailed understanding of the measurement of thickness with induced eddy currents will be obtained by considering a practical example. If a tube rather than a solid rod is inserted into an encircling coil, the impedance variations of the coil will be considerably different as indicated in Fig. 8 (ORNL-LR-DWG 24832). These impedance curves were calculated by making the same assumptions regarding the field of the coil as were made in the previous discussion of solid rod, and the resulting analytical expression for the impedance of the coil is as follows:

$$\frac{R + j\omega L}{\omega Lo} =$$

$$j(1-\nu) + \frac{2\nu^2 j^{\frac{3}{2}} J_1(\sqrt{-j\, f/f_c})\, Y_2([1-2t]\sqrt{-j\, f/f_c}) - Y_1(\sqrt{-j\, f/f_c})\, J_2([1-2t]\sqrt{-j\, f/f_c})}{\sqrt{f/f_c}\, J_0(\sqrt{-j\, f/f_c})\, Y_2([1-2t]\sqrt{-j\, f/f_c}) - Y_0(\sqrt{-j\, f/f_c})\, J_2([1-2t]\sqrt{-j\, f/f_c})}$$

in which $f_c = \frac{2}{\pi\, \mu_0\, \gamma\, D_p^2}$

D_p = OD of tube,

$\nu = D_p/D_c$,

t = tube wall thickness expressed as a fraction of the OD,

$J_{0,1,2}, Y_{0,1,2}$ = Bessel functions of the first and second kind, and the zero, first, and second order, respectively for the arguments indicated in the equation; the other symbols are the same as used in the previous discussion of solid rod.

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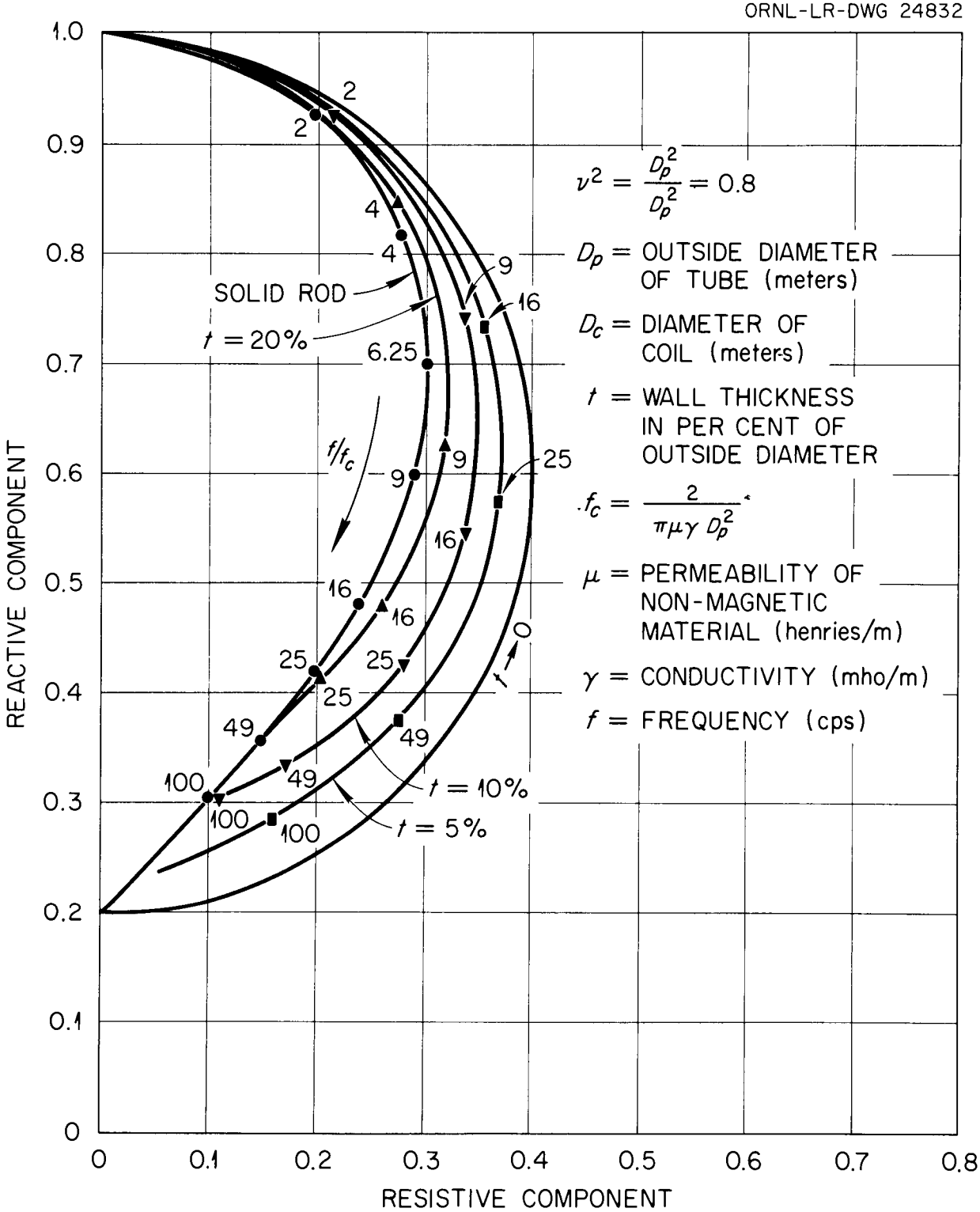

Fig. 8. Impedance Plane for Coil Encircling Tube with f/f_c Variable and the Wall Thickness as a Parameter.

The impedance curves of Fig. 8 were plotted for varying f/f_c and several particular values of tube-wall thickness expressed in per cent of the outside diameter. The limiting curves are that for the solid rod ($t = 50\%$), and that of the thin-membrane wall in which the thickness approaches zero. The fill factor ν^2 was taken equal to 0.8 for this plot. These curves represent the impedance variation that would be encountered for varying conductivity or frequency for the tube-wall thicknesses indicated. The curves for the locus of diameter variation have not been included for purposes of clarity; these curves would follow generally the same paths as those shown in Fig. 2.

If the f/f_c ratio is held constant at some particular value in Fig. 8, and a smooth curve drawn through the points of this particular f/f_c value on the several thickness curves, the curve is the locus of the impedance of the coil for varying wall thickness at the particular value of f/f_c. Varying thickness curves are shown in Fig. 9 (ORNL-LR-DWG 24834) for several values of f/f_c. In this impedance plot the curves for varying wall thickness are the solid curves with the percentage-wall thicknesses indicated along their path, and the dotted curve represents the limiting situation in which the wall thickness approaches 50%. The sensitivity to thickness changes as a function of tube-wall thickness is discernible from Figs. 8 and 9. It should be noted from Fig. 8 that the amount by which the 20% wall-thickness curve is removed from the solid-rod curve is small, and therefore, the sensitivity to wall-thickness variations for tubes having wall thicknesses of 20% or greater will be low. The sensitivity will be low for thick-wall tubes regardless of the frequency used or the conductivity of the tube, since nowhere on the impedance curves does the curve for 20% wall thickness remove very far from the solid-rod curve. Further understanding of the manner in which the sensitivity to a wall-thickness change varies with the wall thickness may be gained by studying the curves of Fig. 9. Consider, for illustration, the varying thickness curve for an f/f_c ratio of 25. The departure of the 20% wall-thickness point from the solid curve is small; if the 20% value is reduced to 10%, the impedance excursion is considerable; if the 10% value is reduced to 5%, the impedance excursion is even greater; thus, the sensitivity to a small thickness change is increasing with decreasing wall thickness.

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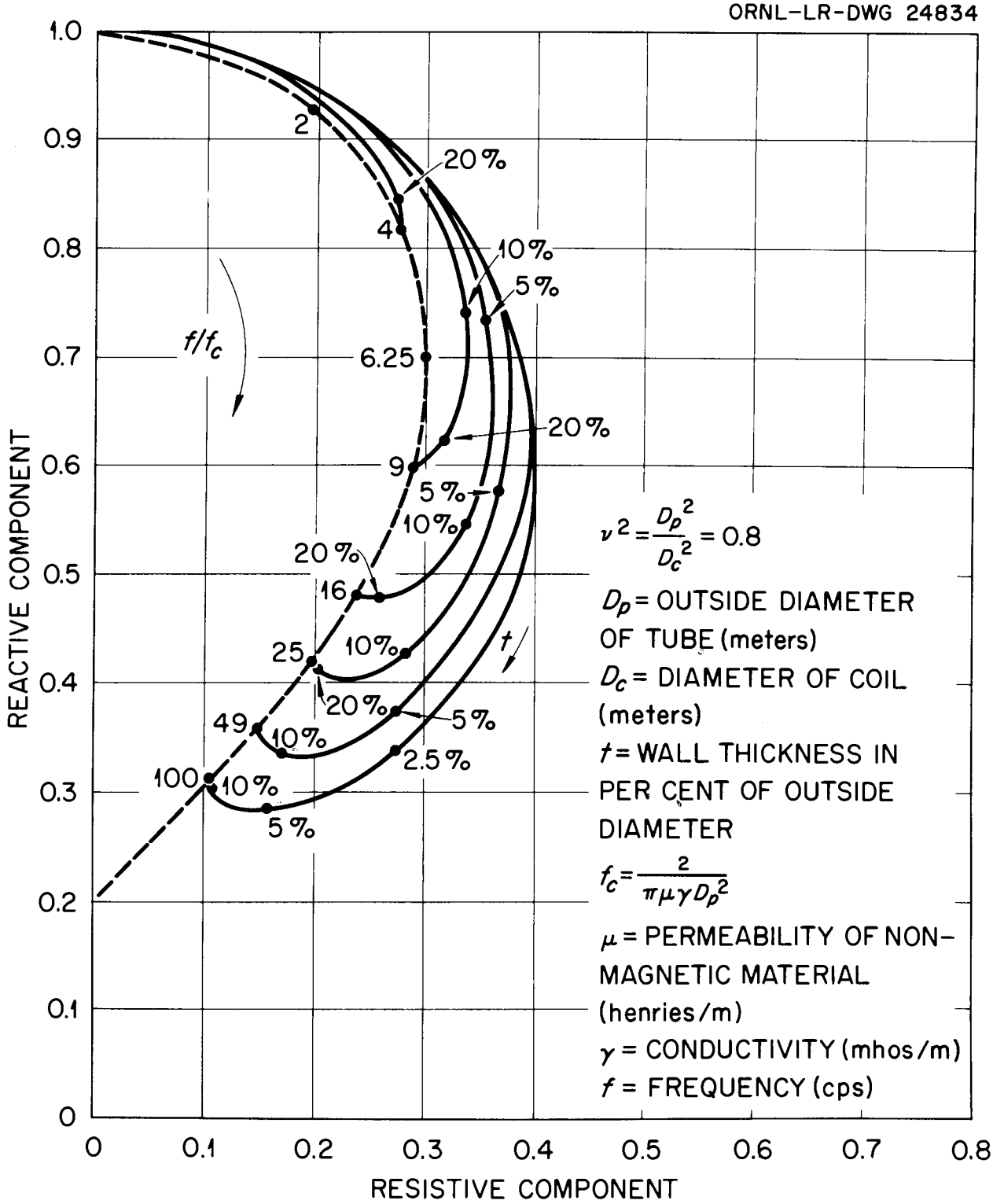

Fig. 9. Impedance Plane for Coil Encircling Tube with Wall Thickness t Variable and with f/f_c as a Parameter.

In order to illustrate the phase relationships between small variations in conductivity, wall thickness, and diameter, a composite of the impedance curves of Figs. 8 and 9 was made for a 10% wall-thickness tube and is shown in Fig. 10 (ORNL-LR-DWG 24833). In this illustration the locus of impedance for the 10% wall-thickness tube and varying f/f_c ratio is represented by the long solid curve; the effects of varying wall thickness is shown at several values of f/f_c by the short, solid curves passing through the points, the arrow indicating the direction of increasing thickness; and the effect of small variations in outside diameter is shown for the same several values of f/f_c by the short dashed curves, the arrow indicating the direction of increasing diameter. The phase angle between variations in thickness and in conductivity (the f/f_c ratio varies directly with conductivity) remains very small until the f/f_c ratio becomes large. It will be remembered, however, that the sensitivity to either a conductivity or a wall-thickness change is low at the higher f/f_c ratios required for appreciable phase separation. It is, therefore, clear that the separate simultaneous measurement of both thickness and conductivity by the use of phase detection is extremely difficult, and in many cases altogether impossible. The phase angles between the effects of varying diameter and wall thickness is small at the very low values of f/f_c. For the 10% wall-thickness tube being considered, this phase separation becomes appreciable as the f/f_c ratio becomes greater than about four, and increases with the f/f_c ratio. From the previous discussion of the sensitivity to variations in wall thickness, the region of high values of f/f_c (greater than about 25 for the 10% wall tube) must be excluded from the consideration since the sensitivity to thickness variations is very small in this region. Therefore, only the central portion of the curve from $f/f_c = 4$ to $f/f_c = 25$, is of interest for the separate and simultaneous measurement of thickness and diameter for the 10% wall tube. Since the eddy-current test is much more sensitive to variations in diameter than it is to variations in thickness, due to the rapid attenuation of the eddy currents with depth, it is desirable to operate in the region of the curve in which maximum sensitivity to thickness variations obtains: from $f/f_c = 9$ to $f/f_c = 16$ which is in the region of the resistive component maximum of the curve. This optimum range of f/f_c values will increase as the wall thickness decreases.

