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**CLAD-THICKNESS MEASUREMENT USING
DUAL-FREQUENCY EDDY CURRENT**

J. T. Hill

May 1975

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ABSTRACT

The purpose of this investigation was to determine the measurement accuracy of a dual-frequency eddy-current instrument for measuring the clad thickness of a conductor upon another conductor. The eddy-current instrumentation and measuring probe used were computer designed to minimize effects due to lift off and electrical conductivity (or resistivity) variations, and maximize the sensitivity to clad-thickness variations. The purpose of using two frequencies was to measure both the conductivity and thickness of the clads and to use the conductivity measurements to correct the thickness measurements for errors due to conductivity variations.

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SUMMARY

The purpose of this investigation was to determine the measurement accuracy of a dual-frequency eddy-current instrument for measuring the clad thickness of a conductor upon another conductor. The eddy-current instrumentation and measuring probe used were computer designed to minimize effects due to lift off and electrical conductivity (or resistivity) variations, and maximize the sensitivity to clad-thickness variations. The purpose of using two frequencies was to measure both the conductivity and thickness of the clads and to use the conductivity measurements to correct the thickness measurements for errors due to conductivity variations.

The experimental data were obtained from clads of two different conductivities and of various thicknesses. The base material had a conductivity value different from either of the clads. The resistivity ratios between the two different clad materials and the base material were approximately $1/2$ and $1/3$. The effect due to variation of lift off was minimized with a compensating circuit.

Responses from the measurements were in terms of voltage-phase shifts. These phase shifts were later applied to a set of linear equations which were solved simultaneously to give an expression representing thickness. The constants in this expression were then set in a computer module, which plugs into the eddy-current instrumentation. The computer module used the constants and the measured phases to calculate the thickness of the clads.

It was determined that the dual-frequency technique measured clad thicknesses with better than a 99% accuracy. This accuracy is indicative of the thickness range incorporated in the phase responses applied to the set of linear equations.

INTRODUCTION

Use of eddy currents for inspecting metal soundness, electrical properties, and thickness is widely used in many metal industries. This study, performed at the Oak Ridge Y-12 Plant,^(a) investigated the thickness measurement of clads. Generally, there are two techniques used in the evaluation of clad thickness. The first technique evaluates the clad thickness as a function of a voltage magnitude change; the second technique determines clad thickness as a function of a voltage phase change or shift. Both techniques make use of a bridge circuit which is either operated in a balanced or unbalanced mode. That is, a change in thickness will either unbalance or balance the bridge circuit. Basically, what takes place in the operation of both techniques can be described simply as follows: An electromagnetic field is generated by an electromagnetic probe. When the probe is placed in the vicinity of a metallic test object, the electromagnetic field is modified by the electrical properties of the test object. The modified field is then sensed by the probe upon reflection from the test object. Presence of the reflected field causes a voltage change to be produced at a bridge circuit. This voltage changes the original balance or unbalance of the bridge which can be detected with an indicator. Of course, this simplified explanation omits the complicated details. More will be said about this operation later.

Both techniques, in addition to being sensitive to thickness variations, are sensitive to the electrical conductivity (or resistivity) and magnetic permeability of the metal, and to lift off (the distance between the measuring probe and the metal). However, the phase-sensing technique is not as sensitive to lift off as the magnitude technique. Variations in lift off encountered in the latter technique usually cause gross errors in the measurement of either of the other parameters just mentioned. The undesired response due to lift off may be electronically compensated for in the phase technique.

Phase-sensing eddy currents have been further developed to include the simultaneous use of two or more electromagnetic fields at different frequencies. This multiple-frequency technique can be used to eliminate the response of one or more unwanted parameters while maximizing the response of a desired parameter. One example of this technique would be the measurement of a clad thickness using two different frequencies simultaneously. In such a case, a high and low frequency would be employed to measure resistivity and thickness, respectively.

This report describes an investigation involving the measurement of cladding thickness using the dual-frequency eddy current. Bronze was the cladding material used in this experiment. The clads were measured on a base material which will be referred to as Alloy 180. No practical application was considered in the use of these materials in this investigation. Two different bronze alloys with distinct resistivity values were measured separately on the Alloy-180 base. The resistivities of the two clads were determined experimentally with a single-frequency, phase-sensing, eddy-current system. A dual-frequency system was set up to

(a) Operated by the Union Carbide Corporation's Nuclear Division for the US Energy Research and Development Administration.

measure the thickness variation of the cladding material upon the base. The frequencies used were determined with the aid of a computer program designed to help analyze eddy-current measurements of cladding thickness.^(b) The eddy-current system parameters were determined by the same computer program.

The measured thickness values were analyzed and compared to the mechanical measurements.

(b) Dodd, C. V., Cheng, C. C., Simpson, W. A., Deeds, D. A., and Smith, J. H.; *The Analysis of Reflection Type Coils for Eddy-Current Testing*, ORNL-TM-4107 (April 1973).

EDDY-CURRENT MEASUREMENT OF CLAD THICKNESS

THEORY

Electromagnetic Induction

The basic principle involved in the eddy-current inspection of a metal test object is electromagnetic induction. The test probe, which essentially is an electromagnet, generates a varying electromagnetic field. The direction and magnitude of the field depend, largely, on the geometry of the test probe. The test probes discussed here are of the reflection type. These probes usually consist of a metal core wound with a current-conductive wire, forming a circular coil. In this particular case, the magnitude of the generated field depends on the number of turns in the coil of wire and the magnitude of the current flowing in the wire. The varying electromagnetic field causes a varying current to be generated in an electrically conducting test object placed in the immediate vicinity of the probe. Just as in the probe, the current flowing in the test object generates a secondary field. If the test object is nonmagnetic, the secondary field will oppose the primary field generated by the probe. The extent of this opposition depends on the electrical conductivity and size of the test object, and on the operating frequency of the test probe. Figures 1 and 2 illustrate a test probe with and without a test object, respectively. Note that the primary field of the test probe above the test object has been drawn to indicate an effective reduction in magnitude due to the presence of the secondary field of the test object. In addition to a change in magnitude, the primary field also suffers a change in phase. The excitation current of the test probe above, in air, is in phase with the primary field of the test probe. A secondary field, which modifies the primary field, is generated as a result of the presence of the test object; thus, a change in phase between the modified primary field and the excitation current is the outcome, shown vectorially in Figure 3. Note also that the voltage of the test probe coil is changed. The voltage, E_p , of the probe in air lags the excitation current, I , by 90 electrical degrees. The eddy currents induced in the test object generate a secondary magnetic field, ϕ_s , and its associated induced voltage, E_s , which lags the field by 90 electrical degrees. In Figure 3, the lagging direction is increasing in the clockwise direction. The vectorial sum of the two voltages is shown in the latter figure. The primary voltage, E_p , is usually subtracted from the total voltage, E_T , in practice. The lengths of the arrows represent the amplitudes of the voltages, while the directions represent the phases. It is these changes of voltage amplitude and phase that are measured in eddy-current inspection.

The primary coil voltage, E_p , is the product of the current, I , flowing through the coil and the total impedance, Z , across the coil circuit. A simple coil circuit may be represented, as noted in Figure 4(a). The impedance of the circuit can be divided into two components: the resistance (measure of the current opposition across the resistor in the circuit) and the reactance (measure of the circuit opposition across the inductance in the circuit). The coil voltage, E_p , is actually the sum of the voltages across these two circuit components. As shown in Figure 4(b), the resistive component lags the reactive component by 90 degrees. Expressed vectorially, the voltage, E_p , is the vector sum of the resistive component, E_R . In terms of impedance, the vectorial representation may be diagrammed, as shown in Figure 4(c), where R is the resistance, X the reactance, and Z the impedance.

Figure 1. TEST PROBE ABOVE A CONDUCTOR.

Magnitude Contours of an Electromagnetic Field
Figure 2. TEST PROBE IN AIR.

Figure 3. MAGNITUDE AND PHASE ANGLE OF THE COIL VOLTAGE.

The value of the reactance is equal to the product of the angular frequency, $2\pi f$, and the inductance, L , of the circuit, thus:

$$X = 2\pi fL \quad (1)$$

The impedance is then given by:

$$Z = R + jX, \text{ or} \quad (2)$$

$$Z = R + j2\pi fL ,$$

where j represents the imaginary axis. The magnitude of the impedance is:

$$Z = \sqrt{R^2 + X^2}, \text{ and the phase is:} \quad (3)$$

$$\theta = \tan^{-1} \frac{X}{R} = \arctan \frac{X}{R} .$$

Figure 4. A SIMPLE COIL CIRCUIT.

Dodd, et al derived an expression for the voltage output of an eddy-current reflection-type probe. The expression is:

$$\begin{aligned}
 V_{out} = & -j \frac{MV_0 R_9 G}{\omega C_6 C_7} \div \left\{ \left(R_0 - \frac{j}{\omega C_6} \right) \omega^2 M^2 \left(R_9 - \frac{j}{\omega C_7} \right) \right. \\
 & + \left[\left(R_0 - \frac{j}{\omega C_6} \right) \left(Z_0 + R_6 - \frac{j}{\omega C_6} \right) + \frac{1}{\omega^2 C_6^2} \right] \\
 & \times \left[\left(R_9 - \frac{j}{\omega C_7} \right) \left(Z_{pu} + R_7 - \frac{j}{\omega C_7} \right) + \frac{1}{\omega^2 C_7^2} \right] \left. \right\}. \quad (4)
 \end{aligned}$$

Figure 5 shows the simplified circuit diagram that was used in the derivation of this expression; Figure 6 shows a typical physical arrangement of a reflection-type probe above a conductor. Included in Figure 6 is a simplified circuit diagram of the same physical arrangement.

