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FEASIBILITY EVALUATION OF ADVANCED MULTIFREQUENCY EDDY CURRENT --ETC(U)

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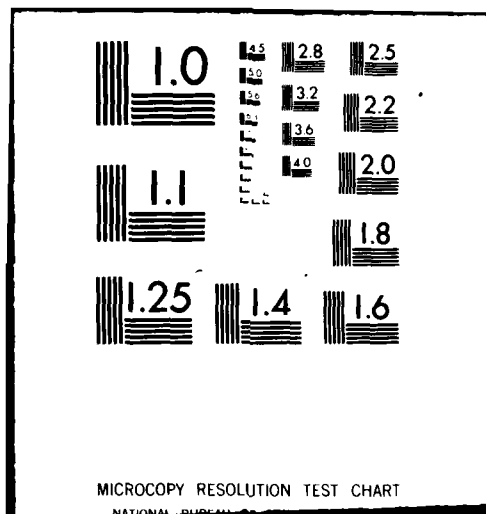
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**FEASIBILITY EVALUATION OF ADVANCED MULTIFREQUENCY
EDDY CURRENT TECHNOLOGY FOR USE
IN NAVAL AIR MAINTENANCE ENVIRONMENT**

Handling and Servicing/Armament Division
Support Equipment Engineering Department
Naval Air Engineering Center
Lakehurst, New Jersey 08733

8 DECEMBER 1980

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Prepared for

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Washington, DC 20361

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FEASIBILITY EVALUATION OF ADVANCED
MULTIFREQUENCY EDDY CURRENT TECHNOLOGY
FOR USE IN
NAVAL AIR MAINTENANCE ENVIRONMENT

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The optimization of a multifrequency eddy current test was performed for the detection and characterization of second-member corrosion using computer programs. The results of the analytical studies showed that both inner and outer surface corrosion could be detected and quantified. Air gap variations could also be distinguished from corrosion using multifrequency data. These results were confirmed experimentally using phase-sensitive eddy current instrumentation.			

SUMMARY AND CONCLUSIONS

Initial studies conducted by Battelle-Columbus Laboratories, reference (a), identified potential advantages in using more advanced eddy current techniques in Naval Air Systems Command maintenance inspection applications. Recommendations were made for a follow-on effort in which an existing inspection problem would be addressed using multifrequency approaches.

Messrs. Eli Nicosia and Richard McSwain at the Naval Air Rework Facility (NAVAIREWORKFAC), Pensacola, were contacted by Mr. Richard Deitrich of the Naval Air Engineering Center, and a candidate problem was identified to be the detection and characterization of corrosion between the T-39 fuselage skin (first member) and the airframe (longerons and ribs - second member). Present NAVAIREWORKFAC Pensacola eddy current inspection techniques rely on the use of a relatively high inspection frequency for the detection of second-member outer surface corrosion, that is outboard surface corrosion. This is accomplished by detecting the presence of a gap which is created between the aircraft skin/structural member as a result of corrosion product expansion. Variations in skin/structural spacing can occur without the presence of corrosion, resulting in the potential for incorrect calls. In addition, second-member inner surface corrosion, that is inboard surface corrosion, cannot be detected using present techniques.

The objective of the present effort was to implement multifrequency techniques with the specific goals of:

1. Detecting corrosion on the inner surface of the second member,
2. Quantifying inner surface and outer surface second-member corrosion depth, and
3. Differentiating between inner surface corrosion and the normally occurring air gap.

The optimization of a multifrequency eddy current method for the detection and characterization of second-member inner and outer surface corrosion was modeled using a computer program originally developed by C. V. Dodd at Oak Ridge National Laboratory. Refinements were made to the program for increased computational efficiency. The results of the analytical studies showed that inner surface and outer surface corrosion could be detected and quantified with regards to depth. Air-gap variations could also be distinguished using multifrequency eddy current data. The analytical results were confirmed experimentally using phase-sensitive eddy current design. Optimization of the overall eddy current test design was greatly aided by the use of the modified computer program.