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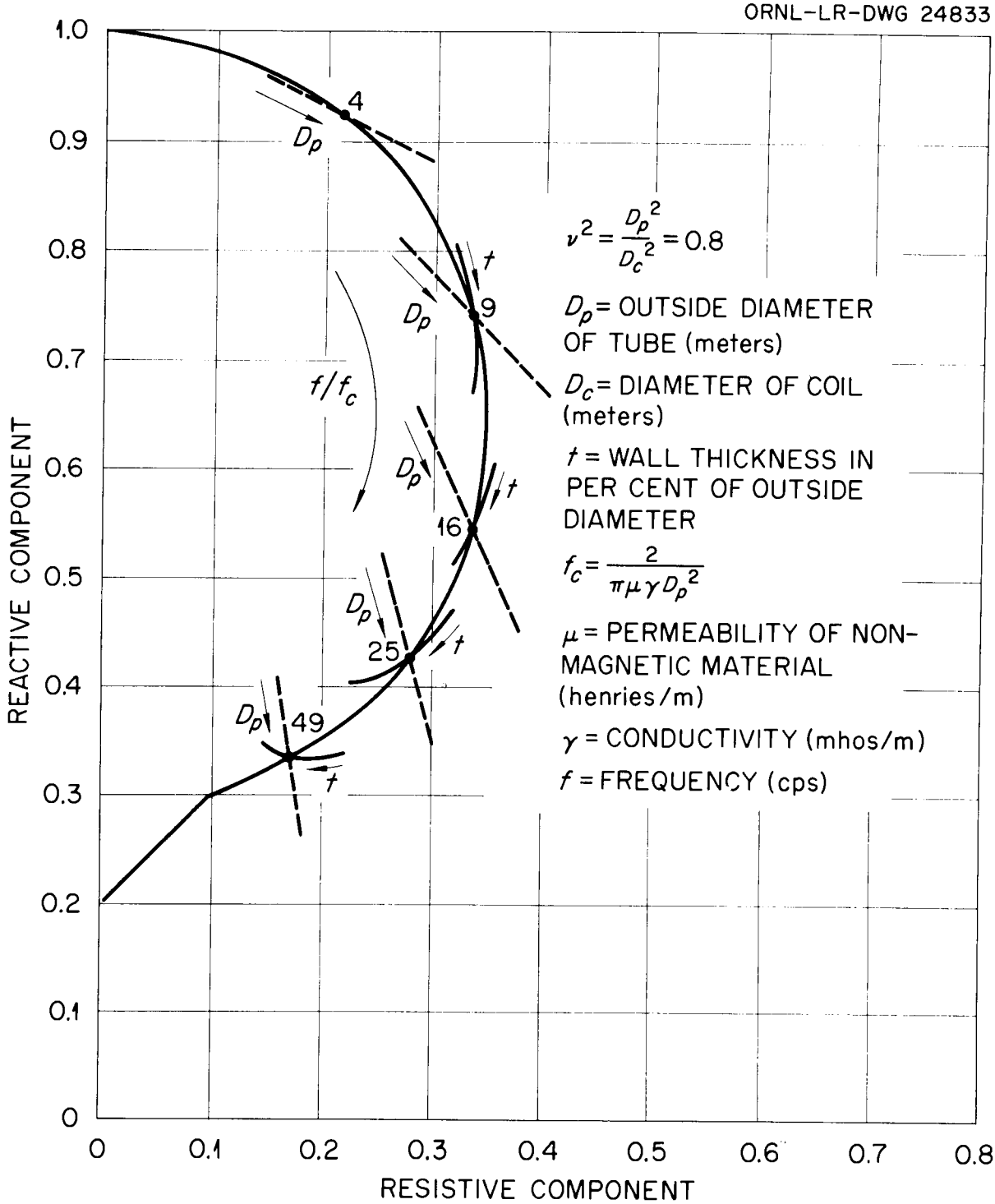

Fig. 10. Impedance Plane for Coil Encircling Tube Having Wall Thickness = 10% of O.D. with f/f_c, t, and D_p Variable

When it is considered that the f/f_c ratio varies with the square of the outside diameter and linearly with the conductivity, it becomes readily apparent, considering the large range of diameters and conductivities which are encountered in commercial tubing, that the frequency utilized in the eddy-current measurement of tube-wall thickness must be varied over a considerable range if the optimum test conditions which were established above are to obtain. The difficulty encountered in the use of phase-sensitive instrumentation is thus apparent, since phase-detection circuits inherently must be operated at a single fixed frequency, and do not readily lend themselves to adjustments required for multiple-frequency operation. This limitation of phase detectors has prompted the conception of an experimental instrument called the "Impedograph," which utilizes indirect methods of obtaining independent measurements of the resistive and reactive components of the impedance of the testing coil.

The most important features of the Impedograph are represented in the block diagram of Fig. 11 (ORNL-LR-DWG 17178). In many respects it is similar to the Cyclograph,[2] in that it is composed primarily of an oscillator in which the bifilar wound, center-tapped testing coil is the frequency-determining element. The amplitude of the alternating voltage generated by the oscillator varies inversely with the resistance of the testing coil, and the frequency varies inversely with the square root of the inductance of the testing coil, as influenced by the eddy currents in the tube wall. The amplitude detector and its associated amplifier provide a direct coupled signal which varies inversely with the resistive component of the impedance of the testing coil, and the frequency discriminator with its associated amplitude limiter and amplifier provides a direct coupled signal which varies inversely with the reactive component of the impedance of the testing coil. Thus, referring to the impedance plane plots of Figs. 8, 9, and 10, both the resistive and reactive components of any excursion from the operating point are measured, and since the operating frequency may be changed at will by

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[2] Oliver, R. B., McClung, R. W., and White J. K., "Immersed Ultrasonic Inspection of Pipe and Tubing," J. Soc. Nondestructive Testing, pp 95 – 100 (May-June 1957).

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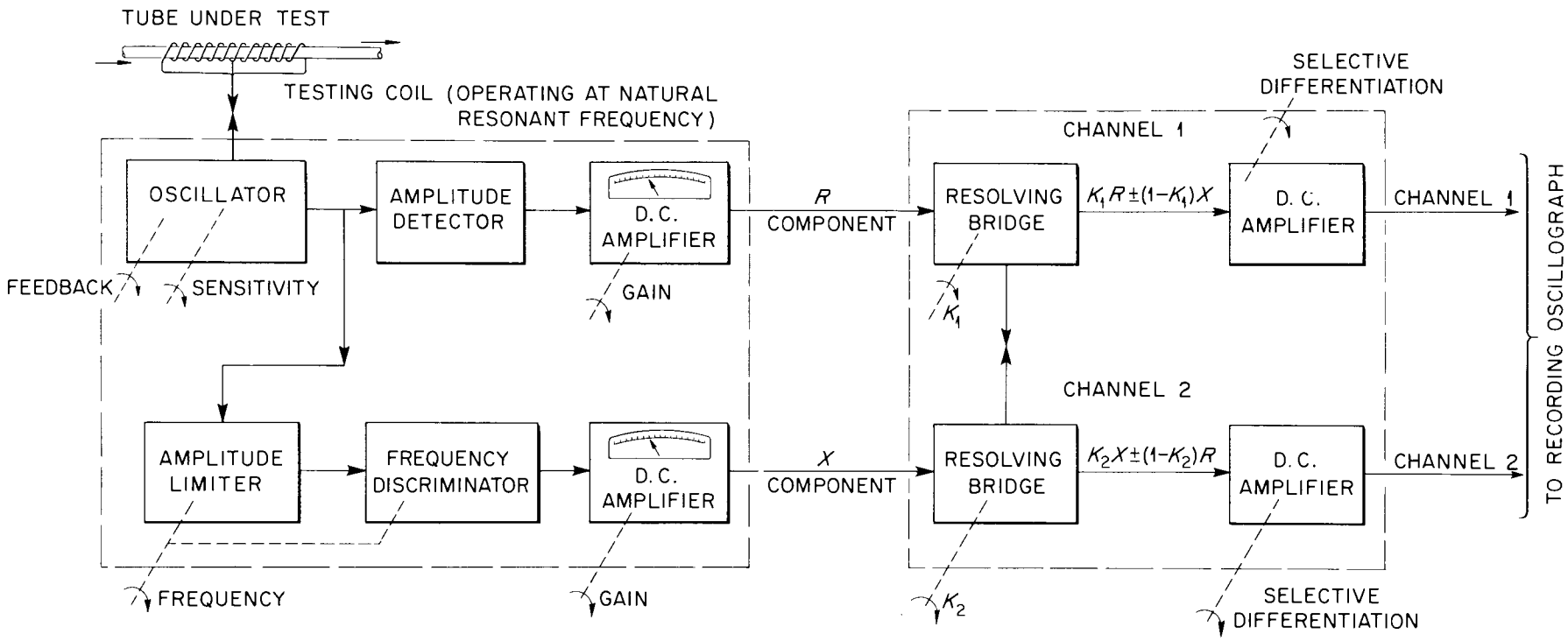

Fig. 11. Block Diagram of Impedograph.

interchanging testing coils, any operating point on the impedance plane which is desired may be selected. The resistive and reactive components of a change in the impedance of a testing coil from the operating point may be resolved into any other set of two orthogonal components by the use of resolving bridges as indicated in the block diagram of Fig. 11.

The operating frequency chosen for use with the Impedograph is selected such that the previously described conditions for optimum sensitivity to wall-thickness changes is obtained. Since under this operating condition the impedance of the coil as a function of thickness is at its maximum resistive value, small changes in wall thickness produce little or no change in the resistive component, but they do produce maximum change in the reactive component. Changes in the outside diameter produce impedance variations which occur at an angle oblique to both the resistive and reactive components, and therefore, they produce signals in both the R and X channels. The control of the resolving bridges may be adjusted as indicated in Fig. 11 until one channel of the instrument responds primarily to variations in diameter and the other primarily to variations in wall thickness.

The ability of this system to distinguish between diameter and wall-thickness variations is illustrated in Fig. 12 (ORNL-LR-DWG 17746) in which the signal traces are recordings from the two signal channels of the Impedograph for two 35-in. lengths of 0.230-in. by 0.025-in. Inconel tubing which was previously stretched to accentuate the dimensional variations. Above the trace is shown a plot of the average wall thickness as measured with the Vidigage (ultrasonic resonance thickness gage) and below the trace is a plot of the average outside diameter as measured with mechanical micrometers. It is readily seen that close correlation exists between the instrument signals and the other independent measurements. These traces were made at an operating frequency of 189 kc, for which the f/f_c ratio is ~ 13 for the 0.230-in.-dia Inconel tube (wall thickness equal 11%), and at a tube speed of ~ 1 ft/sec.

Probe Coils

The thickness of flat metal sheets may be measured with an eddy-current probe coil by utilizing a configuration similar to that described in the preceding section

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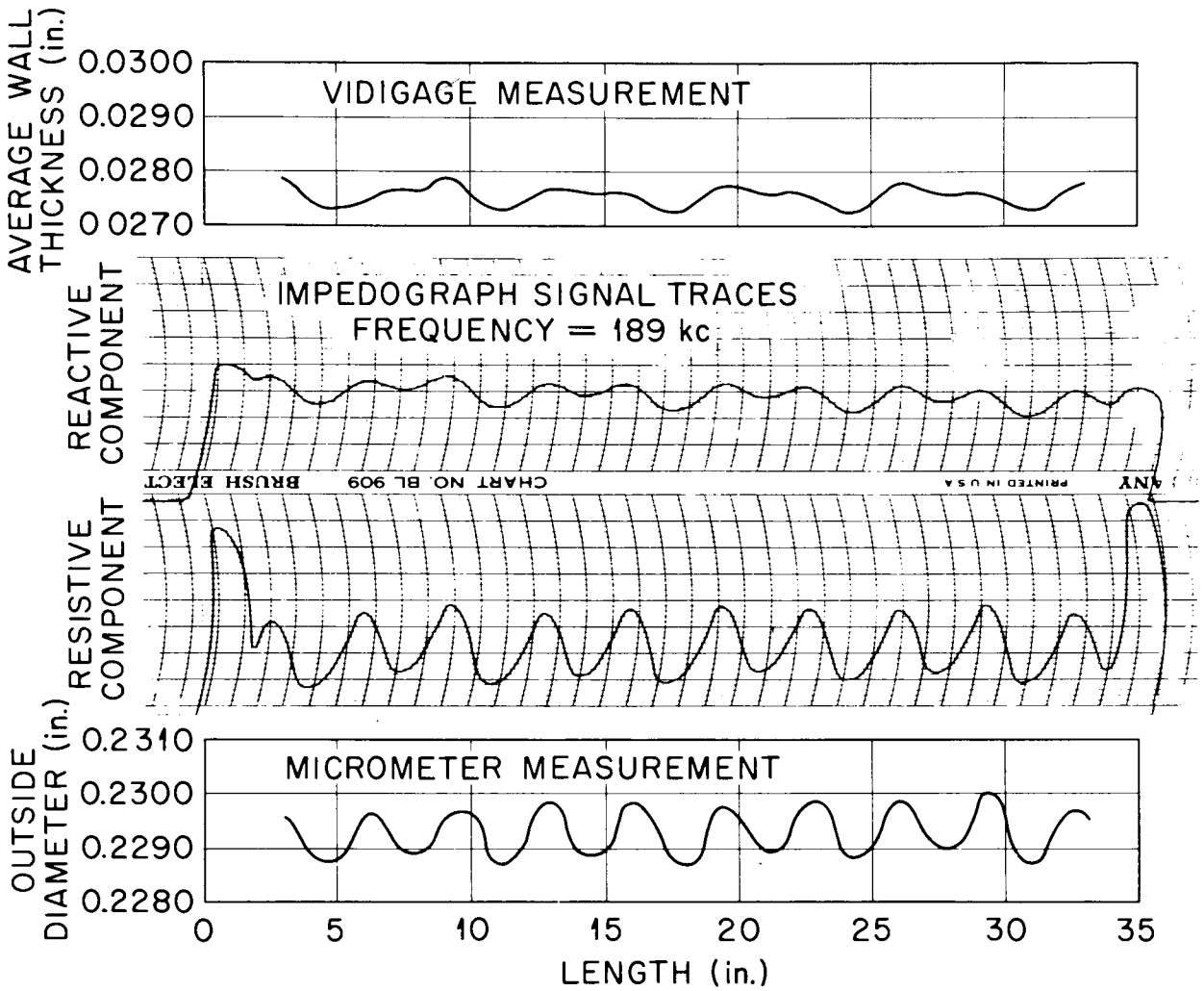

Fig. 12. Comparison of Impedograph Signal Traces with Actual Dimensional Variations. 0.229- x 0.025-in. Inconel Tube. (68-2A)

concerning conductivity measurements. This technique is most useful for thin sections, since for thicker sections existing ultrasonic measuring techniques are much more versatile and accurate than is the eddy-current method. Below about 0.020 in., however, ultrasonic resonance techniques become difficult in application. Fortunately, this is the range of thicknesses to which eddy-current techniques may be most effectively applied. Although the impedance variations of a probe coil in proximity with a metal sheet of finite thickness is somewhat similar to that of the encircling coil, mathematical analyses become largely impractical because of the large number of variables involved, and experimental impedance curves must be utilized entirely.