Impedance Analysis

As mentioned earlier, the magnitude and phase of the primary voltage are usually subtracted from the measured coil signal. Let us, at this point, make an impedance analysis of a simple

- V_0 Driving Voltage
- R_0 Series Resistance in the Driving Circuit
- C_6 Shunt Capacitance of the Driving Circuit
- R_6 DC Resistance of the Driver Coil
- Z_D Impedance of the Driver Coil
- M Mutual Impedance Between the Driver and Pickup Coils
- Z_{PU} Impedance of the Pickup Coils
- R_7 DC Resistance of the Pickup Coils
- C_7 Shunt Capacitance of the Pickup Circuit
- R_9 Amplifier Input Impedance

Figure 5. SIMPLIFIED CIRCUIT DIAGRAM FOR AN EDDY-CURRENT REFLECTION-TYPE PROBE.

Figure 6. PHYSICAL ARRANGEMENT OF AN EDDY-CURRENT PROBE ABOVE A CONDUCTOR; ALSO, ELECTRICAL CONNECTIONS IN THE PROBE.

probe circuit placed above a secondary circuit of resistance R_2 and inductance L_2 . The secondary circuit, for all practical purposes, represents a simple conducting loop. Figure 7(a) shows, schematically, the two circuits. The impedance of the primary coil can be found, as noted in Figure 4(c). If the secondary circuit parameters are added, the new phasor diagram would look like that shown in Figure 7(b). Here, the secondary resistance, R_2 , is added to R_1 , and the secondary inductance, L_2 , is added to L_1 . At the two limits of R_2 (that is, at zero and infinity), the impedance is the same as that shown in Figure 4(c). However, as R_2

Figure 7. CIRCUITRY FOR THE IMPEDANCE ANALYSIS OF A PROBE ABOVE A CONDUCTOR.

is varied from infinity to its zero value, the impedance vector, Z , will follow the path of a circular locus. Figure 8(a) shows such a locus. The same locus could also represent a variation in conductivity, since the resistivity is equal to the reciprocal of the conductivity. The electromagnetic coupling, M , between the two circuits causes a current to flow in the secondary circuit. The current flow sets up a secondary field which opposes and weakens the effect of the primary field. The inductive reactance sensed by the primary circuit is effectively decreased as a result of the decrease in the primary field strength. However, in the case of a solid conductor under the probe, the impedance locus follows a locus somewhat different from that shown in Figure 8(a). The locus looks more like that of Figure 8(b). This difference is due to the greater decrease of the reactance component of the impedance at decreasing resistivity (or increasing conductivity).

Let us turn our attention now to variations of thickness of a solid conductor under an eddy-current probe. Figure 9 shows a typical thickness locus. Note that the end with the high-conductivity value has more of a spiral-like shape than the conductivity locus shown in Figure 8. This variation in locus shape is due, mainly, to two factors—skin effect and shape of the probe coil. Both factors essentially reduce the current density in the conductor as the depth below the surface increases. The current density decreases exponentially with the increasing depth below the surface. The eddy currents generated in the conductor at some depth, X_a , produce a magnetic field at some greater depth, $X_a + \Delta X$. The field opposes the primary field, which weakens the current flow. The current flow gets progressively weaker as the depth of the magnetic field penetration increases. The current density at any depth, X , can be expressed by:

$$J_x = J_0 \text{Exp} \left(-X \sqrt{\pi f \mu \sigma} \right), \quad (5)$$

where J_0 represents the current density at the surface, f the probe operating frequency, μ the magnetic permeability of the conductor, and σ the conductivity of the conductor. The decrease in current density due to depth is associated with the skin effect; reduction due to the coil shape is caused by a cancellation effect on the current flowing on both sides of the coil. The more symmetric the coils, the more cancellation takes place. The majority of the spiraling is due to the skin effect.

Figure 8. REACTANCE VERSUS RESISTANCE FOR RESISTIVITY (OR CONDUCTIVITY) VARIATIONS.

Figure 9. REACTANCE VERSUS RESISTANCE FOR THICKNESS VARIATIONS.

Multiparameter Inspection

Variation in phase with a variation in the resistivity and thickness over a 10% range is fairly linear. Response of both these variables may be represented by linear equations. As mentioned previously, the difference in the phase of the input and output voltages is measured to indicate the value of a parameter using the phase-sensing eddy-current technique. The linear equations, thus, express a relation between the two said variables and their phase-shift response. The equations may be written as:

$$P_h = t T_h + \rho S_h, \text{ and} \quad (6)$$

$$P_l = t T_l + \rho S_l, \quad (7)$$

where P_h and P_l represent the phase at high and low frequencies, respectively, T_h and T_l represent the linear response of the phase shift with thickness at high and low frequencies, S_h and S_l represent the linear response of the phase shift with resistivity (or conductivity) at high and low frequencies, and t and ρ represent the thickness and resistivity, respectively. The two equations may be solved simultaneously for either t or ρ as follows:

$$t = \frac{\begin{vmatrix} P_h & S_h \\ P_l & S_l \end{vmatrix}}{\begin{vmatrix} T_h & S_h \\ T_l & S_l \end{vmatrix}} = \frac{P_h S_l - P_l S_h}{T_h S_l - T_l S_h}, \text{ or} \quad (8)$$

$$\rho = \frac{\begin{vmatrix} T_h & P_h \\ T_l & P_l \end{vmatrix}}{\begin{vmatrix} T_h & S_h \\ T_l & S_l \end{vmatrix}} = \frac{T_h P_l - T_l P_h}{T_h S_l - T_l S_h} \quad (9)$$

Thus, the measurement of one variable may be made completely independent of the other. The constants, T_h , T_l , S_h , and S_l , must be determined, however, by computer calculation or by experimental measurements of known conductors. Once these constants are found, Equations 8 and 9 may be written as:

$$t = a_1 P_h - a_2 P_l, \text{ or} \quad (10)$$

$$\rho = a_3 P_l - a_4 P_h, \quad (11)$$

where:

$$a_1 = \frac{S_l}{T_h S_l - T_l S_h},$$

$$a_2 = \frac{S_h}{T_h S_l - T_l S_h},$$

$$a_3 = \frac{T_h}{T_h S_l - T_l S_h}, \text{ and}$$

$$a_4 = \frac{T_I}{T_h S_I - T_I S_h}$$

Sources of Undesirable Effect Encountered in Eddy Currents

As mentioned previously, the phase-sensing eddy-current technique produced less error due to lift-off variation than the magnitude technique. Lift off is usually the main undesirable variable encountered in thickness measurements. Such factors as metal surface finish, tilting of the measuring probe, and surface flatness cause changes in the probe-to-conductor spacing, or lift off. Such factors are also common in industrial thickness-measurement setups.

One other factor that causes large errors in thickness measurements using the magnitude technique is variation in the coil DC (direct current) resistance. At low frequencies, the DC resistance of the coil can be as high as its impedance value. Again, the phase-sensing technique minimizes the thickness-measurement error due to such variations.

Now, a discussion of the error in thickness measurement due to variations in metal conductivity is in order. It should be pointed out here that a cladding-thickness measurement is the measurement of the thickness of one conductor upon another. Measurements of a conductive coating on a conductor and a conductor placed atop another conductor are examples of cladding-thickness measurements. The greater the ratio between the conductivities of the conductors, the greater the measuring sensitivity to the cladding thickness. Dodd's report^(c) shows, graphically, how the thickness-measuring sensitivity varies with the conductivity ratio of the cladding material and the base material. Figure 10 simply combines several of Dodd's graphs to show this variation. Ratios of 10, 2, 1.25, 0.5, and 0.1 are shown here. As shown on the graph and pointed out in his report, there is adequate sensitivity when the conductivity ratios are as close to 1 as 1.25. The curves on the graphs represent the phase shift at maximum sensitivity for a 10% cladding-thickness change versus cladding thickness divided by the probe radius, r , for various conductivity ratios. These curves also depict some other very important factors in eddy-current-cladding-thickness measurements. These are also discussed in Dodd's report. Note that, on the graph, there are two inverse pairs; that is, 10 and 0.1 and 2 and 0.5. This, of course, simply means in one case a more-conductive metal was placed upon a less-conductive base (ratios 10 and 2). In the other case, a less-conductive metal was placed upon a more-conductive base (ratios 0.1 and 0.5). An impedance analysis can be made to depict these two cases. Let us assume that Metal A is more conductive than Metal B (Figure 11). When Metal A is placed upon Metal B and increases in thickness, the impedance point moves along the Curve AB from B to A; when Metal B is placed upon Metal A and increases in thickness, the impedance point moves along the Curve BA from A to B. In either case, the base metal is sensed by the measuring probe until the cladding metal is too thick to penetrate.

(c) Dodd, C. V.; *Basic Principles of Eddy-Current Testing*; March 27, 1972.

Figure 10. PHASE SHIFT AT MAXIMUM SENSITIVITY FOR A 10% CLADDING THICKNESS CHANGE VERSUS CLADDING THICKNESS, $\bar{r}$, FOR VARIOUS CONDUCTIVITY RATIOS.

CLADDING THICKNESS MEASUREMENT

Introduction

A computer-designed probe and eddy-current system were used to measure the cladding thickness of two different bronze samples on a base material. The base material, which will be referred to as Alloy 180, had an electrical resistivity value of 28.22 microhm-cm. Electrical resistivities of the two bronze claddings were determined experimentally. The claddings, which will be referred to as Clad C and Clad D, were found to have resistivity values of 15.56 and 9.63 microhm-cm, respectively. Following the resistivity determinations, each cladding thickness was measured using a dual-frequency eddy-current system.

Apparatus

A modular, dual-frequency, phase-sensitive eddy-current system was used to make the cladding-thickness measurements in this investigation. Figure 12 presents a block diagram of the instrument. The oscillator and power-amplifier module provides signals for excitation of the driver coil in the probe. This stable sinusoidal voltage signal passes through an attenuator before reaching the eddy-current probe. The probe and cladding conductor are physically arranged, as shown in Figure 6. The signals fed to the driver coil induce currents within the

Figure 11. TWO-LAYER THICKNESS LOCI.

cladding conductor at two different frequencies. The cladding conductor, in turn, generates a secondary electromagnetic field which modifies the primary field and signal at the driver coil. This action modulates the pickup coil output signal. The modulated signal carries with it information about the condition of the cladding conductor. The pickup coil output signal passes through another attenuator into a video amplifier where it is amplified to a suitable magnitude.