Ref: (a) NAVAIRENGCEN Report NAEC-92-128 of 28 Sep 1978: Feasibility Evaluation of Advanced Eddy Current Inspection Equipment For Use in Naval Aviation Maintenance Environment

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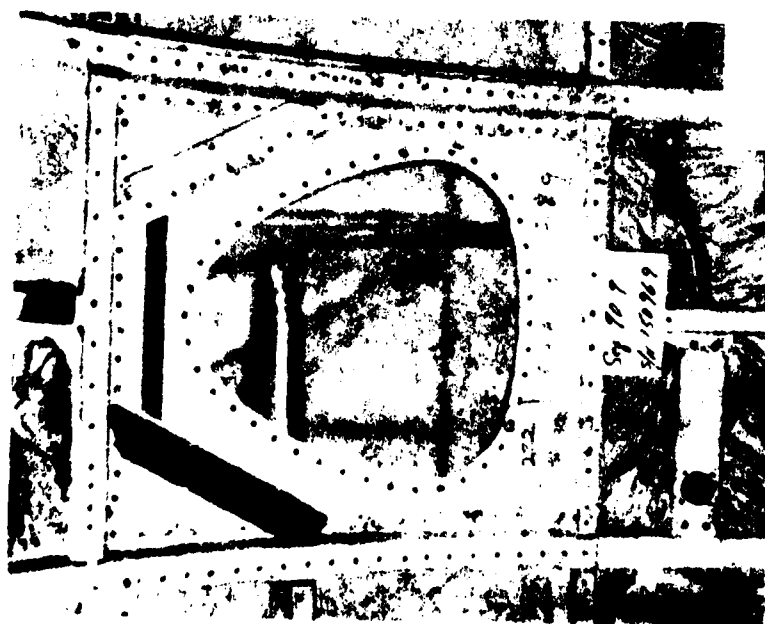
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I. INTRODUCTION

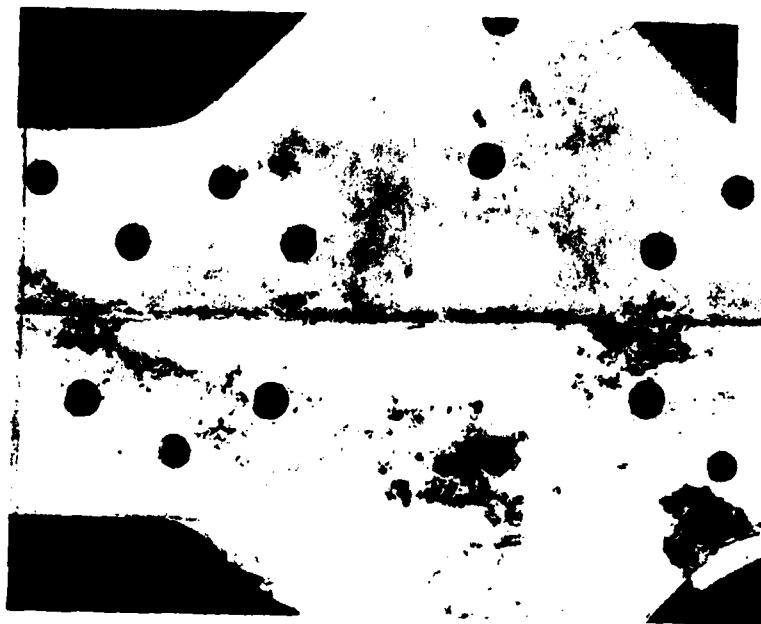
A. GENERAL.