The effect of varying thickness on the impedance of a small probe coil is illustrated in Fig. 13 (ORNL-LR-DWG 19105) which was determined at 20 kc using 6061 aluminum alloy (conductivity equal 45% IACS). The probe coil for which the curve is plotted consists of 540 turns of No. 40 enameled copper wire contained in a 1/2-in.-dia ferroxcube cup. Referring to Fig. 13, the point of apparent infinite thickness describes a section thicker than the effective depth of penetration of the eddy currents. This infinite thickness (~ 0.050 in. in this instance) is a function of the conductivity of the specimen, the frequency used, and the size and geometry of the probe coil. This thickness must be determined experimentally for each different probe coil, material, and frequency encountered.

Also shown in this figure is the effect of lift-off on the impedance of the probe. These curves are seen to have complex shapes rather than simple ones, having at least two inflection points. The complex shape of these curves is not peculiar to any given coil; however, the degree of complexity has been observed to vary. The reason for this phenomenon is not understood.

Two additional impedance curves as a function of thickness are shown in Fig. 14 (ORNL-LR-DWG 19285), and illustrate the advantage of using coils having high-permeability, low-loss cores. These curves were determined using two coils with identical windings, one designated as Mark XI having a high-permeability core, and the other coil, Mark XII, having an air core. It is evident from the graph that the impedance changes are increased greatly by the use of the high-permeability core, and therefore, the intrinsic sensitivity of a probe-coil test is increased by the use of such cores. There are no apparent disadvantages to the use of these cores other than the slight fabrication problems imposed.

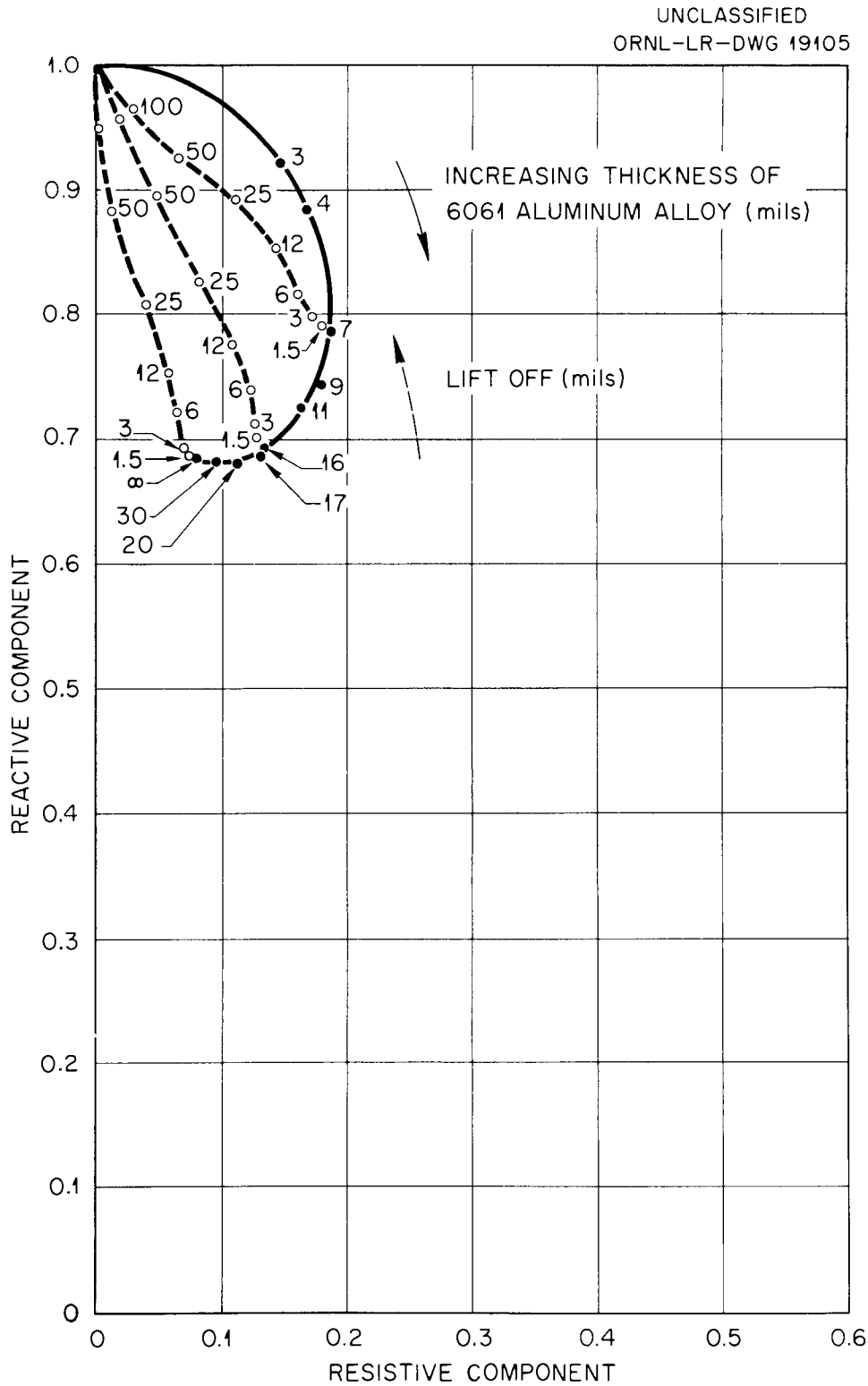

Fig. 13. Impedance Plane of Mark X Probe Coil in Presence of Varying Thickness of 6061 Aluminum Alloy (Conductivity = 45 % IACS) at 20 kc with Lift-off Effect Shown.

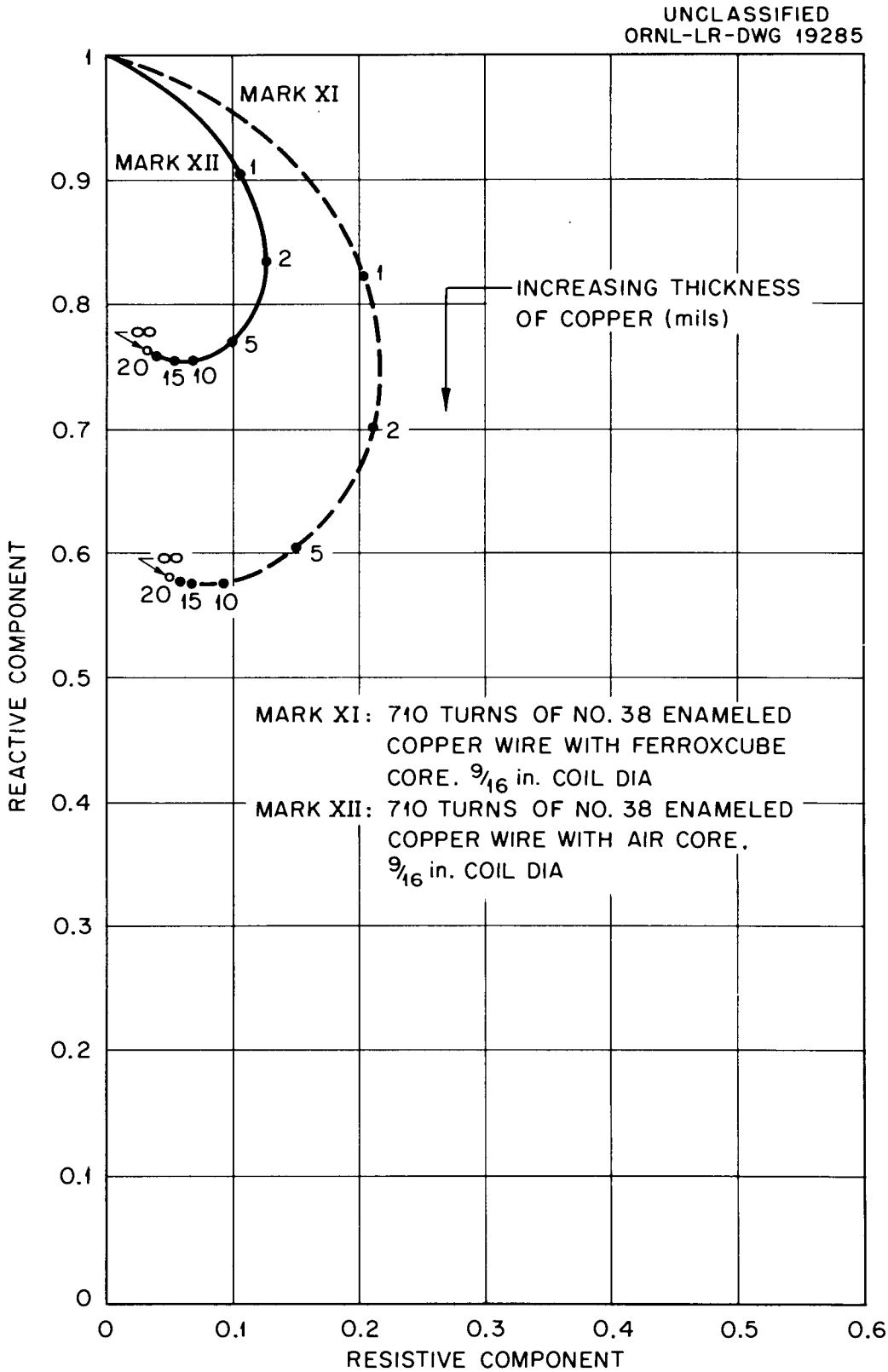

Fig. 14. Comparison of Impedance Planes of Mark XI and Mark XII Probe Coils at 20 kc on Varying Thicknesses of Copper.

Cladding-Thickness Measurements

Eddy-current cladding-thickness measurements utilize the impedance changes which are caused by the presence of two metals in the field of the probe coil. An example is illustrated in Fig. 15 (ORNL-LR-DWG 19108), in which the impedance changes are plotted which were produced at 20 kc both by varying thicknesses of copper on a thick base of Inconel and by varying thicknesses of Inconel on a thick base of copper. Note the similarity between the portion of the curve determined by the copper on the Inconel and previous curves determined by varying the thickness of a single metal in the field of the coil. In contrast, the curve for Inconel on copper has a shape similar to lift-off curves. In situations in which the conductivity of the two metals involved are vastly different, it may be concluded that there are two types of clad-thickness measurements: the first being similar to a simple thickness measurement in which the cladding is the better conductor of the two materials, and the second being similar to lift-off measurements in which the cladding is the poorer conductor of the two. Of importance is the effect of conductivity on the apparent infinite thickness of the two metals: at a frequency of 20 kc, 0.030 in. of copper (conductivity equal 85% IACS) appears infinitely thick to the eddy currents while 0.130 in. of Inconel (conductivity equal 1.8% IACS) is required to produce a similar effect. The apparent infinite thickness is determined not only by the frequency and conductivity of the metal, but also by the geometry of the probe coil being used. The apparent infinite thickness decreases as the diameter of the coil decreases.

A second example of impedance curves for clad metal is shown in Fig. 16 (ORNL-LR-DWG 19106), in which yellow brass (conductivity equal 28% IACS) and 1100 aluminum (conductivity equal 59% IACS) were examined at a frequency of 10 kc. This curve has the same shape as the one in the previous illustration but is much smaller since there is less difference between the conductivities of the two metals. Note also that the apparent infinite thicknesses (~ 0.030 in. for brass and 0.020 in. for aluminum) are not as widely separated as they were in the case of copper and Inconel.