The oscillator and power amplifier module, in addition to providing a signal to the driver coil, simultaneously feeds a signal to the discriminator. The discriminator (a compensating circuit) makes it possible to adjust the signal from the video amplifier. Since the same signal that goes to the driver coil is fed to the discriminator, the latter circuit can be adjusted to null out the signal received from the video amplifier. The phase shift between the reference input voltage signal and the detected output voltage signal is measured in the discriminator.

Figure 12. DUAL-FREQUENCY CONFIGURATION FOR THE MODULAR, PHASE-SENSITIVE EDDY-CURRENT INSTRUMENT.

Since the initial input signal carries two frequencies, two discriminators and two video amplifiers were used

The signals from the two discriminators are then fed to a filter-computer module and a digital panel. At this stage, the signals are separated by wave filters having passbands centered at the two excitation frequencies. A fixed set of four predetermined constants are set in on the front panel of the computer module. The computer uses these constants, along with the measured phase shift, to calculate the cladding thickness and conductivity. Equations 8 and 9 represent the transformation from phase-shift response to the calculated parameters—thickness and conductivity—respectively. The calculated parameters are then fed to the digital panel meter where they are displayed for recording.

Following is a list of the specific modules used in this investigation:

1. Dual-Frequency Oscillator and Power Amplifier (DPA-2) - This unit provides a stable, low-distortion signal with an amplitude of 10 volts peak to peak and a frequency range from 1 kHz to 5 MHz.
2. Video Amplifiers (VA-206-T and VA-212-T) - These units amplify the low-level signals from the test probe to voltage levels that would drive the discriminator.
3. Discriminators (Disc 204 and Disc 102) - These units generate a DC voltage that is proportional to the phase shifts between the signals from the power amplifiers and the signals from the video amplifiers. The discriminator level was variable between 0 and ± 10 volts.

In addition to the variable voltage levels on the two discriminators, there is also a lift-off compensator. This portion of the discriminator allows the adjustment of the voltage trigger level to be at some point slightly above the zero level, which minimizes the effect of lift off. This fact may be better understood if stated as follows: As the probe-to-cladding distance is varied (say, due to surface finish), a large change in the voltage amplitude and a small change in the voltage phase are produced. Normally, the phase shift between the input and output voltages is measured at the point where the voltage passthrough is zero. However, when lift off is encountered, the original input phase shifts slightly. The discriminator can now be set to trigger at a point where the maximum and zero lift offs have the same phase shift. This relationship is illustrated in Figure 13. In the figure, V_1 represents the point at which the voltage discriminator triggers.

Figure 13. VOLTAGE WAVE FORM FOR ZERO AND MAXIMUM LIFT OFF.

Test Results

Resistivities of the bronze samples were determined with a single-frequency, phase-sensing eddy-current system. The reflection-type probe had a driver coil with a mean radius of 40 mils and pickup coils with mean radii of 21 mils. The system was calibrated to read in

degrees directly with the aid of an RLC calibrator circuit. The circuit was plugged into the connector where the test probe is used. The circuit was equipped with a switch with dial positions ranging from 0 to ± 80.00 degrees in 10-degree increments. Also included were positions for ± 0.5 , ± 79.5 , and ± 80.5 degrees. The system was then calibrated for resistivity measurement using seven known standards whose resistivities ranged from 1.726 (copper) to 50.106 microhm-cm (constantan). The seven standards and their resistivities are:

Standard	Resistivity (microhm-cm)
Copper	1.726
1100 Aluminum Alloy	2.934
6061 Aluminum Alloy	3.474
2024 Aluminum Alloy	3.687
60 Alloy	9.727
180 Alloy	28.220
Constantan	50.106

A lift off of 3 mils was set in the lift-off compensation circuit. This setting was accomplished by placing a 3-mil shim on the constantan standard and adjusting the lift-off circuit to balance at minimum (without shim) and maximum (with shim) lift off.

Tables 1 and 2 contain the data taken from this part of the investigation. Each set of data was made with a different calibration. Figures 14 through 20 provide plots of each set of data fitted to a second-order, least-squares fit. Each of the curves were generated by plotting the log of the standard resistivities against the measured phase shifts. Log of the resistivity versus phase shift is approximately linear over a large resistivity variation. Frequencies of 1, 2, and 5 MHz were used to obtain the data given in Tables 1 and 2. Each set of runs taken on the two bronze samples were statistically analyzed. Results of this analysis are given in Table 3. The averages of the two bronze clads—Clad C and Clad D—were found to be 15.560 and 9.630 microhm-cm, respectively.

Table 1
EDDY-CURRENT MEASUREMENTS OF CLAD C

Measurement Number	Phase Shift (degrees)			
	2 MHz			1 MHz
	Run 1	Run 2	Run 3	Run 4
1	-16.66	-16.76	-17.01	-23.85
2	-16.60	-16.60	-16.82	-23.65
3	-16.62	-16.75	-17.01	-23.88
4	-16.48	-16.59	-16.95	-23.77
5	-16.67	-16.77	-16.99	-23.86
6	-16.48	-16.60	-16.84	-23.62
7	-16.69	-16.72	-17.02	-23.81
8	-16.48	-16.55	-16.84	-23.62
9	-16.62	-16.72	-17.01	-23.82
10	-16.51	-16.66	-16.86	-23.81

Table 2
EDDY-CURRENT MEASUREMENTS OF CLAD D

Measurement Number	Phase Shift (degrees)		
	1 MHz	2 MHz	5 MHz
1	-18.43	-13.80	-10.48
2	-18.41	-13.70	-10.44
3	-18.34	-13.78	-10.51
4	-18.50	-13.80	-10.55
5	-18.42	-13.77	-10.45
6	-18.48	-13.74	-10.42

Figure 14. PHASE SHIFT VERSUS RESISTIVITY FOR CLAD C, RUN 1.

Figure 15. PHASE SHIFT VERSUS RESISTIVITY FOR CLAD C, RUN 2.

After determining the resistivities of the two bronze claddings, the constant values in Equation 8 were determined. As mentioned previously, all of the system parameters, including the operating frequency, were determined by computer. For maximum thickness sensitivity, the two frequencies chosen were 20 and 200 kHz. These two frequencies were set on the dual-frequency eddy-current oscillator and power amplifier.

Figure 16. PHASE SHIFT VERSUS RESISTIVITY FOR CLAD C, RUN 3.

Figure 17. PHASE SHIFT VERSUS RESISTIVITY FOR CLAD C, RUN 4.

To determine the constants in Equations 10 and 11, several sets of measurements were made to find the phase-shift values corresponding to the change of thickness and conductivity on the two claddings. The eddy-current system was divided into two channels: the low frequency (20 kHz) was set on Channel 1 and the high frequency (200 kHz) was set on Channel 2. Each channel consisted of a video amplifier and discriminator. Each channel fed through the latter two circuits into the filter computer and digital panel meter. The signal to the digital panel meter was selected by a six-position rotary switch. However, for the purpose of this investigation, only four of the six positions were used. The positions labeled Phase 1 and Phase 2 were used to obtain the signal from the discriminators of Channels 1

Figure 18. PHASE SHIFT VERSUS RESISTIVITY FOR CLAD D AT 1 MHz.

Figure 19. PHASE SHIFT VERSUS RESISTIVITY FOR CLAD D AT 2 MHz.

and 2, respectively. (The other two positions used in this investigation will be discussed later.) Channel 1 was used to monitor the phase shifts corresponding to thickness changes; Channel 2 to monitor conductivity.

After the system was calibrated (as described previously) and lift off set for a maximum variation of 3 mils, each cladding was placed (one at a time) on the base material. Three different thicknesses of Clad C (15.56 $\mu\Omega$ -cm) were measured for phase shifts on the two

Figure 20. PHASE SHIFT VERSUS RESISTIVITY FOR CLAD D AT 5 MHz.

Table 3
SUMMARY OF DATA TAKEN FOR RESISTIVITY MEASUREMENT

Sample Run	Frequency (Hz)	Average Phase Shift (degrees)	Standard Deviation	95 Percent Confidence Limits	Calculated Resistivity (microhm-cm)	Standard Deviation
Clad C Run 1	2M	-16.581	0.085	0.053	15.536	0.13
Clad C Run 2	2M	-16.672	0.082	0.051	15.383	0.12
Clad C Run 3	2M	-16.935	0.084	0.052	15.636	0.13
Clad C Run 4	1M	-23.749	0.111	0.069	15.799	0.12
Clad D Run 1	1M	-18.430	0.056	0.045	9.744	0.04
Clad D Run 2	2M	-13.765	0.039	0.031	9.617	0.04
Clad D Run 3	5M	-10.475	0.048	0.039	9.528	0.06

channels. Two thicknesses of Clad D ($9.63 \mu\Omega\text{-cm}$) were measured. Table 4 contains the data taken from these measurements. Note, in Table 4 that the variation in phase shift using 200 kHz is much less than that using 20 kHz. This difference, of course, is due, primarily, to the fact that the electromagnetic field is concentrated more at the surface of the claddings. The

Table 4
SUMMARY OF DATA TAKEN FROM CLADDING MEASUREMENTS

Measurement Number	Clad on Base	Thickness (mils)	Phase Shift (deg)	
			20 kHz	200 kHz
1	Clad C	21	10.99	3.88
		42	13.39	4.15
2	Clad C	21	11.02	4.01
		42	13.47	4.52
3	Clad C	21	10.85	3.92
		42	13.44	4.45
4	Clad C	21	10.95	4.00
		42	13.47	4.47
5	Clad C	21	10.96	4.02
		42	13.57	4.48
1	Clad D	20	15.36	11.79
		40	19.71	11.85
		60	21.00	11.74
2	Clad D	20	15.61	11.70
		40	19.68	11.74
		60	20.91	11.75
3	Clad D	20	15.35	11.73
		40	19.62	11.66
		60	20.74	11.78
4	Clad D	20	15.37	11.80
		40	19.67	11.72
		60	20.96	11.81
5	Clad D	20	15.53	11.74
		40	19.64	11.95
		60	20.84	11.90

average of the thickness phase shifts was calculated for each cladding. To determine the constants in Equations 10 and 11, the following values were first found:

$$S_l = \left(\frac{\Delta P}{\Delta \rho} \right)_l,$$

$$S_h = \left(\frac{\Delta P}{\Delta \rho} \right)_h,$$

$$T_l = \left(\frac{\Delta P}{\Delta t} \right)_l, \text{ and}$$

$$T_h = \left(\frac{\Delta P}{\Delta t} \right)_h,$$

where $(\Delta P/\Delta \rho)_l$ and $(\Delta P/\Delta \rho)_h$ are the changes in phase shifts with respect to resistivity at the low and high frequencies, respectively; $(\Delta P/\Delta t)_l$ and $(\Delta P/\Delta t)_h$ are the changes in phase shifts with respect to thickness at the low and high frequencies, respectively. For consistency, the phase shifts corresponding to 42 mils (Clad C) and 20 and 40 mils (Clad D) were used in the constant calculation, thus:

$$S_h = \frac{(11.784 - 4.414) \text{ deg}}{(9.63 - 15.56) \mu\Omega\text{-cm}} = -1.2428 \text{ deg}/\mu\Omega\text{-cm},$$

$$S_l = \frac{(19.66 - 13.468) \text{ deg}}{(9.63 - 15.560) \mu\Omega\text{-cm}} = -1.0442 \text{ deg}/\mu\Omega\text{-cm},$$

$$T_l = \frac{(15.444 - 19.664) \text{ deg}}{(20 - 40) \text{ mils}} = 0.2110 \text{ deg}/\text{mil}, \text{ and}$$

$$T_h = \frac{(11.752 - 11.784) \text{ deg}}{(20 - 40) \text{ mils}} = 0.0016 \text{ deg}/\text{mil}.$$

Therefore:

$$a_{11} = \frac{S_l}{T_h S_l - T_l S_h} = -4.0075 \text{ mil/deg},$$

$$a_{12} = \frac{S_h}{T_h S_l - T_l S_h} = -4.7697 \text{ mil/deg},$$

$$a_{21} = \frac{T_l}{T_h S_l - T_l S_h} = 0.0442 \mu\Omega\text{-cm/deg}, \text{ and}$$

$$a_{22} = \frac{T_h}{T_h S_l - T_l S_h} = 0.0003 \mu\Omega\text{-cm/deg}.$$

The ratio between Constants a_{11} and a_{12} is 0.84.

The measurements were made a second time, but this time with the reference thickness (40 mils) and resistivity ($9.63 \mu\Omega\text{-cm}$) phase shifts nulled to zero. The results are given in Table 5. The four constants were calculated to be as follows:

$$a_{11} = -1.8748 \text{ mil/deg},$$

$$a_{12} = -2.2038 \text{ mil/deg},$$

$$a_{21} = 0.3859 \mu\Omega\text{-cm/deg}, \text{ and}$$

$$a_{22} = 0.0071 \mu\Omega\text{-cm/deg}.$$

Table 5
CLADDING THICKNESS MEASUREMENTS
WITH REFERENCE AT 40 MILS
AND 9.63 MICROHM-CM

Clad	Thickness (mils)	Phase Shift (deg)	
		20 kHz	200 kHz
C	21	-19.11	-16.44
	42	-13.28	-15.46
	20	- 9.22	- 0.02
D	40	0.00	0.15
	60	2.60	0.32

The ratio between Constants a_{11} and a_{12} is 0.85. Figures 21 and 22 are plots of phase shifts versus cladding thickness for Clad D at 20 kHz. The curves are approximately linear between 60 and 40 mils; however, they make a hyperbolic cosine approach toward the 20-mil point. Figures 23 and 24 are plots of phase shifts versus cladding thickness for Clad D at 200 kHz. The curves are approximately linear. The latter two figures indicate very little change in phase shift with thickness for the high frequency. This, of course, is in agreement with the basic theory

By monitoring the phase shift at the two frequencies (20 and 200 kHz) and applying the determined constants to the expression relating phase shift and thickness or resistivity (or conductivity), the thickness of the claddings can be measured independently of the resistivity (or conductivity).

Figure 21. THICKNESS VERSUS PHASE SHIFT AT 20 kHz.

Figure 22. THICKNESS VERSUS PHASE SHIFT AT 20 kHz WITH THE REFERENCE AT 40 MILS.

For cladding thickness measurements, Constants a_{11} and a_{12} were dialed on the computer unit. This unit was incorporated into the system by turning the mode-control dial on the digital meter panel to either Comp 1 or Comp 2. The constants become the basic functions for the transformation from phase-shift readings to parameter readings. The phase shifts themselves are considered as input coefficients. Variations in the cladding thickness or resistivity cause the phase shifts or coefficients to vary.

Figure 23. THICKNESS VERSUS PHASE SHIFT AT 200 kHz.

Figure 24. THICKNESS VERSUS PHASE SHIFT AT 200 kHz WITH THE REFERENCE AT 40 MILS.

The 40-mil cladding was used as a reference for both thickness and resistivity measurements. In the Comp 1 position, the constant-adjustment dials were varied until the digital panel meter read zero. In the Comp 2 position, the constant-adjustment dials were varied until the digital panel meter read the difference between the resistivities of the two claddings ($\Delta\rho = 5.93\mu\Omega\text{-cm}$). These adjustments, of course, changed the original calculated constants dialed in earlier. The differences between the constants will be discussed later. Since the 40-mil cladding was used as a reference, 40 mils would have to be added to each of the

digital panel meter readings to obtain the measured cladding thickness. The value of $9.63 \mu\Omega\text{-cm}$ would have to be added to each of the digital panel meter readings to obtain the measured cladding resistivity. As mentioned earlier, the Comp 1 position was used for the thickness measurement and the Comp 2 position for resistivity. Table 6 contains the data taken from the two positions. The means and standard deviations are given in Table 7.

Table 6
THICKNESS AND RESISTIVITY USING COMPUTER UNIT

Clad D (9.63 microhm-cm)					Clad C (15.56 microhm-cm)			
Measurement Number	Instrument Reading for				Measurement Number	Instrument Reading for		
	20 Mils	40 Mils	60 Mils	Conductivity		21 Mils	42 Mils	Conductivity
1	-20.22	-01.11	+03.65	+00.05	1	-08.99	+02.06	+06.08
2	-20.65	-01.42	+03.76	+00.08	2	-09.02	+02.70	+05.85
3	-19.96	+00.04	+03.99	+00.72	3	-10.74	+02.30	+06.02
4	-19.95	+00.19	+04.78	+00.58	4	-10.40	+02.49	+06.14
5	-20.07	-00.26	+04.44	+00.60	5	-10.78	+02.50	+05.96
6	-20.00	+00.16	+04.44	+00.56	6	-10.62	+03.24	+06.07
7	-19.38	-00.08	+04.71	+00.50	7	-11.00	+01.96	+05.99
8	-19.40	+00.26	+05.02	+00.60	8	-10.48	+03.25	+06.06
9	-20.20	-00.03	+04.06	+00.47	9	-09.33	+01.44	+06.02
10	-19.98	-00.10	+05.16	+00.51	10	-12.95	+02.45	+06.23
11	-20.47	-00.33	+04.84	+00.46	11	-12.59	+02.50	+06.20
12	-19.95	+00.08	+05.42	+00.52	12	-09.15	+00.45	+06.15
13	-19.87	+00.10	+05.36	+00.54	13	-09.34	+01.80	+05.99

Table 7
SUMMARY OF THICKNESS AND RESISTIVITY MEASUREMENTS
USING THE COMPUTER UNIT

Actual Thickness (mils)	Mean and Standard Deviation of the Measured Thickness (mils)	Percent Deviation between the Actual and Measured Thickness	Actual Resistivity (microhm-cm)	Mean and Standard Deviation of the Measured Resistivity (microhm-cm)	Percent Deviation between the Actual and Measured Resistivity
20	19.990 $\pm$ 0.356	0.05	9.630	10.106 $\pm$ 0.195	5.00
40	39.807 $\pm$ 0.509	0.05			
60	44.589 $\pm$ 0.589	25.68			
21	29.585 $\pm$ 1.281	40.88	15.560	15.688 $\pm$ 0.826	0.83
42	42.241 $\pm$ 0.743	0.56			

Discussion of Errors

One of the most undesirable variables that is encountered in eddy-current measurements is lift off (probe-to-metal spacing). Although this investigation included compensating circuitry for lift off, the actual effect was the minimization of lift-off errors and not their elimination. The lift-off range was chosen to be small, thus lessening the lift-off effect. However, the cladding-thickness measurement range was approximately a 33% variation. The lift-off effect increases as the range of measurements increases.

One other source of error was the stacking of the claddings to vary the thickness. Two and three 20-mil layers of Clad C were used to obtain thicknesses of 40 and 60 mils, respectively. This arrangement, of course, meant having layers of air between the claddings. The amount of error encountered due to the air gaps could not be determined.

Coil-temperature variations produced as a result of handling the probe coil can affect the readings. Temperature variation causes undesirable drift in the eddy-current system, thus resulting in error.

Still one other source of error was the drift in the system due to the input power fluctuation. However, this effect seemed to be quite small.

The latter two sources of error also played a major role in determining the constants for the computer unit. System drifts due to power fluctuations and temperature variations caused the input coefficients or phase shifts to vary, thus causing a change in the constant settings. Approximately 24 hours elapsed between the determination of the constants and the cladding thickness measurements. The percent deviations between the calculated constants for the thickness measurement and the set used were approximately 13 and 14% for Constants a_{11} and a_{12} , respectively.

CONCLUSIONS

This investigation has shown that cladding thicknesses can be measured with a dual-frequency eddy-current system with an accuracy greater than 99%. The thickness range measured in this investigation was much greater than the 10% linear range. Nevertheless, the sample thicknesses used to determine the computer constants were experimentally determined to within 1%. However, due to the nonlinearity, the points that fell between 20 and 40 mils (see Figure 22) exhibit deviations from zero to a maximum of approximately 3 mils. This maximum occurs at approximately 30 mils on the straight line on Figure 22. Also, due to nonlinearity, the points above 40 mils and below 20 mils exhibit progressive deviations.