An example of practical and successful clad-thickness measurements with eddy-current probe coils is the inspection method which was developed by the Nondestructive Test Development Group, Metallurgy Division, Oak Ridge National Laboratory,

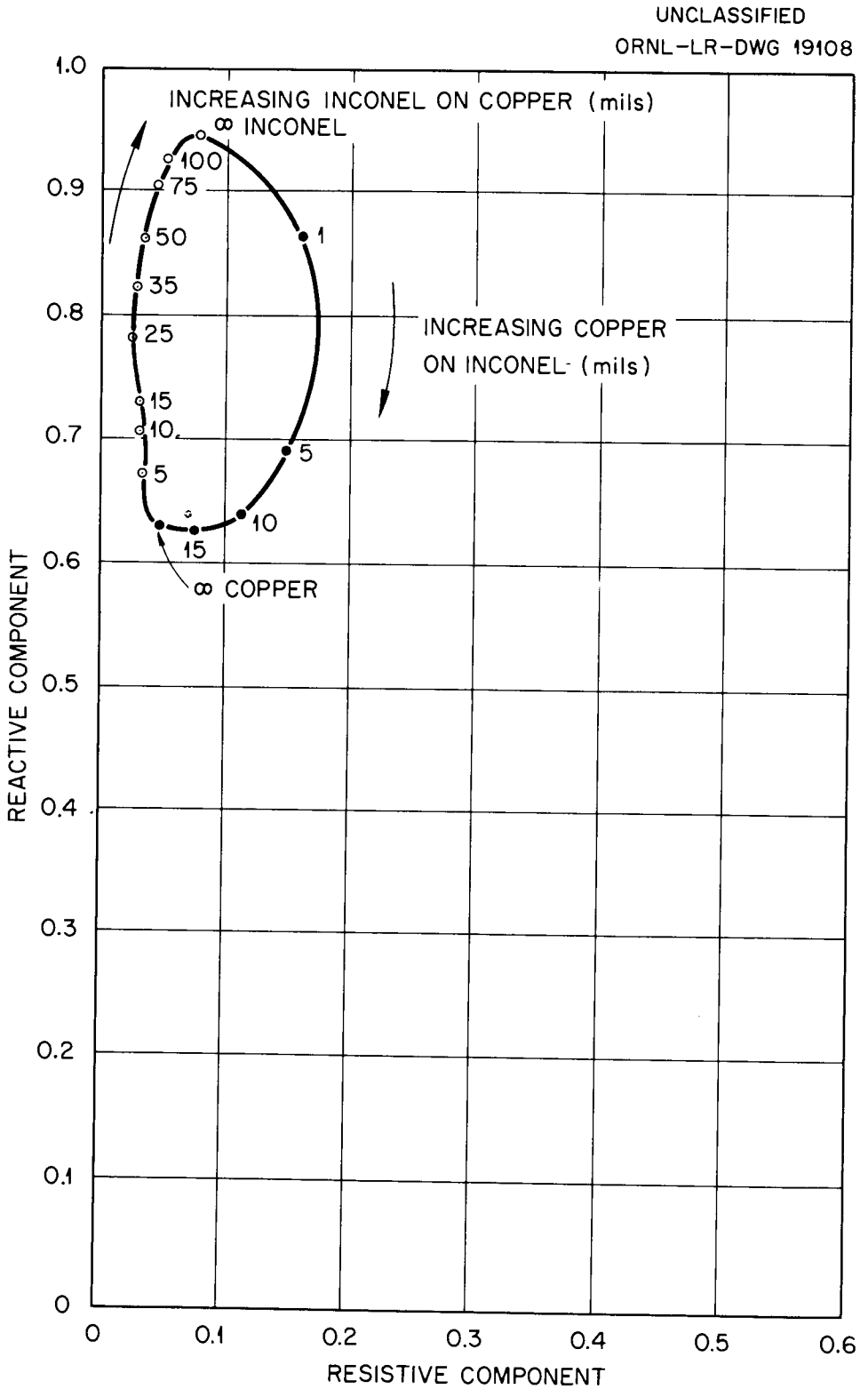

Fig. 15. Impedance Plane of Mark X Probe Coil in Presence of Copper (Conductivity = 85 % IACS) and Inconel (Conductivity = 1.8 % IACS) at 20 kc

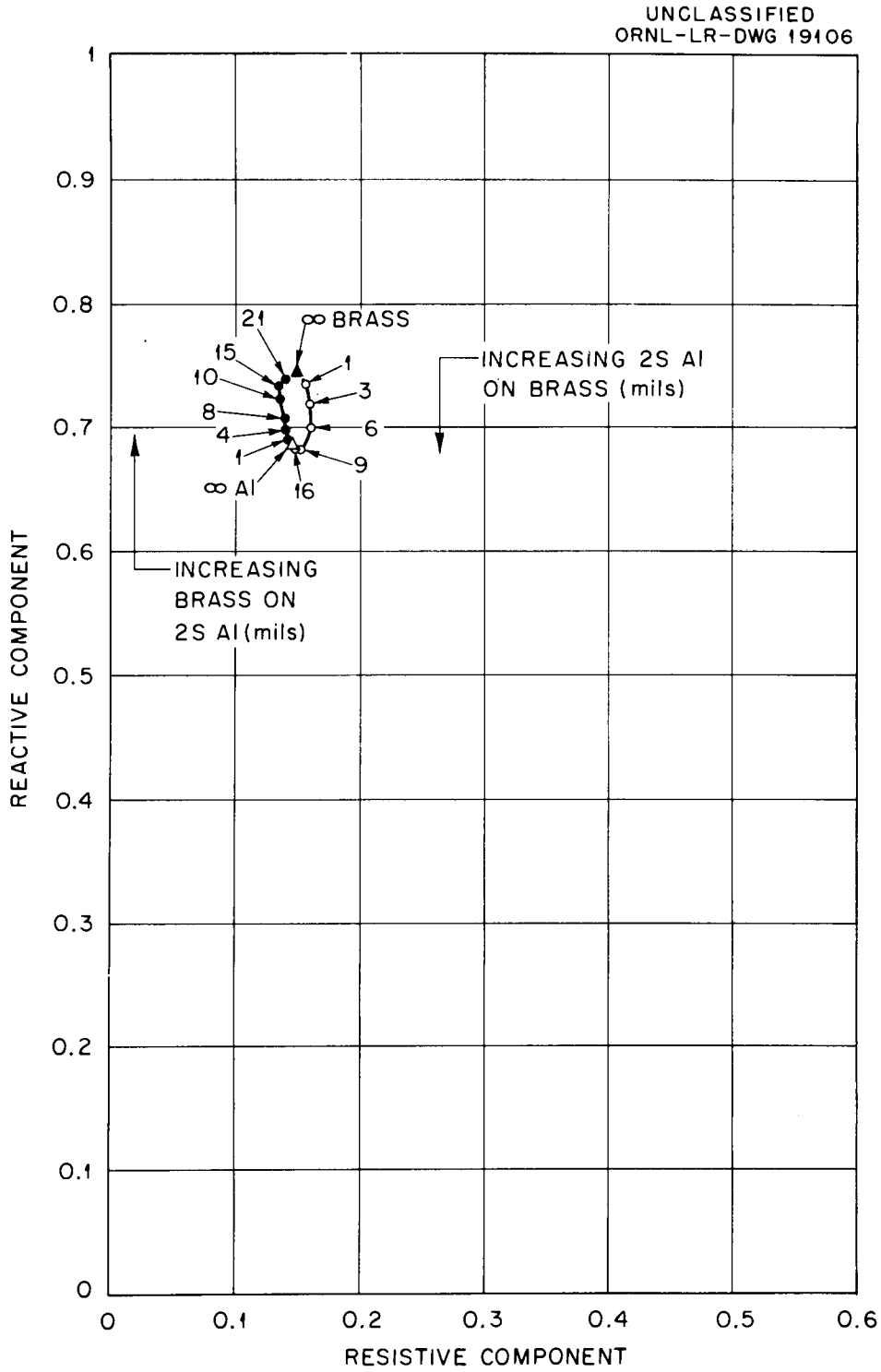

Fig. 16. Impedance Plane of Mark X Probe Coil in Presence of 2S Aluminum (Conductivity = 59% IACS) and Yellow Brass at 10 kc (Conductivity = 28% IACS).

for the determination of the cladding thickness of the Mark X fuel plate for the Materials Testing Reactor.[3] This fuel plate is composed of a 48 wt % uranium-aluminum alloy core of 0.022-in. nominal thickness clad with 6061 aluminum alloy of 0.020-in. nominal thickness. The deformation characteristics of the core and clad alloy are different; hence, during the rolling of the plate to a uniform thickness, the deformation of the core frequently is non-uniform. The result is a thick section at each end of the core, the longitudinal cross section of which resembles a "dog bone." Since the plate is of uniform total thickness, the cladding over the thick sections at the extremities of the core is much thinner than the 0.020-in. nominal thickness. The possibility of from 0.003 to 0.005 in. of corrosion during the life of the plate necessitates the location and rejection of fuel plates which have excessive "dog boning."

The impedance curve of 6061 aluminum-alloy cladding on the uranium-aluminum-alloy core at 20 kc is shown in Fig. 17 (ORNL-LR-DWG 19110). Since the difference in the conductivities of the two materials is relatively small, the resulting impedance changes are also small. Small impedance changes are difficult to measure; therefore, the curve was enlarged and the axes shifted, by appropriate instrumentation, to such a position that the origin of the curve was at the apparent infinite thickness of the 6061 aluminum alloy as illustrated in Fig. 18 (ORNL-LR-DWG 19107). At such a position the length of the impedance vector to any point on the impedance curve, by proper calibration, can be utilized as a measure of the cladding thickness.

The Mark X probe coil which is used for this application is 7/16 in. in diameter and consists of ~ 540 turns of No. 40 enameled copper wire in a small ferroxcube cup. The coil assembly is contained in a heavy brass holder, as illustrated in Fig. 19 (ORNL-LR-DWG 18095), and the probe is spring loaded against the metal surface. The use of this mechanism eliminates spurious signals caused by by the varying coupling associated with a "hand held" probe.

The following three considerations were of primary importance in selecting an optimum test frequency for this inspection:

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[3] Nance, R. A. and Allen, J. W., "Eddy-Current Measurement of Metal Thickness and Cladding Thickness," J. Soc. Nondestructive Testing. (To be published.)

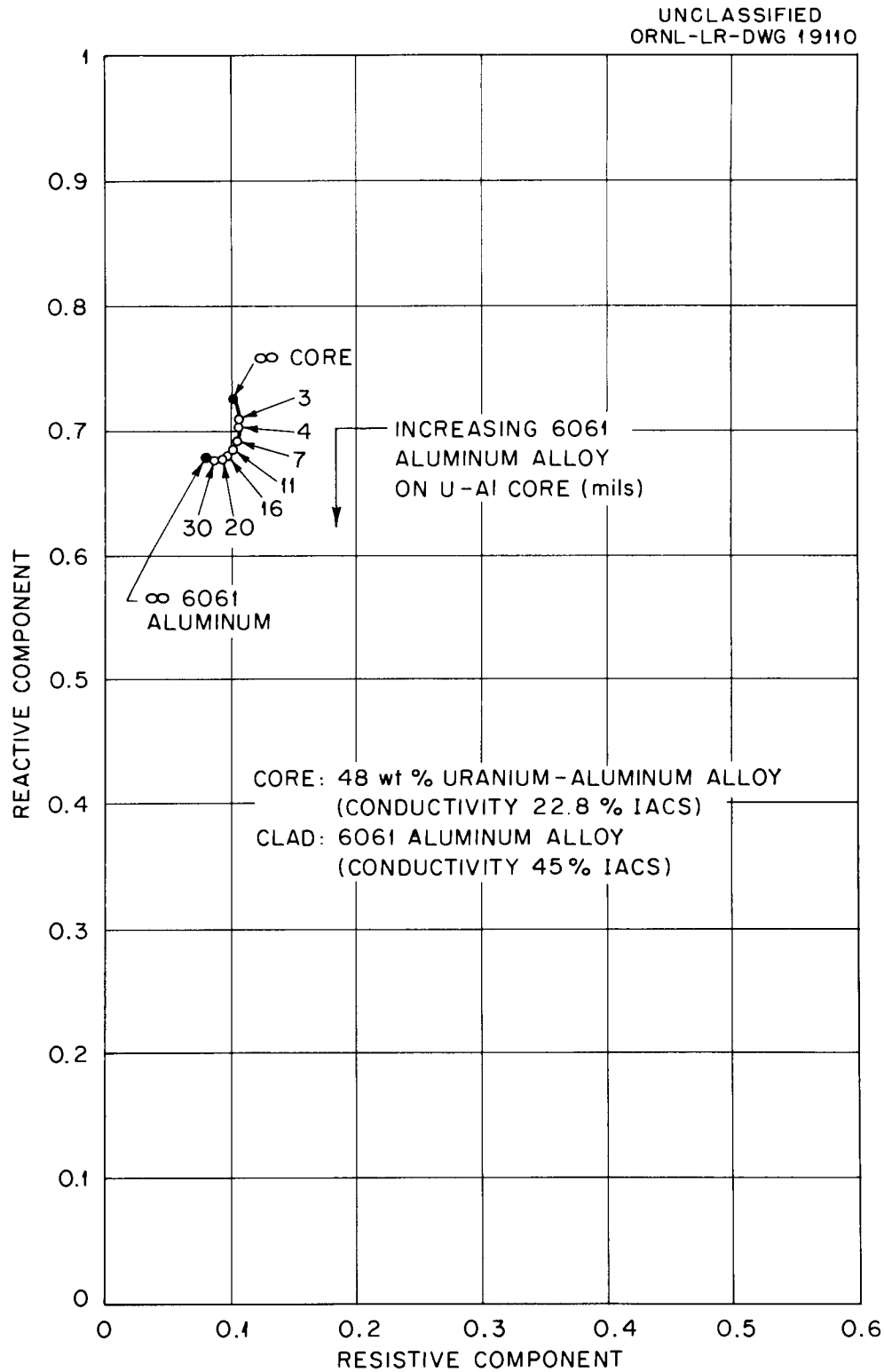

Fig. 17. Impedance Plane of Mark X Probe Coil in Presence of Mark X MTR Fuel Plate at 20 kc.