The portion of the experimental curve between 40 and 60 mils appears quite linear (see Figure 22). Had sample thicknesses been measured in this range, the deviations would have been quite small compared to the 20 to 40-mil range. The former range fits the thickness-phase shift relation in Equation 8 better than the latter range.

APPENDIX A

COMPUTER PROGRAM FOR PROCESSING EDDY-CURRENT DATA

This computer program is used to process the eddy-current data taken from the experiment.

```

10 DIM X(20,20),Y(20),Z(20)
20 PRINT LIN4
30 PRINT TAB24"EDDY CURRENT PLOT FOR J.T.HILL"
40 PRINT LIN3
50 DISP "LOAD PLOTTER PAPER,CONT";
60 STOP
70 DISP "X-MIN FOR PLOT=";
80 INPUT X1
90 DISP "X-MAX FOR PLOT=";
100 INPUT X2
110 DISP "NO OF X DIVISIONS=";
120 INPUT X3
130 DISP "Y-MIN FOR PLOT=";
140 INPUT Y1
150 DISP "Y-MAX FOR PLOT=";
160 INPUT Y2
170 DISP "NO. OF Y DIVISIONS=";
180 INPUT Y3
190 X4=(X2-X1)/X3
200 Y4=(Y2-Y1)/Y3
210 SCALE X1,X2,Y1,Y2
220 XAXIS Y1,X4
230 YAXIS X1,Y4
240 PLOT X2,Y1
250 PLOT X2,Y2
260 PLOT X1,Y2,-1
270 BEEP
280 DISP "MOVE PEN DOWN APPROX 1/2 Y DIV";
290 STOP
300 LABEL (310,1.3,1.7,0,8.5/11)
310 FORMAT 3F4.0
320 FOR X=X1+X4 TO X2-X4 STEP X4
330 PLOT X,Y1,1
340 CPLLOT -2,3
350 LABEL (310)X
360 NEXT X
370 PLOT 5*X4+X1,Y1
380 LABEL (*,2,1.7,0,8.5/11)"PHASE SHIFT (DEGREES) --->"
390 BEEP
400 DISP "RETURN PEN TO ORIG. ORIGIN"
410 WAIT 2000
420 BEEP
430 DISP "MOVE PEN OVER APPROX 1/2 X DIV";
440 STOP
450 LABEL (*,1.3,1.7,0,8.5/11)
460 FOR Y=Y1 TO (Y2-Y4) STEP Y4
470 PLOT X1,Y,1
480 CPLLOT 3,-0.03
490 LABEL (310,1.3,1.7,0,8.5/11)Y
500 NEXT Y
510 PLOT X1+0.2*X4,Y1+Y4
520 DEG

```

```

1180 T6=S5-A3*T8
1190 A1=(T6+T8-T5*T7)/(M*T8-T7*T7)
1200 A2=(M*T5-T6*T7)/(M*T8-T7*T7)

1240 PRINT TAB20"A1",A2
1250 PRINT
1260 PRINT TAB20"A2",A3
1270 PRINT LIN4
1280 FOR X=X1 TO X2 STEP X4/10
1290 Y=A1+A2*X+A3*X^2
1300 IF Y<Y1 THEN 1330
1310 IF Y>Y2 THEN 1330
1320 PLOT X,Y
1330 NEXT X
1340 PEN
1350 DISP "CHANGE PEN COLOR";
1360 STOP
1370 PRINT TAB34"PART VALUES"
1380 PRINT LIN3
1390 PRINT TAB6"AVERAGE";TAB20"STANDARD";TAB39"95 PERCENT";
1400 PRINT TAB60"CALCULATED"
1410 PRINT TAB7"PHASE";TAB20"DEVIATION";TAB39"CONFIDENCE";TAB60"RESISTIVITY"
1420 PRINT TAB7"SHIFT";TAB41"LIMITS";TAB58"(MICRO-OHM CM)"
1430 PRINT LIN3
1440 S1=S2=S3=S4=0
1450 DISP "NO. SAMPLES CHECKED=";
1460 INPUT M
1470 FOR I=1 TO M
1480 S1=S2=0
1490 FIXED 0
1500 DISP "NO. PHASE SHIFTS FOR PT NO.";I;"=";
1510 INPUT N
1520 FOR J=1 TO N
1530 DISP "PHASE SHIFT FOR PT NO";J;"=";
1540 INPUT X
1550 S1=S1+X
1560 S2=S2+X^2
1570 NEXT J
1580 X=S1/N
1590 S=SQR((N*S2-S1*S1)/(N*(N-1)))
1600 R=1.96*S/SQRN
1610 Y=A1+A2*X+A3*X^2
1620 FIXED 5
1630 PRINT TAB6,X;TAB22,S;TAB40,R;TAB62,Y
1640 PRINT
1650 PLOT X,Y;-1
1660 PLOT X,Y+Y4/20
1670 PLOT X+X4/10,Y-Y4/20
1680 PLOT X-X4/10,Y-Y4/20
1690 PLOT X,Y+Y4/20
1700 PEN
1710 NEXT I
1720 PRINT LIN10
1730 END

```

```

530 LABEL (*,2,1.7,90,8.5/11)"RESISTIVITY (MICRO-OHM CM) --->"
540 BEEP
550 DISP "RETURN PEN TO ORIG. ORIGIN";
560 STOP
570 PRINT TAB32"STANDARD VALUES"
580 PRINT LIN2
590 PRINT TAB7"RESISTIVITY";TAB24"AVERAGE";TAB40"STANDARD";
600 PRINT TAB50"PERCENT"
610 PRINT TAB55"MICRO OHM CM";TAB75"NOISE";TAB
      ENCE
620 PRINT TAB25"STANDARD LIMITS"
640 PRINT LIN3
650 S1=S2=S3=S4=S5=S6=S7=T7=T8=0
660 DISP "NO. OF STD RESISTIVITIES=";
670 INPUT M
680 FOR I=1 TO M
690 S1=S2=0
700 FIXED 0
710 DISP "RESISTIVITY FOR STD NO.";I;"=";
720 INPUT Y[I]
730 DISP "NO. PHASE SHIFTS FOR STD NO.";I;"=";
740 INPUT N
750 Z[I]=0
760 FOR J=1 TO N
770 DISP "PHASE SHIFT FOR PT NO";J;"=";
780 INPUT X[I,J]
790 S1=X[I,J]+S1
800 S2=X[I,J]^2+S2
810 NEXT J
820 S3=S4=S5=S6=S7=0
830 Z[I]=S1/N
840 S=SQR((N*S2-S1*S1)/(N*(N-1)))
850 R=(1.96*S)/(SQRN)
860 FIXED 5
870 PRINT TAB7,Y[I];TAB23,Z[I];TAB40,S;TAB60,R
880 PRINT
890 PLOT Z[I],Y[I],-1
900 PLOT Z[I],Y[I]+Y4/20
910 PLOT Z[I]+X4/10,Y[I]-Y4/20
920 PLOT Z[I]-X4/10,Y[I]-Y4/20
930 PLOT Z[I],Y[I]+Y4/20
940 PEN
950 NEXT I
960 FOR I=1 TO M
970 T7=T7+Z[I]
980 T8=T8+Z[I]^2
990 S3=S3+Z[I]^3
1000 S4=S4+Z[I]^4
1010 S5=S5+Y[I]
1020 S6=S6+Z[I]*Y[I]
1030 S7=S7+Z[I]^2*Y[I]
1040 NEXT I
1050 PRINT LIN4
1060 PRINT TAB27"SECOND ORDER LEAST SQUARES"
1070 PRINT TAB32"FIT COEFFICIENTS"
1080 PRINT LIN3
1090 T1=M*(T8*S4-S3*S3)
1100 T2=T7*(T7*S4-T8*S3)
1110 T3=T8*(T7*S3-T8*T8)
1120 T4=T1-T2+T3
1130 T1=M*(T8*S7-S3*S6)
1140 T2=T7*(T7*S7-T8*S6)
1150 T3=S5*(T7*S3-T8*T8)
1160 A3=(T1-T2+T3)/T4
1170 T5=S6-A3*S3

```

APPENDIX B

COMPUTER PROGRAM TO CALCULATE VOLTAGE MAGNITUDE AND PHASE

This program calculates the magnitude and phase of the voltage that is fed to the phase-measuring circuits of the phase-sensitive eddy-current instrument, and is designed to help analyze eddy-current measurements of cladding thickness. The input data for the program is contained in Lines 250 through 520. The data are inputted as follows:

00250	R5	= (coil mean radius in inches)
00260	R1	= (normalized inner radius of driver coil)
00270	R2	= (normalized outer radius of driver coil)
00280	L3	= (normalized length of driver coil)
00290	R3	= (normalized inner radius of pickup coil)
00300	R4	= (normalized outer radius of pickup coil)
00310	L4	= (normalized length of pickup coil)
00320	L5	= (normalized length of recess of each pickup coil from the face of the driver coil)
00330	L6	= (normalized minimum lift off of the driver coil)
00340	R6	= (resistance of driver coil in ohms)
00350	R7	= (resistance of both pickup coils in ohms)
00360	N3	= (number of turns on the driver coil)
00370	N4	= (number of turns on each pickup coil)
00380	R0	= (driver amplifier series resistance in ohms)
00390	R9	= (pickup amplifier shunt resistance in ohms)
00400	C6	= (shunt capacitance of driver circuit in farads)
00410	C7	= (shunt capacitance of pickup circuit in farads)
00420	V0	= (output voltage in volts)
00430	GAIN	= (amplifier gain)
00440	FREQ	= (operating frequency in Hertz)

00450	L2	= (normalized lift-off increment of the driver coil)
00460	RH01	= (resistivity of base material in microhm-cm)
00470	U1	= (relative magnetic permeability of base material)
00480	RH02	= (resistivity of cladding material in microhm-cm)
00490	U2	= (relative magnetic permeability of cladding material)
00500	CLAD(1)	= (numerical value of minimum cladding thickness in inches)
00510	CLAD(2)	= (numerical value of nominal cladding thickness in inches)
00520	CLAD(3)	= (numerical value of maximum cladding thickness in inches)

```

00010C IN THIS PROGRAM, THE BASE RESISTIVITY IS RH01 AND
00020C THE CLADDING RESISTIVITY IS RH02
00030C SIGMA IS THE GAMMA FACTOR
00040     COMPLEX BETA1,BETA2,EX1,RNUM,DEN,SIGMA
00050     COMPLEX TMUT,DRIVER,PICKUP
00060     REAL L3,L4,L5,L6,L2,N3,N4,K1,K2
00070     COMMON X,Z,Q1,PI/B1/R1,K2,R3,R4,L3,L4,R0,R6,R7
00080     COMMON /B1/R9,C6,C7,V0,GAIN,W,FREQ,R5,N3,N4
00090     COMMON /B2/TMUT,DRIVER,PICKUP,AIR1,AIR2/B3/GAGE,XIN
00100     COMMON /B3/XOUT,XLEN,TURNS,N1A,J1,PERLAY,XCAY
00110     DIMENSION CLAD(3),RL(5),SIGMA(3),TMUT(3,5),DRIVER(3,5)
00120     DIMENSION PICKUP(3,5),TMAG(3,5),PHASE(3,5),SHIFT(3,5)
00130     EQUIVALENCE (RH01,K1),(RH02,K2),(GAIN,G5),(FREQ,F)
00140     PI=3.14159265
00150     RAD=180.0/PI
00160C
00170C
00180C
00190C
00200C
00210C
00220     JKL=0
00230C THE FOLLOWING ARE INPUT DATA FOR THE PARAMETERS OF
00240C THE COILS,MATERIAL, AND CIRCUIT
00250     R5=.08325
00260     R1=.75
00270     R2=1.25
00280     L3=.36
00290     R3=.36
00300     R4=.696
00310     L4=.096
00320     L5=0.0
00330     L6=.1
00340     R6=79.36
00350     R7=530.5
00360     N3=360.0
00370     N4=410.0
00380     R0=1.0E6
00390     R9=1.0E6
00400     C6=1.0E-12
00410     C7=1.0E-12
00420     V0=10.0
00430     GAIN=1.0
00440     FREQ=1.0E4
00450     L2=0.025
00460     RH01=5.393
00470     U1=1.0
00480     RH02=3.632
00490     U2=1.0
00500     CLAD(1)=0.0266
00510     CLAD(2)=0.028
00520     CLAD(3)=0.0294
00530     5 W=2.0*PI*FREQ
00540     IF(RH01.GT.1.0E9) GO TO 10
00550     RM1=0.5094*U1*FREQ*R3*R5/RH01
00560     GO TO 20
00570     10 RM1=0.0
00580     20 RM2=0.5094*U2*FREQ*R5*R5/RH02
00590C THE SYSTEM PARAMETERS ARE PRINTED OUT