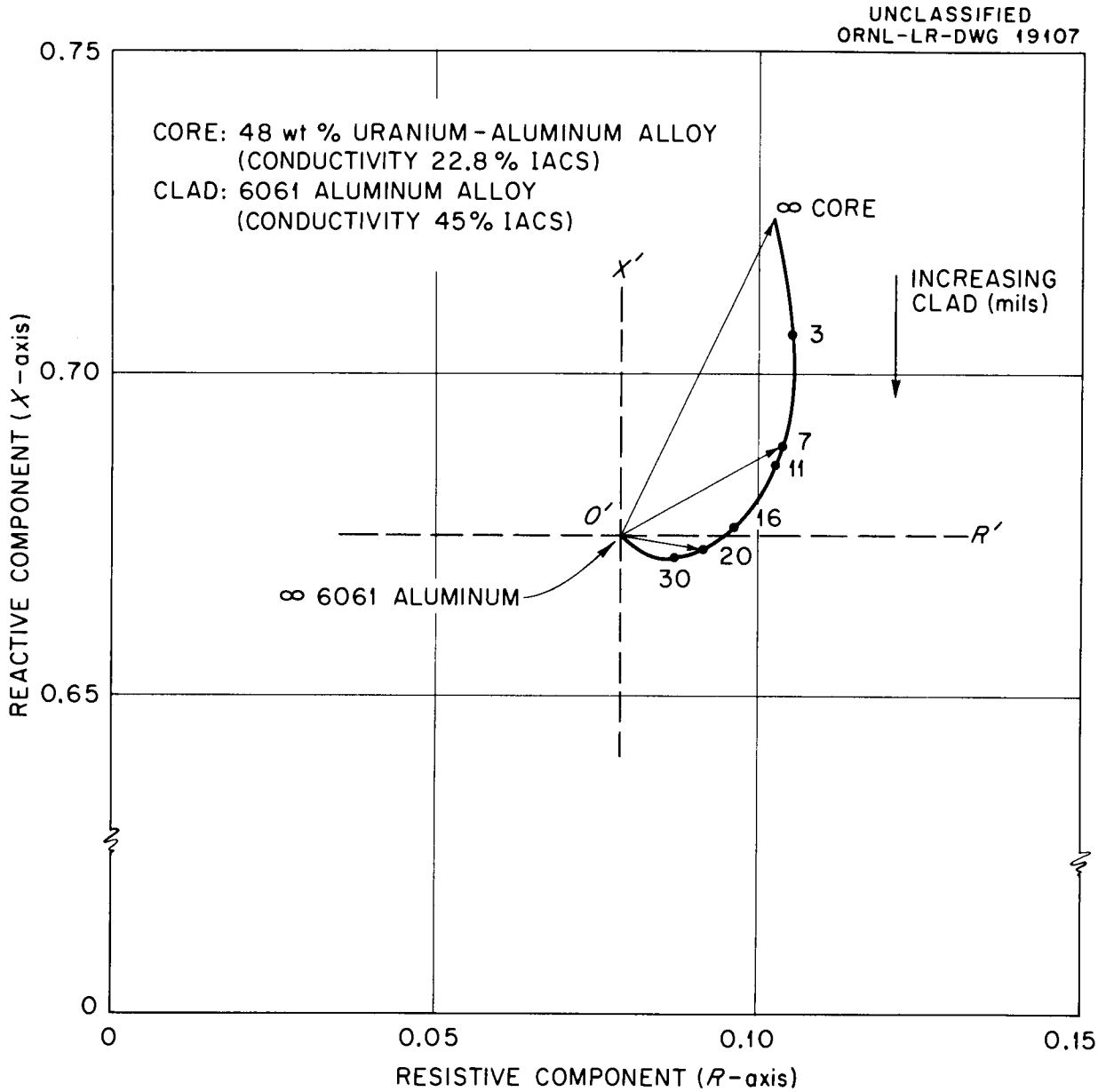

Fig. 18. Enlarged View of Impedance Plane of Mark X Probe Coil in Presence of Mark X MTR Fuel Plate at 20 kc.

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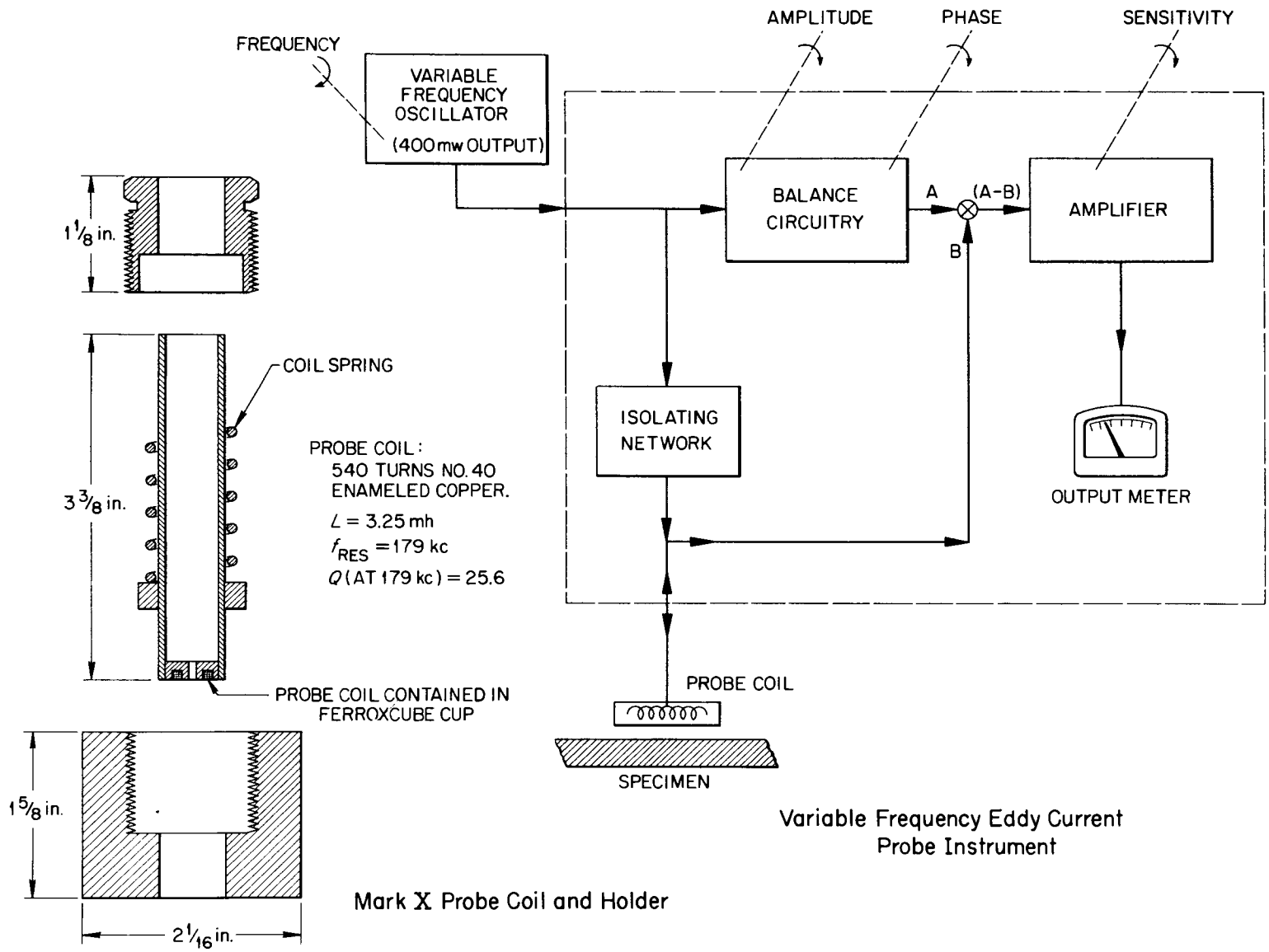

Variable Frequency Eddy Current Probe Instrument

Mark X Probe Coil and Holder

Fig. 19. Diagram of Eddy-Current Probe and Instrument.

1. A frequency sufficiently high to detect sensitively the difference between the 6061 aluminum-alloy cladding (conductivity equal 45% IACS) and the uranium-aluminum alloy core (conductivity equal 22.8% IACS).
2. A frequency sufficiently low to penetrate the nominal 0.020-in. cladding and be sensitive to small changes in its thickness.
3. A frequency sufficiently high that the 0.022-in. core underneath the 0.020-in. cladding appears infinitely thick (that is, no eddy-current penetration through the core). This is necessary to prevent the cladding thickness on the "back side" of the plate from influencing the thickness determination. A frequency of 20 kc was determined experimentally to be the optimum frequency for satisfying these conditions.

The instrument constructed for this inspection is shown in block diagram form in Fig. 19. It consists of a variable-frequency oscillator which supplies low-distortion alternating current to a balancing network and to the probe coil through an isolating network. The isolating network prevents the presence of the probe coil from affecting the voltage supplied to the balancing circuitry, and supplies the probe coil with a current of constant amplitude. Thus, the voltage at the terminals of the probe is directly proportional to its impedance, which in turn is influenced by the metal specimen.

The balancing network alters the input voltage until it is equal to the voltage of the coil, under some initial test conditions, in both amplitude and phase. This voltage is subtracted from the voltage of the coil and the net difference is amplified and indicated on a meter. Any variation in the test condition changes the coil voltage in phase or amplitude or both resulting in a deflection of the meter. In terms of the impedance curve shown in Fig. 18, the instrument was balanced while the probe coil was in contact with a thick block of 6061 aluminum resulting in a shift of both the X and R axes to the indicated X' and R' positions. As the thickness of the cladding varies, the change in the impedance of the coil causes a deflection of the meter which is proportional to the vector length from the new origin to the point on the impedance curve representing the thickness of cladding under surveillance. The gain of the amplifier

was increased until full-scale meter deflection was obtained for zero cladding thickness. With the instrument adjusted under these conditions the calibration curve shown in Fig. 20 (ORNL-LR-DWG 18096) was plotted to relate the meter deflection to the thickness of the cladding.

Several fuel plates were examined using this system and all variations from the nominal cladding thickness were marked. Four of the most significant areas on one plate were sectioned as shown in Fig. 21 (ORNL-LR-DWG 18097) and subjected to a metallographic examination for correlation and evaluation of the eddy-current measurements. Referring to Fig. 21, section 1 was taken through the thickest portion of the cladding on the core while section 2 was taken through the thinnest portion of the cladding excluding the end. Sections 3 and 4 were taken through the cladding present over the "dog bone" at the end of the core.

The results of the metallographic measurements are shown in Fig. 21. All measurements shown were made on one side of the plate only. The measurements for section 1 were made on the side of the plate containing the thickest portion of the cladding, while the remaining sections were measured on the side containing a minimum cladding. It should be noted that in all cases where the metallographic measurement differs from the eddy-current measurement, the difference is only 0.001 in.

Considerations and Limitations of Probe Coils

Several considerations and limitations must be kept in mind for any eddy-current applications utilizing surface-probe coils. These are discussed in the following paragraphs: (1) choice of operating frequency, (2) coil configuration, (3) the elimination of lift-off signals and signals from other variations which are not related to the variable under consideration, (4) the dependence of sensitivity upon the difference between conductivities of the two component metals in a cladding measurement, and (5) the necessity of adequate reference standards for instrument calibration.

1. Choice of Operating Frequency

The importance of a proper choice of operating frequency cannot be overemphasized, since the depth of penetration desired will be the determining factor in the choice of a test frequency. The only accurate method by which the choice can be made is experimental.

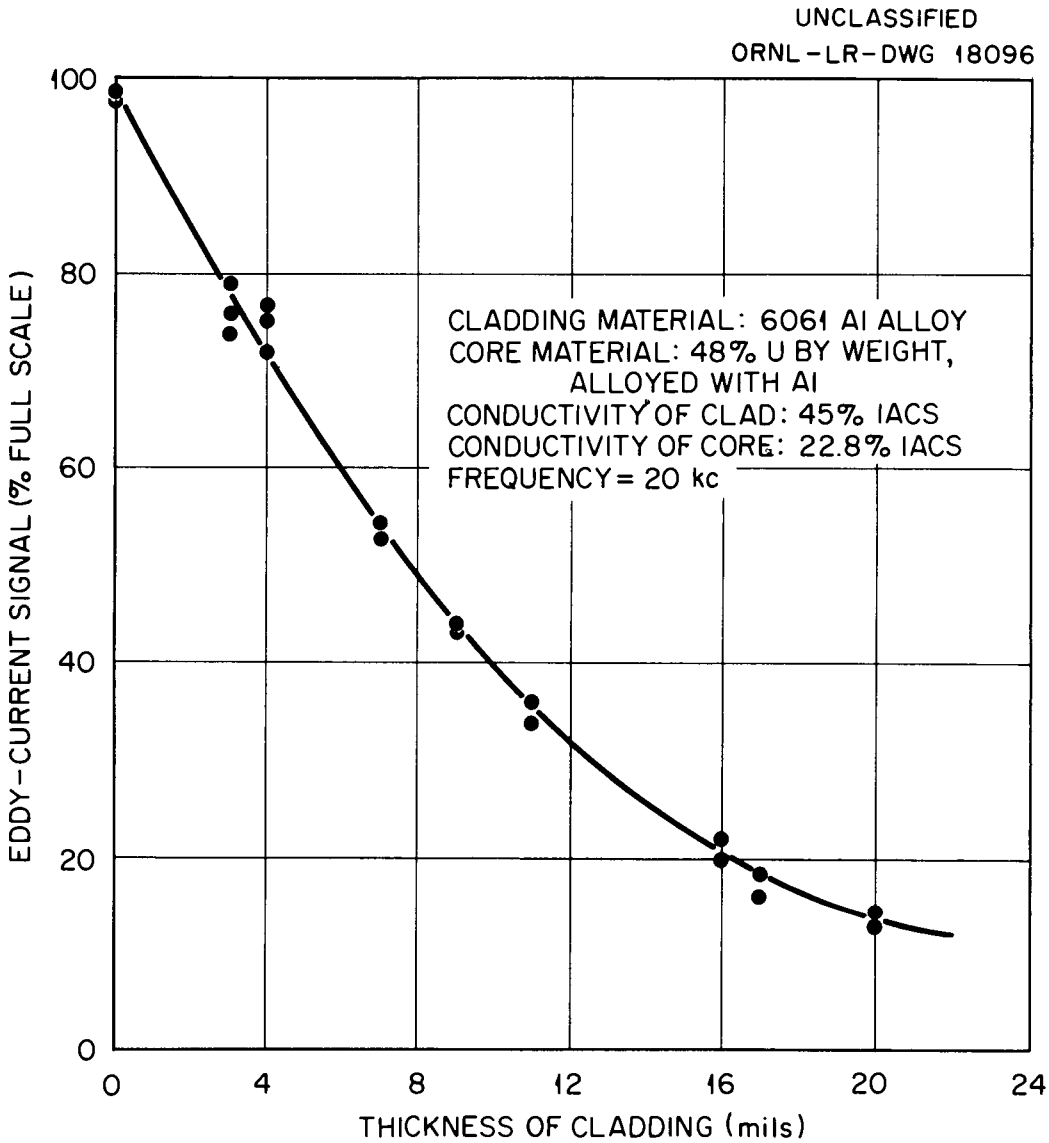

Fig. 20. Eddy-Current Signal Calibration Curve for Mark X MTR Fuel Plates.

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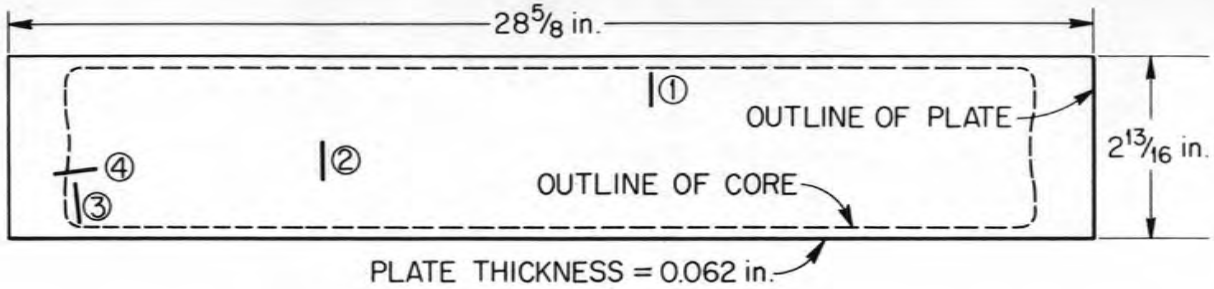

Location of Sections Taken for Metallographic Examination (Mark X MTR Fuel Plate).

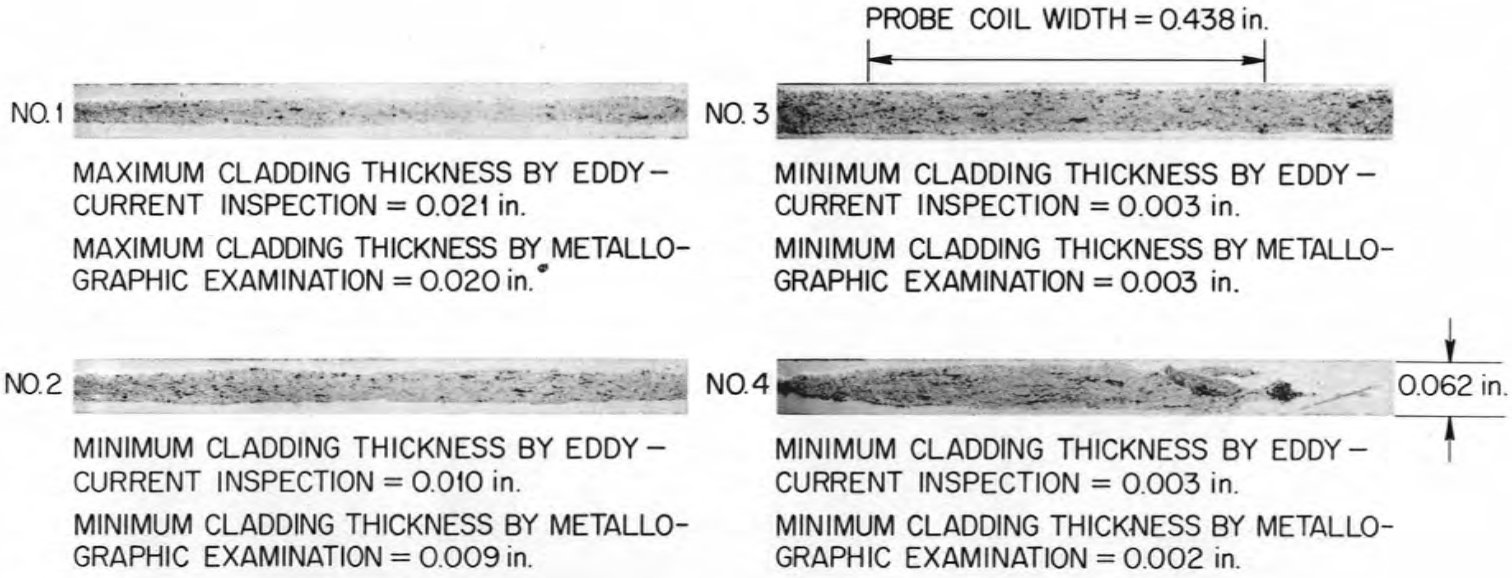

Fig. 21. Cross Sections of Mark X MTR Fuel Plates. Cladding—6061 Al Alloy.
Core—48% U by wt., Alloyed with Al.
"Original Magnification 10 X".

2. Coil Configuration

The design of the coil will be determined by the configuration of the part and the type of information desired. Secondary sensing coils may or may not be used, depending upon the choice of the design. As in frequency choice, the final design must be determined experimentally.

3. Lift-Off Signals

The elimination of lift-off signals in flat-plate inspection usually can be accomplished better by mechanical probe holders than electronically. Other applications, of course, may present problems which can be solved only by electronic methods.

4. Cladding Thickness

Since the eddy currents cannot distinguish between two metals having the same conductivity, there is a necessity of a finite difference between their conductivities. For a large difference in conductivity, cladding thickness can be easily measured. As the difference becomes smaller, the difficulty of obtaining accurate measurements rapidly increases.

5. Reference Standards

It is imperative that adequate reference materials be used for the calibration of eddy-current instruments. These materials must have received identical mechanical and thermal treatment as the part being inspected, since conductivity varies with this treatment. The preparation of reference standards for the inspection of MTR fuel plates is simplified because these fuel plates are annealed after fabrication. Shims of the cladding material and a specimen of core material therefore, are annealed prior to use as reference standards. The inspection of cladding in the "as worked" condition, however, is more difficult, since thin shims of the reference material receive more cold work during fabrication than do thick shims, and as a result they have different conductivities. The variation in conductivities introduces inaccuracies, the magnitude of which is a function of the difference between the conductivity of the reference standard and that of the part being inspected.

EDDY-CURRENT INSPECTION FOR QUALITY

This section of this paper concerns the detection and evaluation of surface and internal discontinuities and other conditions relating to quality. A large number of different techniques are in use in nondestructive testing involving special sensing coil systems and data-processing circuitry which depend upon the particular shape of the part to be inspected, or some other property peculiar to the part, for their successful utilization. Generalizations regarding these many techniques are unwarranted and in many instances very misleading. There are, however, several underlying factors which are common to most all of the techniques, and these will be discussed briefly at the risk of over-simplification. It should be understood that this discussion will exclude such tests as radio-frequency detection of surface discontinuities, the use of phenomena peculiar to magnetic material, etc.

Discontinuities may be detected in metal parts if they are situated in such a manner that they locally interrupt the flow of induced eddy currents in sufficient quantity to alter appreciably the impedance of the eddy-current coil. A very tight discontinuity which lies in a plane parallel to the direction of the eddy-current flow will not be detectable, since it will not alter appreciably the flow of current. For example, a radial crack in a tube being inspected with an encircling coil would be detectable, since it would interrupt the induced current circulating around the tube wall; but a discontinuity lying in a plane parallel to the principle surfaces of the tube would not be detectable (a gross lamination in which considerable separation occurred in the metal, of course, would be detectable).

The density of the induced currents in a metal part decreases as a function of depth below the surface of the part. The exact nature and severity of the attenuation with depth is a function of the conductivity and permeability of the part, the frequency of the exciting current, and the configuration of the part and coil system. Thus, identical discontinuities at different depths below the surface will produce impedance changes in the coil which are not identical, the signal produced by a discontinuity of given size decreasing as a function of depth below the metal surface. This phenomenon seriously hampers efforts to produce

quantitative eddy-current tests. In addition, it is quite possible that the conditions which produce the discontinuity also produce changes in the permeability or conductivity of the metal adjacent to the discontinuity which further hampers attempts to produce quantitative inspections.

Another factor which must be considered in the detection and evaluation of discontinuities is the separation of signals produced by discontinuities from signals produced by the large number of other variables in the inspection system. Since the exact nature of the signals which are obtained, and therefore, the interpretation of the signals, depend entirely upon the configuration of the part and the type of coil system employed no further generalizations are of value. The remainder of this section will be concerned with the inspection of small-diameter non-ferromagnetic tubing. This problem will be considered because of its wide application, and because it contains most of the problems which are encountered in other inspection applications.

Small Diameter Tubing

In the chart of Fig. 22 (ORNL-LR-DWG 19102) are illustrated the three basic coil systems which can be used on small-diameter tubing: the encircling or "feed through" coils, inside-probe or "bobbin" coils, and surface probe coils. Also illustrated for each case is the use of both "absolute"[4] and differential methods. The encircling-coil system is used more commonly than the other two because of the relative ease with which it may be utilized and the relatively high inspection speeds which may be obtained. The mechanical difficulties involved in the application of bobbin coils are considerable, particularly in the case of long lengths of very small-diameter tubing; however, their use may be warranted in spite of the mechanical problems for the inspection of the bore of heavy-wall tubing or duplex tubing. The surface probe coil is not in general use for the inspection of small-diameter tubing because of the inherent mechanical problems and the slow inspection speeds imposed by their use. The high sensitivity to small discontinuities

[4] This term is commonly used to convey the connotation of measurement without a direct reference, and in this usage does not carry its true definition.

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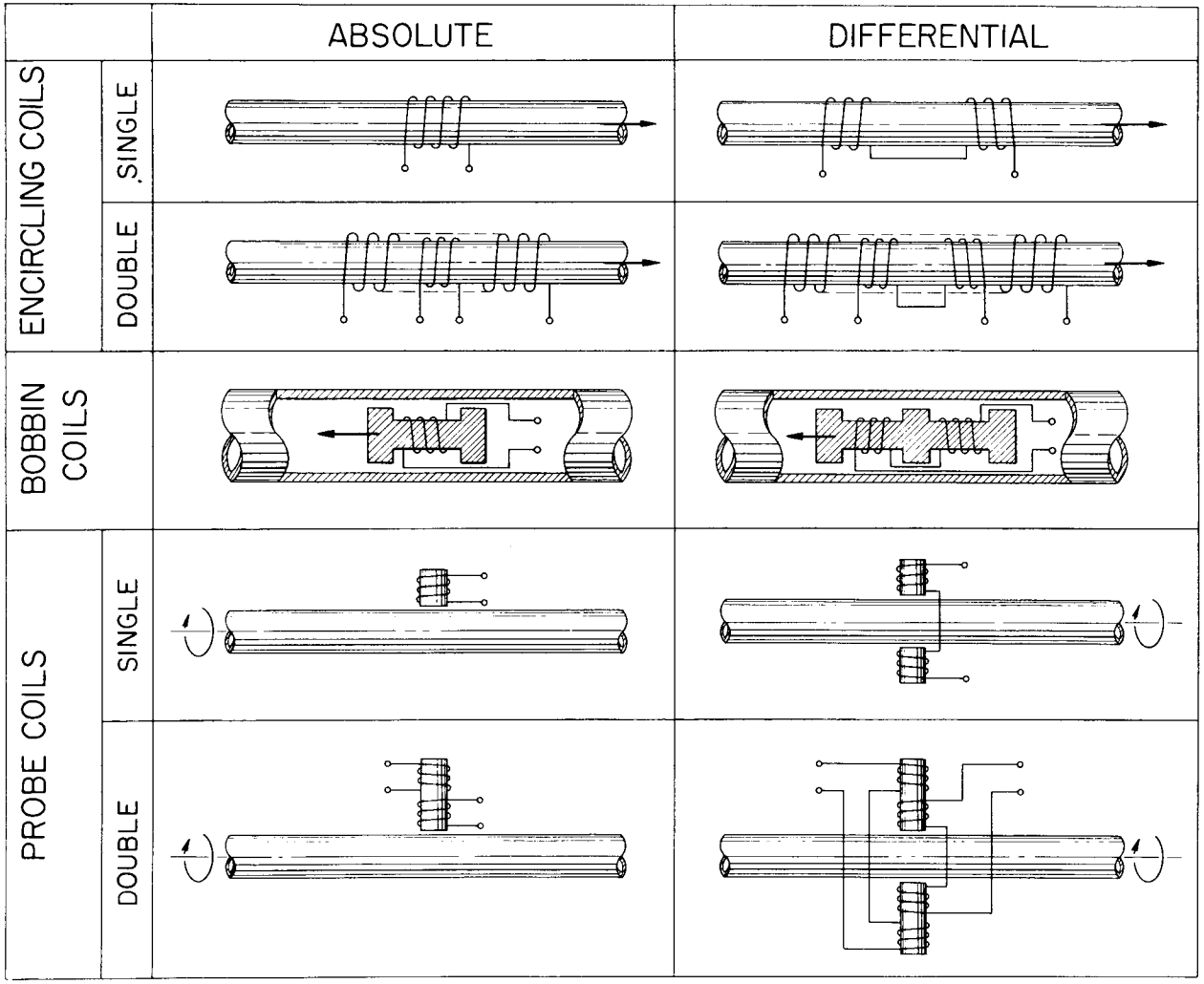

Fig. 22. Comparison of Testing Coil Configurations for Eddy-Current Testing of Small Diameter Tubing.

and the definitive ability of the surface-probe arrangements, however attractive, are largely offset by the imposed low inspection speed which makes the technique competitive with more sensitive ultrasonic techniques.[5]

The use of both single and double coil arrangements are also illustrated in Fig. 22. In the case of the double encircling-coil system, the alternating current excitation is applied to the outer coil and the voltage induced into the inner pickup coil is examined. The advantage gained by the use of this arrangement is that the pickup coil may be made very thin (having a very small dimension in the longitudinal direction) and thus be sensitive to very short discontinuities; at the same time, the exciting field may be made almost geometrically perfect,[6] in the vicinity of the pickup coil, by the use of an elongated exciting coil.