```

```

00600      IF(JKL.NE.0) GO TO 105
00610      TYPE 30,R1,R2,L3
00620      30 F0RMAT(1H ,3HR1=,F8.5,3X,3HR2=,F8.5,3X,14HDRIVER LENGTH=,
00630      1F8.5)
00640      TYPE 40,R3,R4,L4
00650      40 F0RMAT(1H ,3HR3=,F8.5,3X,3HR4=,F8.5,3X,14HPICKUP LENGIH=,
00660      1F8.5)
00670      TYPE 50,R5,FREQ
00680      50 F0RMAT(1H ,17HC01L MEAN RADIUS=,F8.5,7H INCHES,3X,
00690      120H0PERATING FREQUENCY=,1PE12.5)
00700      TYPE 60,L5
00710      60 F0RMAT(1H ,15HPICKUP RECESSED,F8.5)
00720      TYPE 70,L6,L2
00730      70 F0RMAT(1H ,13HMIN LIFT-0FF=,F8.5,3X,19HLIFT-0FF INCREMENT=,
00740      1F8.5)
00750      TYPE 80,U1,RM1,RH01
00760      80 F0RMAT(1H ,3HU1=,F6.2,5X,3HM1=,F9.5,2X,12HRESISTIVITY=,
00770      11PE12.5,11H MICR0HM CM)
00780      TYPE 90,U2,RM2,RH02
00790      90 F0RMAT(1H ,3HU2=,F6.2,5X,3HM2=,F9.5,2X,12HRESISTIVITY=,
00800      11PE12.5,11H MICR0HM CM)
00810      TYPE 100,CLAD(1),CLAD(2),CLAD(3)
00820      100 F0RMAT(1H ,10HTHICKNESS=,F8.5,2(8X,F8.5))
00830C THE INTEGRATION IS PERFORMED BY THE TRAPEZOIDAL METHOD,
00840C EVALUATING AT THE CENTER OF THE INTERVAL; FOR X LARGE
00850C THE INTEGRAL CONVERGES RAPIDLY,S0 LARGER INTERVALS
00860C ARE TAKEN
00870C IN THE INTEGRATION TMUT, DRIVER, PICKUP, AIR1, AND
00880C AIR2 ARE CALCULATED
00890      105 S1=0.01
00900      S2=5.0
00910      B1=0.0
00920      B2=S2
00930      AIR1=0.0
00940      AIR2=0.0
00950      D0 108 J=1,3
00960      D0 108 K=1,5
00970      DRIVER(J,K)=(0.0,0.0)
00980      PICKUP(J,K)=(0.0,0.0)
00990      TMUT(J,K)=(0.0,0.0)
01000      108 CONTINUE
01010      110 I1=(B2-B1)/S1
01020      X=B1-S1/2.0
01030      D0 170 I=1,11
01040      X=X+S1
01050      Z=R2*X
01060      Q1=R2
01070C SUBROUTINE BESSEL EVALUATES THE INTEGRAL OF
01080C THE PR0DUCT OF THE BESSEL FUNCTION AND ITS
01090C ARGUMENT
01100      CALL BESSEL(VAL2)
01110      Z=R1*X
01120      Q1=R1
01130      CALL BESSEL(VAL1)
01140      Z=R4*X
01150      Q1=R4
01160      CALL BESSEL(VAL4)
01170      Z=R3*X
01180      Q1=R3

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01190      CALL BESSEL(VAL3)
01200      S3=S1*(VAL4-VAL3)*(VAL2-VAL1)
01210      S4=S1*(VAL2-VAL1)*(VAL2-VAL1)
01220      S5=S1*(VAL4-VAL3)*(VAL4-VAL3)
01230      EX3=EXP(-X*L3)
01240      W1=1.0-EX3
01250      EX4=EXP(-X*L4)
01260      W2=1.0-EX4
01270      EX5=EXP(-X*L5)
01280      W3=EX3/(EX4*EX4*EX5*EX5)
01290      IF(X.GT.30.0) G0 T0 160
01300C FROM HERE THROUGH LINE 130, SIGMA IS CALCULATED
01310      BETA2=CSQRT(CMPLX(X*X, RM2))/U2
01320      D0 130 J=1,3
01330      IF(REAL(CLAD(J)/R5*BETA2*U2).GT.15.0) G0 T0 120
01340      FX1=CFXP(2.0*CLAD(J)/R5*BETA2*U2)
01350      BETA1=CSQRT(CMPLX(X*X, RM1))/U1
01360      RNUM=(X+BETA2)*(BETA2-BETA1)+(X-BETA2)*(BETA2+BETA1)*EX1
01370      DEN=(X-BETA2)*(BETA2-BETA1)+(X+BETA2)*(BETA2+BETA1)*EX1
01380      SIGMA(J)=RNUM/DEN
01390      G0 T0 130
01400 120 SIGMA(J)=(X-BETA2)/(X+BETA2)
01410 130 CONTINUE
01420      EX2=EXP(-2.0*X*L2)
01430      EX6=EXP(-2.0*X*L6)
01440      W4=1.0-EX4*W3
01450      W5=EX5*EX6*W1*W2*W4
01460      W6=EX6*W1*W1
01470      W7=W2*W2*EX6*EX5*EX5*W4*W4
01480      RL(1)=1.0
01490      D0 140 K=2,5
01500 140 RL(K)=EX2*RL(K-1)
01510      D0 150 K=1,3
01520      D0 150 L=1,5
01530      TMUT(K,L)=TMUT(K,L)+S3*W5*RL(L)*SIGMA(K)
01540      DRIVER(K,L)=DRIVER(K,L)+S4*W6*RL(L)*SIGMA(K)
01550 150 PICKUP(K,L)=PICKUP(K,L)+S5*W7*RL(L)*SIGMA(K)
01560 160 AIR1=AIR1+S4*2.0*(X*L3-W1)
01570      AIR2=AIR2+S5*(4.0*(X*L4-W2)-2.0*W2*W2*W3)
01580 170 CONTINUE
01590      B1=B2
01600      B2=B2+S2
01610      S1=0.05
01620      IF(X.LT.9.0) G0 T0 110
01630      S1=0.1
01640      IF(X.LT.29.0) G0 T0 110
01650      S1=0.2
01660      IF(X.LT.39.0) G0 T0 110
01670      S1=0.5
01680      IF(X.LT.79.0) G0 T0 110
01690C THE INTEGRATION ENDS HERE
01700      IF(JKL.NE.0) G0 T0 552
01710C NEXT THE PROPERTIES OF THE COILS ARE DETERMINED AND PRINTED
01720 180 CALL CIRCT(TMAG, PHASE, Q0, T1, T2)
01730      CALL PHASET(TMAG, PHASE, SHIFT, V1, SET)
01740      TYPE 190
01750 190 FORMAT(1H ,10HDRIVER RES,4X,10HINDUCTANCE,4X,8HN0 TURNS,
01760      16X,9HSHUNT CAP,5X,9HN0R IM PT)
01770      Q1=Q0*T1*T1*AIR1/W

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01780      Q2=(REAL(DRIVER(2,3))+AIR1)/AIR1
01790      Q3=Q0*T2*T2*AIR2/W
01800      Q4=(REAL(PICKUP(2,3))+AIR2)/AIR2
01810      TYPE 200,R6,Q1,N3,C6,Q2
01820 200 F0RMAT(1H ,1PE12.5,2X,1PE12.5,2X,OPF8.1,6X,1PE12.5,2X,
01830      1OPF9.6)
01840      TYPE 210
01850 210 F0RMAT(1H ,10HPICKUP RES,4X,10HINDUCTANCE,4X,8HN0 TURNS,
01860      16X,9HSHUNT CAP,5X,9HN0R IM PT)
01870      TYPE 200,R7,Q3,N4,C7,Q4
01880      TYPE 220
01890 220 F0RMAT(1H ,12HDRIVING V0LT,2X,10HSERIES RES,4X,
01900      18HAMP GAIN,6X,9HINPUT IMP)
01910      TYPE 230,V0,R0,GAIN,R9
01920 230 F0RMAT(1H ,F5.1,9X,1PE12.5,2X,OPF8.1,6X,1PE12.5)
01930      TYPE 240,V1
01940 240 F0RMAT(1H ,22HDISCRIMINAT0R V0LTAGE=,1PE12.5)
01950      TYPE 250
01960 250 F0RMAT(1H )
01970      RL(1)=L6
01980      D0 260 I=2,5
01990 260 RL(I)=L2+RL(I-1)
02000      TYPE 270,RL
02010 270 F0RMAT(1H ,4(F6.3,8X),F6.3)
02020      TYPE 250
02030C THE V0LTAGE MAGNITUDE,PHASE,AND SHIFT ARE PRINTED F0R
02040C THE VARIOUS LIFT-OFF VALUES
02050      D0 280 I=1,3
02060      TYPE 290,(TMAG(I,J),J=1,5)
02070      TYPE 290,(PHASE(I,J),J=1,5)
02080      TYPE 290,(SHIFT(I,J),J=1,5)
02090      TYPE 250
02100 280 C0NTINUE
02110 290 F0RMAT(1H ,4(1PE12.5,2X),1PE12.5)
02120      CALL SENS(SHIFT,RAD,SEN)
02130C THE USER SELECTS ONE 0F F0UR P0SSIBILITIES
02140 295 TYPE 300
02150 300 F0RMAT(' 1 C0IL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK
02160      1  4 C0N CAL')
02170      TYPE 250
02180      ACCEPT 310,N5
02190 310 F0RMAT(11)
02200      G0 T0(320,450,540,690),N5
02210C THE FIRST P0SSIBILITY PRINTS FACT0RS IN THE C0IL
02220C DESIGN; USER INPUTS INTEGER DATA AS REQUESTED
02230 320 TYPE 330
02240 330 F0RMAT(' DRIVER WIRE GAGE, TURNS, PICKUP WIRE GAGE,
02250      1 TURNS')
02260      TYPE 250
02270      ACCEPT 340,N1A,N2A,N3A,N4A
02280 340 F0RMAT(4I)
02290      IF (N1A*N2A.EQ.0) G0 T0 350
02300      GAGE=N1A
02310      XIN=R1*R5
02320      X0UT=R2*R5
02330      XLEN=L3*R5
02340      TURNS=N2A
02350      N3=N2A
02360      N1A=-1

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02370      J1=1
02380      CALL GAGER(R6)
02390      G0 T0 370
02400 350 IF(N1A.EQ.0) G0 T0 360
02410      GAGE=N1A
02420      XIN=R1*R5
02430      XOUT=R2*R5
02440      XLEN=L3*R5
02450      J1=1
02460      CALL GAGER(R6)
02470      N3=URNS
02480      G0 T0 370
02490 360 IF(N2A.EQ.0) G0 T0 390
02500      N3=N2A
02510      URNS=N2A
02520      XIN=R1*R5
02530      XOUT=R2*R5
02540      XLEN=L3*R5
02550      J1=0
02560      CALL GAGER(R6)
02570 370 TYPE 380,URNS,GAGE,PERLAY,XLAY,R6
02580 380 F0RMA1(1H ,6H1RIVER,F6.1,10H URNS 0F#,F5.1,4HWIRE,
02590      1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4H0HMS)
02600 390 IF(N3A*N4A.EQ.0) G0 T0 400
02610      GAGE=N3A
02620      URNS=N4A
02630      N4=N4A
02640      XIN=R3*R5
02650      XOUT=R4*R5
02660      XLEN=L4*R5
02670      J1=1
02680      CALL GAGER(R7)
02690      R7=2.0*R7
02700      G0 T0 420
02710 400 IF(N3A.EQ.0) G0 T0 410
02720      GAGE=N3A
02730      XIN=R3*R5
02740      XOUT=R4*R5
02750      XLEN=L4*R5
02760      J1=1
02770      CALL GAGER(R7)
02780      N4=URNS
02790      R7=2.0*R7
02800      G0 T0 420
02810 410 IF(N4A.EQ.0) G0 T0 440
02820      N4=N4A
02830      URNS=N4A
02840      XIN=R3*R5
02850      XOUT=R4*R5
02860      XLEN=L4*R5
02870      J1=0
02880      CALL GAGER(R7)
02890      R7=2.0*R7
02900 420 TYPE 430,URNS,GAGE,PERLAY,XLAY,R7
02910 430 F0RMA1(1H ,6HPICKUP,F6.1,10H URNS EA#,F5.1,4HWIRE,
02920      1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4H0HMS)
02930 440 G0 T0 180
029400 THE SECON0 POSSIBLITY DEALS WITH ATTENUATOR DESIGN;

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02950C   USER INPUTS REQUESTED DATA IN E FIELD TYPE
02960   450 TYPE 460
02970   460 F0RMAT(' DRIVER SERIES RES, SHUNT CAP, PICKUP SHUNT RES,
02980       1 SHUNT CAP')
02990       TYPE 250
03000       ACCEPT 470,P1,P2,P3,P4
03010   470 F0RMAT(4E)
03020       IF(P1.E0.0.0) G0 T0 480
03030       R0=P1
03040   480 IF(P2.E0.0.0) G0 T0 490
03050       C6=P2
03060   490 IF(P3.E0.0.0) G0 T0 500
03070       R9=P3
03080   500 IF(P4.E0.0.0) G0 T0 510
03090       C7=P4
03100   510 Q5=1.0/(W*SQRT(Q1*Q2*C6))
03110       Q6=SQRT(Q1*Q2/C6)
03120       Q7=R0/(W*Q1*Q2)
03130       Q8=1.0/(W*SQRT(Q3*Q4*C7))
03140       Q9=SQRT(Q3*Q4/C7)
03150       Q10=R9/(W*Q3*Q4)