One approach to the problem of distinguishing between signals from discontinuities and those resulting from dimensional variations is the use of the differential coil system as illustrated in Fig. 22. In this scheme the signals from coils encircling two adjacent sections of the tube are subtracted; the theory of operation being that the dimensional variations occur more slowly as a function of tube length than do the discontinuities, and therefore, if the two coils are closely spaced, the signals from the dimensional variations will be eliminated. In order for the differential system to be insensitive to dimensional variations, the two coils must be very close together; all drawn tubing contains a periodic variation in both wall thickness and diameter, with a period of two to eight inches, depending upon the material, tube size, and the manufacturing processes used. Thus, if the two coils are not very close together, the dimensional signals will only be partially subtracted or possibly added.

A signal which is produced by the differential system is only a measure of the size of a discontinuity for the case in which the length of the discontinuity is less than the distance between the two coils. For discontinuities longer than the distance between the coils, the signal obtained is a measure of the size of the

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[5] Oliver, R. B., McClung, R. W., and White, J. K., "Immersed Ultrasonic Inspection of Pipe and Tubing," J. Soc. Nondestructive Testing, pp 140 – 144 (May-June 1957).

[6] A geometrically perfect field in this case is a cylinder of alternating flux parallel to the axis of the coil and of uniform density in the absence of the tube.

leading and trailing edges of the discontinuity over a length equal to the coil spacing, and a measure of the rate of change or gradient with respect to tube length and all intermediate points. Thus, the signals from such a system are sometimes difficult to interpret. This is the primary disadvantage of the differential-coil system.

Another approach to separating discontinuity signals from those produced by dimensional variations, conductivity and permeability changes, and other variations, is by the use of phase detectors or other methods of obtaining a two-component readout. The difficulty of separating the effects of diameter, wall thickness, and conductivity was shown in the preceding section on thickness measurements. To this system of variables add signals from discontinuities, and the possibility of signal separation by a two-component readout appears remote. If it is also considered that the phase angle of discontinuity signals relative to the other variations is known to vary[7] with the size and location of the discontinuity, the prospect of separating discontinuity signals from other variation signals appears impractical.

A scheme which is used quite frequently in practice for the separation of discontinuity signals from dimensional variations is that of time differentiation of the signals from the testing coil. The theory of operation is that the discontinuities, being more abrupt in nature than the dimensional variations, will produce signals having a much larger time rate of change for a given tube speed through the coil. The abruptness of discontinuity signals is illustrated in Fig. 23 (ORNL-LR-DWG 14995R) which shows an eddy-current signal trace from an absolute-coil Cyclograph-type readout. The gross crack in the 3/16-in. x 0.025-in. Inconel tube produced the sharp spike in the signal trace, which is seen to be very abrupt in comparison with the other signals. Although time differentiation is often very helpful in separating some discontinuity signals from the other unwanted signals, it should be used with caution. This technique has the disadvantage of being sensitive to the shape of the leading edge of the discontinuity. Also detrimental

[7] Hochschild, Richard, "Eddy-Current Testing by Impedance Analysis," J. Soc. Nondestructive Testing, pp 35 – 44 (May-June 1954).

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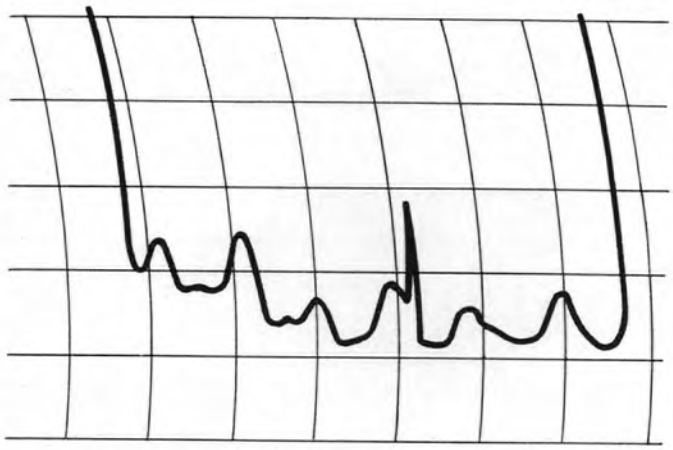

ENCIRCLING COIL EDDY CURRENT TRACE
FREQUENCY = 200 kc

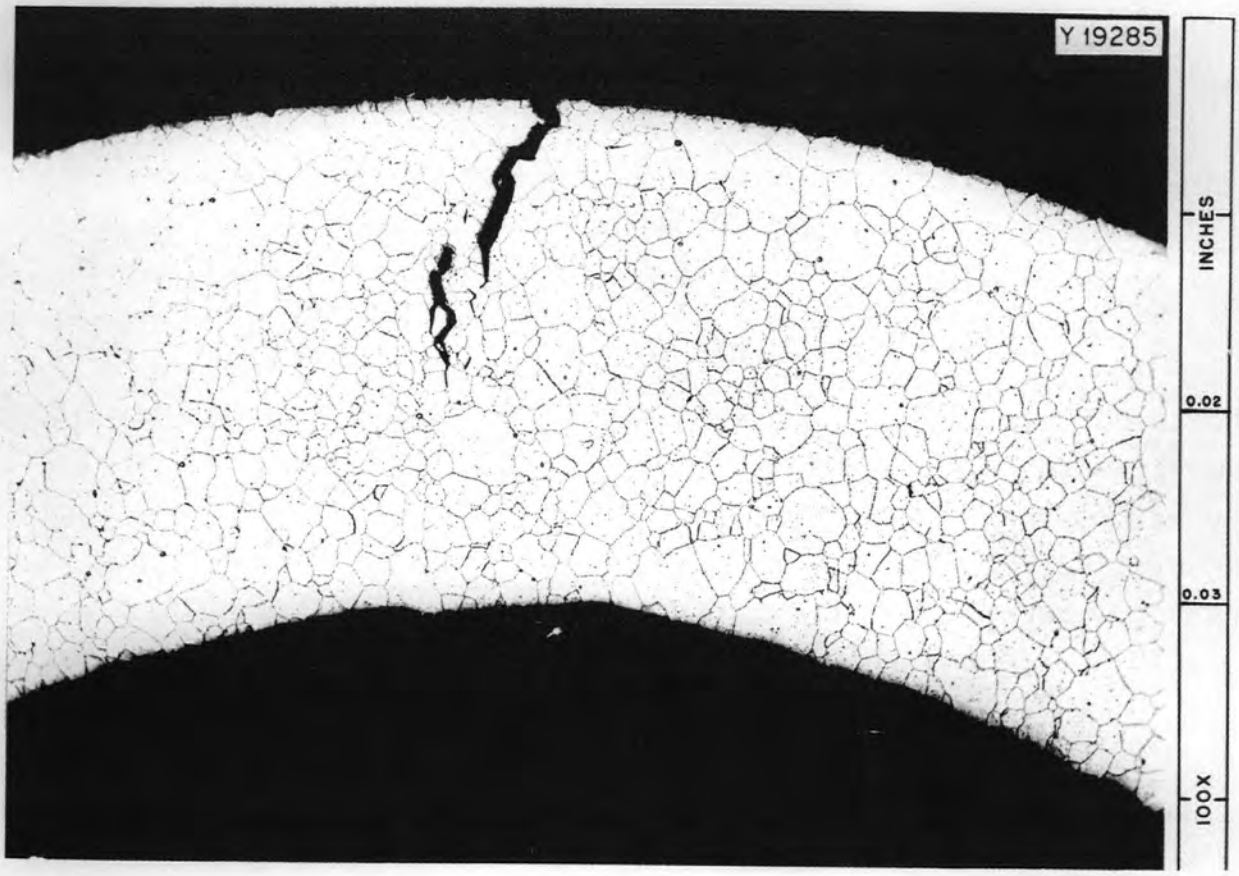

Fig. 23. Eddy Current Signal of Defective 3/16-in. x 0.025-in. Inconel Tubing.

conditions in tubing are not always abrupt. As an example consider the illustration of Fig. 24 (ORNL-LR-DWG 17573), which shows the signal trace of a 1/2-in. x 0.0625-in.-Nimonic alloy tube containing an area of 0.002-in.-deep intergranular attack on the inside surface. The signal was not differentiated and it should be noted that the signal produced by the condition of intergranular corrosion is no more abrupt than are the other smaller variations in the signal trace. Thus, a time differentiation of this signal would not have aided in the detection of the intergranular corrosion. It is advisable in situations where differentiated signals are desirable, that both direct-coupled and differentiated signals be obtained.

Since it has been shown that all of the techniques for eliminating unwanted signals have their disadvantages and limitations, the question, "How can practical eddy-current defect detection in small-diameter tubing best be accomplished?" immediately suggests itself. The answer to this question lies in the usage of a combination of the various techniques discussed. At the present stage of development, the closely spaced differential-coil system is the most effective means of eliminating signals from variations in tube dimensions and from slowly changing chemistry and heat treatment, in spite of its disadvantages. Time differentiation and other speed-sensitive circuits can be used sometimes to advantage, and if an undifferentiated signal channel is monitored also, their limitations are not objectionable. Phase-sensitive methods, including the "carrier system" introduced by Libby[8] are somewhat limited in usefulness, but can be helpful in some applications. A particularly troublesome source of undesirable signals encountered in the inspection of austenitic stainless steel tubing is the presence of localized magnetic regions. The pronounced effect of such regions is shown in the upper signal trace of Fig. 25 (ORNL-LR-DWG 29902). These signal traces were made on a 3/4-in. x 0.020-in. type 304 stainless steel tube, using a differential-coil system at an operating frequency of 50 kc. The lower trace of Fig. 25 illustrates the effectiveness of a d-c saturating field in reducing the size of the signals

[8] Libby, H. L., "Basic Principle and Techniques of Eddy-Current Testing," J. Soc. Nondestructive Testing, 14(6), 17 (November-December 1956).

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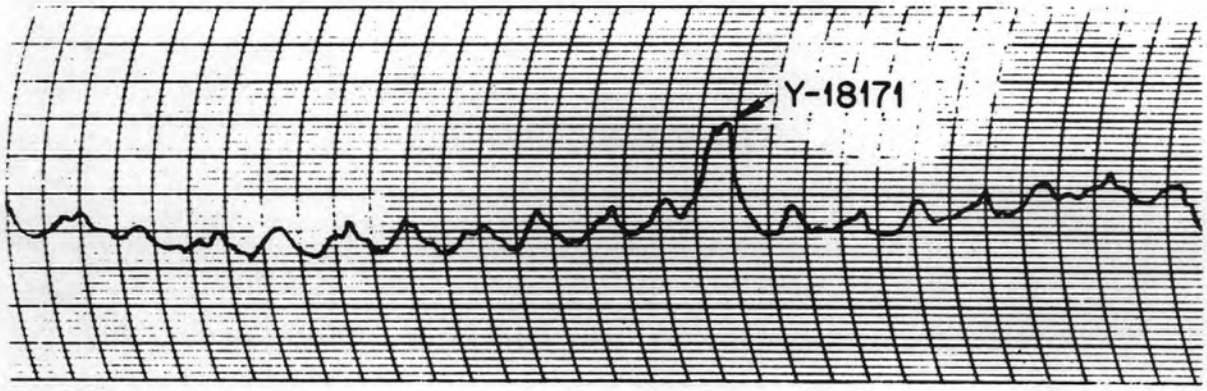

INSTRUMENTATION: CYCLOGRAPH TYPE WITH ENCIRCLING COIL
FREQUENCY: 78 kc
TUBING: ½- x 0.0625-in. NIMONIC

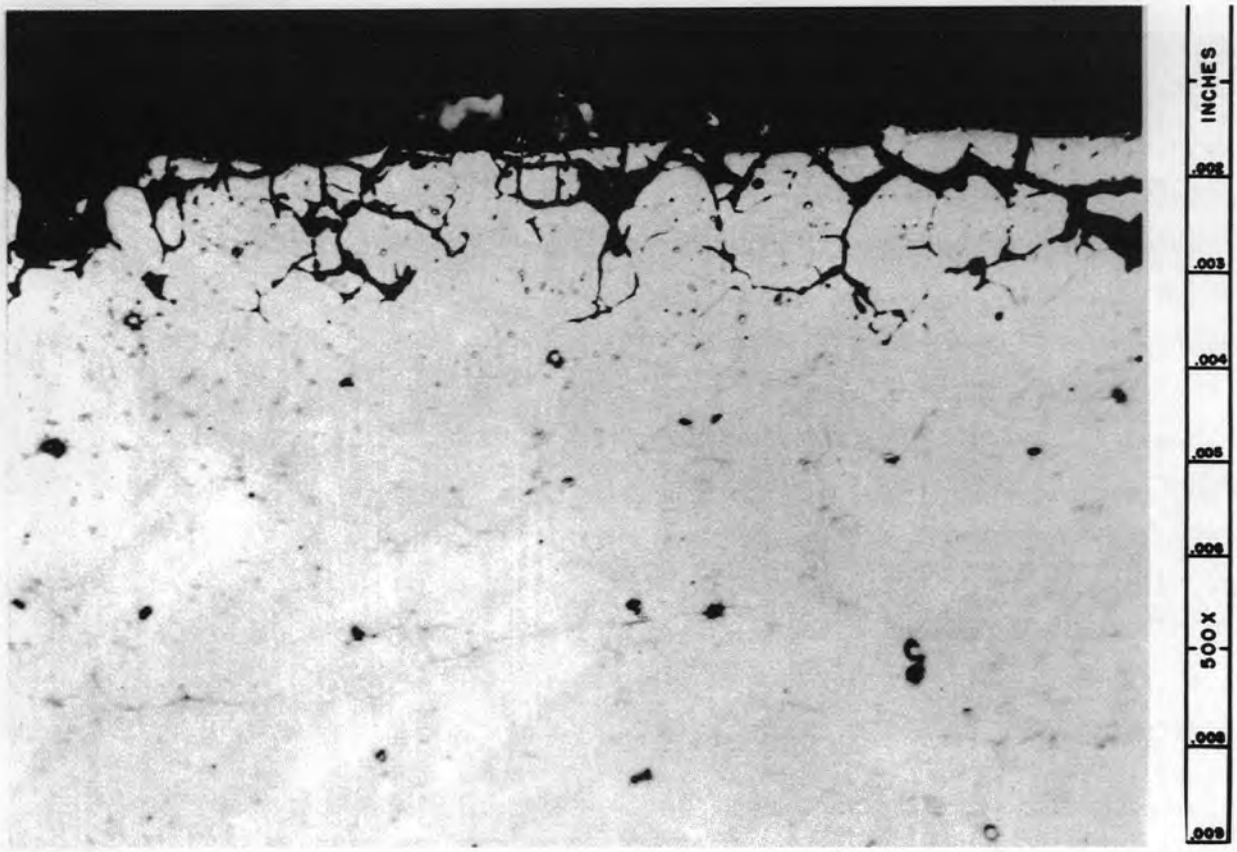

Fig. 24. Eddy Current Signal Trace of Intergranular Corrosion on Inside Surface of Nimonic Tubing.