03160       TYPE 520,Q5,Q6,Q7
03170   520 F0RMAT(1H ,7HDVR CKT,1PE12.5,10H BELOW RES,1PE12.5,
03180       18H 0PT RES,1PE12.5,11H RES/REACT.)
03190       TYPE 530,Q8,Q9,Q10
03200   530 F0RMAT(1H ,7HP-U CKT,1PE12.5,10H BELOW RES,1PE12.5,
03210       18H 0PT RES,1PE12.5,11H RES/REACT.)
03220       G0 T0 180
03230C   THE THIRD POSSIBILITY EXAMINES THE EFFECTS OF DRIFT
03240C   ON THE SYSTEM
03250   540 TYPE 550
03260   550 F0RMAT(1H ,23HSYSTEM DRIFT VARIATIONS)
03270       DR1=0.01
03280       DR2=0.01
03290       DR3=0.01
03300       DR4=0.01
03310       DR5=0.01
03320       DR6=0.01
03330       DR7=0.01
03340       DR8=0.01
03350       DR9=0.01
03360       DR10=0.01
03370       DR11=0.01
03380       G0 T0 559
03390   552 CALL CIRCT1(SET,V1,SHIFT,RAD,SEN,
03400       G0 T0 (675,678,681,684),JKL
03410   559 TYPE 560
03420   560 F0RMAT(1H ,11H% VARIATION,3X,13HPARAMETER VAR,1X,
03430       17HRADIANS,7X,7HDEGREES,7X,10H% OF RANGE)
03440       IF(DR1.E0.0.0) G0 T0 580
03450       R6=R6*(1.0+DR1)
03460       DR100=100.0*DR1
03470       TYPE 570,DR100
03480   570 F0RMAT(1H ,F4.1,10X,13HDRIVER RES    $)
03490       CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03500       R6=R6/(1.0+DR1)
03510   580 IF(DR2.E0.0.0) G0 T0 600
03520       R7=R7*(1.0+DR2)
03530       DR100=100.0*DR2

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03540      TYPE 590,DR100
03550 590 F0RMAT(1H ,F4.1,10X,13HPICKUP RES  $)
03560      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03570      R7=R7/(1.0+DR2)
03580 600 IF(DR3.EQ.0.0) G0 T0 620
03590      C6=C6*(1.0+DR3)
03600      DR100=100.0*DR3
03610      TYPE 610,DR100
03620 610 F0RMAT(1H ,F4.1,10X,13HDVR SHUNT CAP$)
03630      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03640      C6=C6/(1.0+DR3)
03650 620 IF(DR4.EQ.0.0) G0 T0 640
03660      C7=C7*(1.0+DR4)
03670      DR100=100.0*DR4
03680      TYPE 630,DR100
03690 630 F0RMAT(1H ,F4.1,10X,13HP-U SHUNT CAP$)
03700      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03710      C7=C7/(1.0+DR4)
03720 640 IF(DR5.EQ.0.0) G0 T0 660
03730      R0=R0*(1.0+DR5)
03740      DR100=100.0*DR5
03750      TYPE 650,DR100
03760 650 F0RMAT(1H ,F4.1,10X,13HSERIES RES  $)
03770      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03780      R0=R0/(1.0+DR5)
03790 660 IF(DR6.EQ.0.0) G0 T0 671
03800      R9=R9*(1.0+DR6)
03810      DR100=100.0*DR6
03820      TYPE 670,DR100
03830 670 F0RMAT(1H ,F4.1,10X,13HAMP INPUT RES$)
03840      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03850      R9=R9/(1.0+DR6)
03860 671 IF(DR7.EQ.0.0) G0 T0 673
03870      V0=V0*(1.0+DR7)
03880      DR100=100.0*DR7
03890      TYPE 672,DR100
03900 672 F0RMAT(1H ,F4.1,10X,13HAPPLIED V0LT.$)
03910      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03920      V0=V0/(1.0+DR7)
03930 673 IF(DR8.EQ.0.0) G0 T0 676
03940      FREQ=FREQ*(1.0+DR8)
03950      DR100=100.0*DR8
03960      TYPE 674,DR100
03970 674 F0RMAT(1H ,F4.1,10X,13HFREQUENCY  $)
03980      JKL=1
03990      G0 T0 5
04000 675 FREQ=FREQ/(1.0+DR8)
04010      JKL=0
04020 676 IF(DR9.EQ.0.0) G0 T0 679
04030      R5=R5*(1.0+DR9)
04040      DR100=100.0*DR9
04050      TYPE 677,DR100
04060 677 F0RMAT(1H ,F4.1,10X,13HMEAN RADIUS  $)
04070      JKL=2
04080      G0 T0 5
04090 678 R5=R5/(1.0+DR9)
04100      JKL=0
04110 679 IF(DR10.EQ.0.0) G0 T0 682
04120      RH01=RH01*(1.0+DR10)
04130      DR100=100.0*DR10

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04140      TYPE 680,DR100
04150 680 F0RMAT(1H ,F4.1,10X,13HBASE RESISTVY$)
04160      JKL=3
04170      G0 T0 5
04180 681 RH01=RH01/(1.0+DR10)
04190      JKL=0
04200 682 IF(DR11.E0.0.0) G0 T0 295
04210      RH02=RH02*(1.0+DR11)
04220      DR100=100.0*DR11
04230      TYPE 683,DR100
04240 683 F0RMAT(1H ,F4.1,10X,13HCLADDING RES $)
04250      JKL=4
04260      G0 T0 5
04270 684 RH02=RH02/(1.0+DR11)
04280      JKL=0
04290      G0 T0 295
04300C THE FOURTH POSSIBILITY ENDS CALCULATIONS
04310 690 CALL EXIT
04320      END
04330      SUBROUTINE BESSEL(VAL)
04340      COMMON X,Z,01,PI
04350      IF(Z.GT.5.0) G0 T0 1010
04360      K=2.0*Z
04370      L=K+3
04380      F1=0.5*01*01*01
04390      VAL=F1/3.0
04400      D0 1000 I=1,L
04410      AI=I
04420      F1=-F1*0.25*Z*Z/(AI*AI+AI)
04430      VAL=VAL+F1/(2.0*AI+3.0)
04440 1000 CONTINUE
04450      G0 T0 1020
04460 1010 X0=(((-188.1357/Z+109.1142)/Z-23.79333)/Z+2.050931)/Z
04470      X0=((X0-0.1730503)/Z+0.7034845)/Z-0.064109E-3
04480      X1=(((-5.817517/Z+2.105874)/Z-.6896196)/Z+.4952024)/Z
04490      X1=(X1-0.187344E-2)/Z+0.7979095
04500      VAL=(1.0-SQRT(Z)*(X1*C0S(Z-PI/4.0)-X0*SIN(Z-PI/4.0)))/
04510      1(X*X*X)
04520 1020 RETURN
04530      END
04540      SUBROUTINE PHASET(A,B,C,V1,03)
04550      DIMENSION A(3,5),B(3,5),C(3,5)
04560      01=A(2,5)*SIN(B(2,5))-A(2,1)*SIN(B(2,1))
04570      02=-(A(2,5)*C0S(B(2,5))-A(2,1)*C0S(B(2,1)))
04580      03=ATAN2(01,02)
04590      V1=A(2,1)*SIN(03+B(2,1))
04600      D0 2000 I=1,3
04610      D0 2000 J=1,5
04620 2000 C(I,J)=03-ATAN2(V1,SQRT(A(I,J)*A(I,J)-V1*V1))+B(1,J)
04630      RETURN
04640      END
04650      SUBROUTINE SENS(0,RAD,01)
04660      DIMENSION 0(3,5)
04670      09=0(1,1)
04680      00=0(1,1)
04690      D0 3010 I=2,5
04700      IF(0(1,I).LT.09) G0 T0 3000
04710      09=0(1,I)
04720 3000 IF(0(1,I).GT.00) G0 T0 3010

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04730      Q0=Q(1,1)
04740 3010 CONTINUE
04750      Q1=(Q(1,1)+Q(1,2)+Q(1,3)+Q(1,4)+Q(1,5))/5.0
04760      Q1=Q1-(Q(3,1)+Q(3,2)+Q(3,3)+Q(3,4)+Q(3,5))/5.0
04770      XL0=Q9-Q0
04780      PERCT=100*XL0/Q1
04790      DEGR1=Q1*RAD
04800      DEGR2=XL0*RAD
04810      TYPE 3020,Q1,XL0,PERCT
04820 3020 FORMAT(1H,12HPHASE SHIFT=,1PE12.5,2X,8HLIF10FF=,
04830      11PE12.5,2X,2H%=,1PE12.5)
04840      TYPE 3030,DEGR1,DEGR2
04850 3030 FORMAT(1H,7HDEGREE=,1PE13.5,5X,1PE13.5)
04860      RETURN
04870      END
04880      SUBROUTINE GAGER(RES)
04890      COMMON /B3/G,D1,D2,RLN,T5,N1,J1,D,E
04900      PI=3.1415926536
04910      IF(J1.EQ.1) G0 T0 4015
04920      N1=-1
04930      D3=0.95*SQR((D2-D1)*RLN/T5)
04940      X2=1.0371E-5/(D3*D3)
04950      Q=40.0
04960 4000 G=40.0+10.0*(ALOG(X2)-ALOG(.9989+.017*(Q/10.0-1.0)))/2.3
04970      10259
04980      IF(ABS(Q-G).LT.1.0E-4) G0 T0 4010
04990      Q=G
05000      G0 T0 4000
05010 4010 IG=G
05020      G=IG
05030 4015 X2=(.9989+.017*(G/10.0-1.0))*10.0**((G/10.0-4.0)
05040      D3=SQR(1.0371E-5/X2)
05050      IF(G.GT.40.0) G0 T0 4020
05060      X3=(.460655*ALOG(D3*1.E3)-.43444)*1.E-3
05070      G0 T0 4030
05080 4020 X3=(.98.02228*D3+2.56791E-2)*1.E-3
05090 4030 ID=(RLN/(D3+X3))
05100      D=ID
05110      IE=(D2-D1)/(D3+X3)
05120      E=IE
05130      IF(N1.EQ.-1) G0 T0 4040
05140      T5=D*E
05150 4040 RES=T5*X2*(D2+D1)*PI/12.0
05160      RETURN
05170      END
05180      SUBROUTINE CIRCT(TMAG,PHASE,Q0,T1,T2)
05190      COMMON /B1/R1,R2,R3,R4,RL3,RL4,R0,R6,R7,R9,C6,C7,V0,GAIN
05200      COMMON /B1/W,FREQ,RBAR,URNS1,URNS2/B2/TMUT,DRIVER
05210      COMMON /B2/PICKUP,AIR1,AIR2
05220      COMPLEX TMUT,DRIVER,PICKUP,Z1,Z2,Z3,Z4,Z5,Z6,Z7
05230      COMPLEX DENOM,TNUM,V0LT
05240      DIMENSION TMUT(3,5),DRIVER(3,5),PICKUP(3,5)
05250      DIMENSION TMAG(3,5),PHASE(3,5)
05260      T1=URNS1/((R2-R1)*RL3)
05270      T2=URNS2/((R4-R3)*RL4)
05280      Q0=6.300475204E-7*FREQ*RBAR
05290      Z1=CMPLX(W*R0*C6,-1.0)
05300      Z2=CMPLX(W*R9*C7,-1.0)
05310      Z3=CMPLX(0.0,-R0)

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05320      Z4=CMPLX(0.0,-R9)
05330      D0 5000 I=1,3
05340      D0 5000 J=1,5
05350      Z5=Q0*T1*T2*TMUT(I,J)
05360      Z6=Q0*T1*T1*(0.0,1.0)*(DRIVER(I,J)+AIR1)
05370      Z7=Q0*T2*T2*(0.0,1.0)*(PICKUP(I,J)+AIR2)
05380      DEN0M=Z1*Z2*Z5*Z5+(Z1*(Z6+R6)+Z3)*
05390      5 (Z2*(Z7+R7)+Z4)
05400      TNUM=V0*R9*GAIN*(0.0,-1.0)*Z5
05410      V0LT=TNUM/DEN0M
05420      TMAG(I,J)=CABS(V0LT)
05430 5000 PHASE(I,J)=ATAN2(AIMAG(V0LT),REAL(V0LT))
05440      RETURN
05450      END
05460      SUBROUTINE CIRCT1(Q1,V1,0,RAD,SEN)
05470      DIMENSION Q(3,5),TMAG(3,5),PHASE(3,5)
05480      CALL CIRCT(TMAG,PHASE,Q0,T1,T2)
05490      Q1=0.0
05500      D0 6000 I=1,3
05510      D0 6000 J=1,5
05520      Q2=Q1-ATAN2(V1,SQRT(TMAG(I,J)*TMAG(I,J)-V1*V1))
05530      1+PHASE(I,J)-Q(I,J)
05540      IF(ABS(Q1).GT.ABS(Q2)) G0 T0 6000
05550      Q1=Q2
05560 6000 CONTINUE
05570      Q2NEW=RAD*Q1
05580      Q3=100.0*Q1/SEN
05590      TYPE 6010,Q1,Q2NEW,Q3
05600 6010 FORMAT(1H+,1X,2(1PE12.5,2X),1PE12.5)
05610      RETURN
05620      END

```

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