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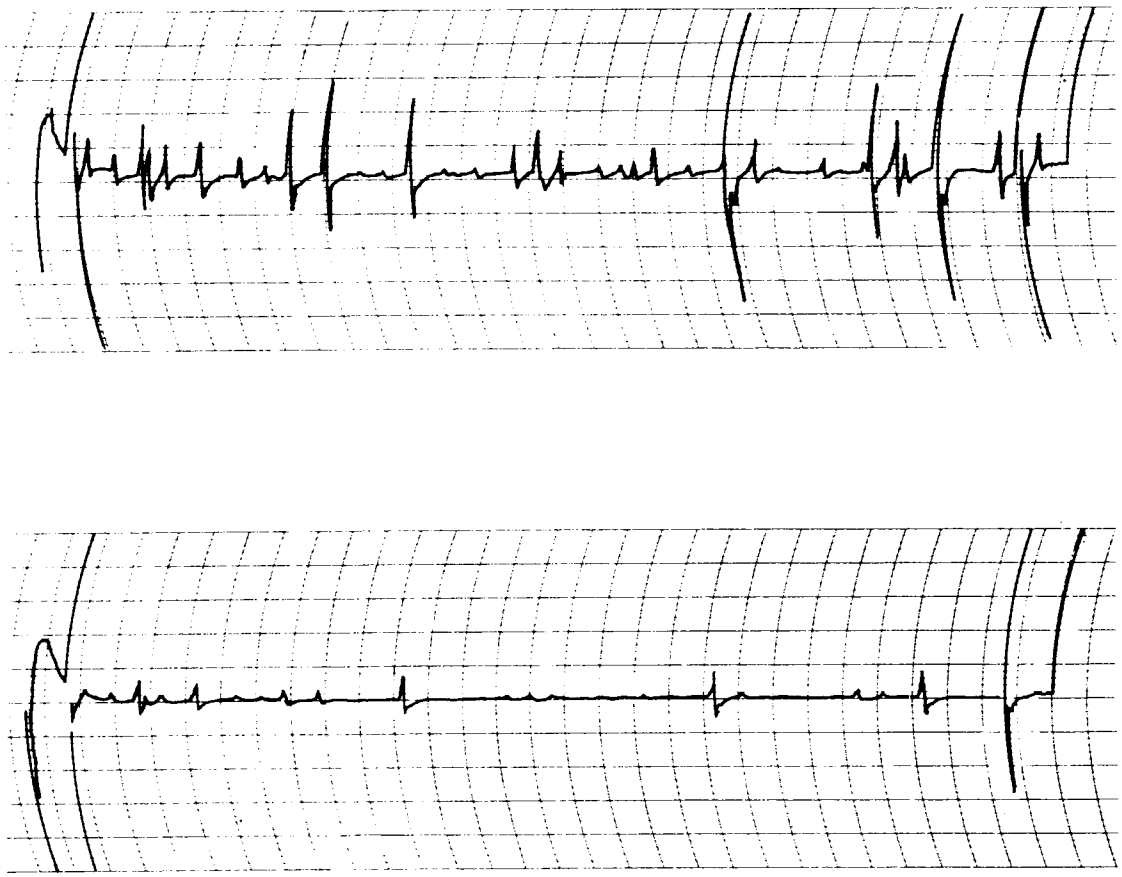

Fig. 25. Differential Coil Eddy-Current Traces of 3/4 in. x 0.020 in. Type 304 Stainless Steel Tube. Frequency = 50 kc.

from the high-permeability regions. The field used in this case was only 250 gauss which was not sufficient for complete saturation. The signals near the ends of the traces were produced by 1/32-in.-dia drilled holes through the tube wall.

In the eddy-current inspection of austenitic stainless steel and other refractory-alloy tubing, high "background noise" is often encountered as illustrated in the upper signal traces of Figs. 26 (ORNL-LR-DWG 30151) and 27 (ORNL-LR-DWG 29883). This "noise" is produced by a myriad of short, small variations in dimensions, conductivity, and permeability, and is a function of the processes used in the manufacture of the tubing. Special electronic circuits called "noise rejection circuits" can be used to advantage in interpreting the signal traces from "noisy" tubing. These circuits selectively reduce the amplification of small signals such that the signal amplification increases with the size of the signal. The effectiveness of the "noise rejection" in increasing the interpretability of the traces is shown by the comparisons of Figs. 26 and 27, the amount of rejection being higher in Fig. 27. The large signals on these traces were caused by machined, longitudinal notches on the outside surface of the tube. Although the use of "noise rejection circuits" aids in the interpretation of signal traces, it does impose an inspection of lower sensitivity to small discontinuities than can be obtained on tubing having a low-noise background.

The techniques and instrumentation of the eddy-current method for quality inspection of small-diameter tubing have not yet advanced to the level at which automation can be applied successfully. Automation cannot be applied successfully until the method is standardized to give at least, semi-quantitative indications of defect depths and lengths. The problem of standardization will be very difficult because:

1. Every variation in the tubing may produce indications which will obscure or confuse the defect indication.
2. The density of the induced currents decreases with depth into the tube wall; hence, similar defects at the inner and outer surfaces of the tube wall will give signals of different amplitudes and phases.

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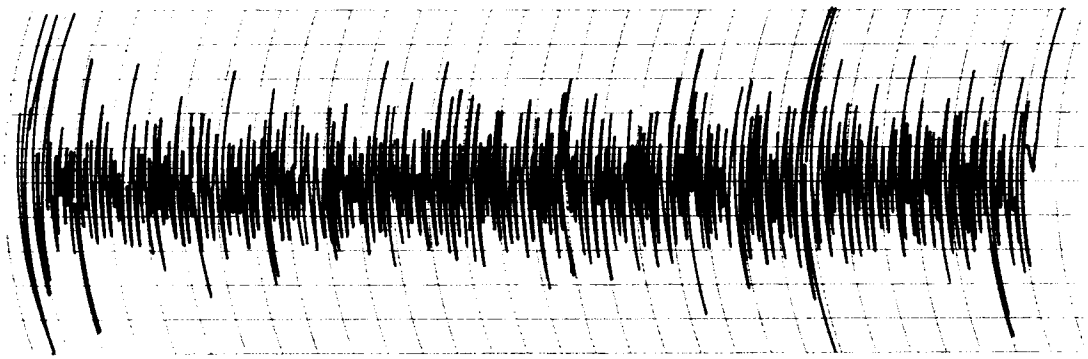
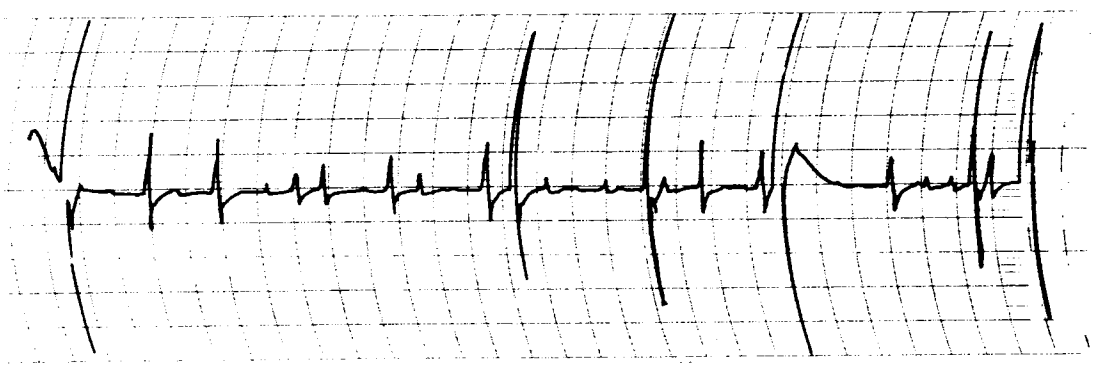


WITHOUT "NOISE" REJECTION



WITH "NOISE" REJECTION

Fig. 26. Differential Coil Eddy-Current Traces of 3/4 in. x 0.020 in. Type 304 Stainless Steel Tube. Frequency = 50 kc.

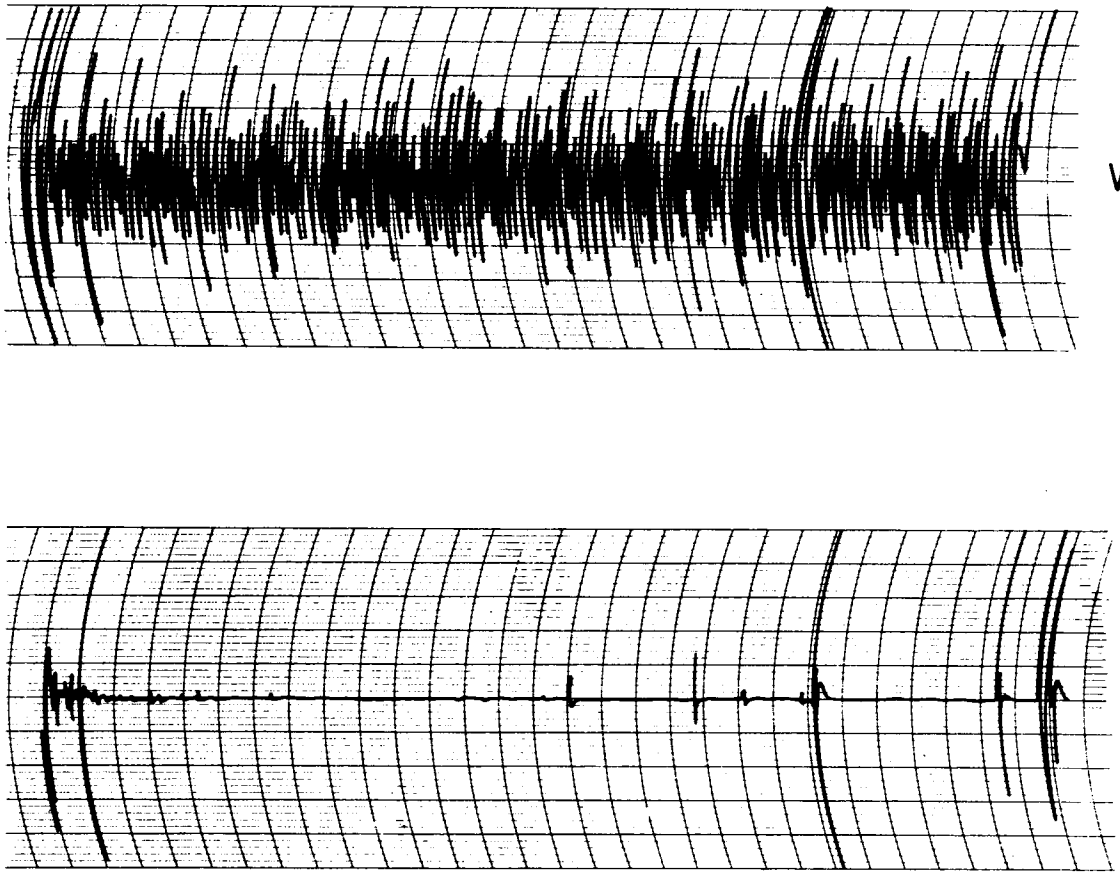


Fig. 27. Differential Coil Eddy-Current Traces of 3/4 in. x 0.020 in. Type 304 Stainless Steel Tube. Frequency = 50 kc.

The complexities of the eddy-current method make interpretation difficult unless the inspection is intended to locate only gross defects. For more critical inspection applications, the method requires the experience and judgment of trained inspectors to separate and evaluate the signals from the large number of possible variables.

CONCLUSION

The basic problem which underlies the use of eddy currents as a nondestructive testing method is the separation of variables. This problem is encountered in identifying or sorting metals, in measuring thickness or cladding thickness, or in inspecting materials for defects. In this paper the fundamentals have been discussed to explain the manner in which the many variables behave. Also several examples of practical eddy-current tests have been presented to show how the separation of effects has been accomplished in some applications.

In many eddy-current testing problems there is inherently no difficulty in measuring the variable of interest. In still others the variables are so great in number and so interrelated that the successful application borders on the impossible. In the area between these two extremes are a tremendous number of industrial problems which can be solved potentially with eddy currents. Success in solving most of these problems will be achieved through the continued development of techniques and instrumentation. Upon obtaining a satisfactory inspection with eddy currents, no other nondestructive method can match its speed, convenience, and economy.

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