1. The objective of this program was to demonstrate the benefits of multifrequency eddy current technology as applied to a particular Naval Air Systems Command (NAVAIRSYSCOM) maintenance inspection problem--the detection and characterization of corrosion hidden beneath the T-39 aircraft skin surfaces. Corrosion presently initiates on the aircraft structural member at either the inner or outer surface. Inner surface structural corrosion (ISSC) is presently undetectable using existing NAVAIRSYSCOM maintenance inspection procedures. Outer surface structural corrosion (OSSC) product, if severe, forces a separation between the two members. Existing NAVAIRSYSCOM maintenance inspection methods rely on the use of an eddy current technique for the detection of this skin/structure air gap. The gap magnitude is indicative of corrosion severity. Variation in skin/structure spacing can occur without any structural corrosion being present. Hence regions which do not exhibit any corrosion can be incorrectly identified as being corroded. Figure 1 illustrates T-39 ISSC and OSSC as they typically occur.

2. In order to systematically investigate the overall problem of the detection and characterization of aircraft structural member corrosion, computer programs developed by C. V. Dodd at Oak Ridge National Laboratory were utilized. These programs were modified for increased computational efficiency and were used to study two important eddy current test parameters which are coil excitation frequency and coil size. ISSC and OSSC were modeled as extended areas of change in overall skin/structural member thickness. The effects of air-gap variations between the skin and structural member were handled analytically by considering a three-layer model of the aircraft skin and structural member where the spacing between the two is variable. The results of the computer studies suggest that a two-frequency multifrequency system can detect and characterize ISSC and OSSC as well as distinguish between air-gap variations. The analytical results were confirmed experimentally using simulated sections of corroded panels. Phase-sensitive eddy current instrumentation incorporating reflection coils was used for data acquisition.



Backside of T-39 Window Showing
Inner Surface Structure Corrosion



Areas of Outer Surface Structural Corrosion
on an Extruded Longeron

FIGURE 1. EXAMPLES OF INNER SURFACE AND OUTER SURFACE STRUCTURAL CORROSION

II. REFLECTION COIL INSTRUMENTATION

A. COILS.

1. Phase-sensitive eddy current instrumentation incorporating reflection coils was utilized throughout the course of this program. Features of this type of instrumentation are described and compared with the more conventional eddy current instrumentation.

B. COIL TYPES. The most common type of coil used in conventional eddy current testing is the parametric coil. A parametric coil is defined as any coil in which the eddy current generator (drive coil) is the same as the detector (pickup coil). An alternate type, in which the drive and pickup coils are physically separated, is called a transformer coil. The voltage detected by the eddy current instrument is induced in the pickup coil by transformer-like action, that is through mutual inductance effects.

1. The use of transformer coils offers two primary advantages over parametric coils. The first advantage is the simplification of the associated electronic circuitry afforded by the isolation of the power driving circuits and the measuring circuits. Secondly, it is very difficult to isolate variations in the intrinsic impedance ($R + j\omega L$) of parametric coils from variations of the coil impedance due to the variation of test parameters such as thickness, conductivity, or the presence of discontinuities.

2. Variations in coil resistance with temperature are especially difficult to eliminate, and may cause drastic errors in the eddy current measurements. Transformer coils, in principle, can be made free of this effect if the drive coil is driven with a constant current source, and pickup coil voltage is measured with a high impedance vector voltmeter. Simplicity of design, though, is a considerable advantage of parametric coils over transformer coils, as will be shown below.

3. The main contributor to the design and use of transformer coils in this country has been C. V. Dodd at the Oak Ridge National Laboratory. His design of a transformer coil, which he calls a reflection coil, is shown in Figure 2. As can be seen, it consists of a large drive coil surrounding two smaller pickup coils. The pickup coils are connected in series opposition so that the voltage induced in the secondary windings away from any material is zero, and the voltage across the secondary is due only to the electromagnetic and dimensional properties of the material being tested.

4. Reflection coils may be characterized by several sets of parameters. These are:

- a. dimension of the drive coil (r_1, r_2, l_1 ; 3 parameters)
- b. dimensions of the pickup coils (r_3, r_4, l_3 ; 3 parameters)
- c. location of the pickup coils with respect to the drive coil (l_5 ; 1 parameter)

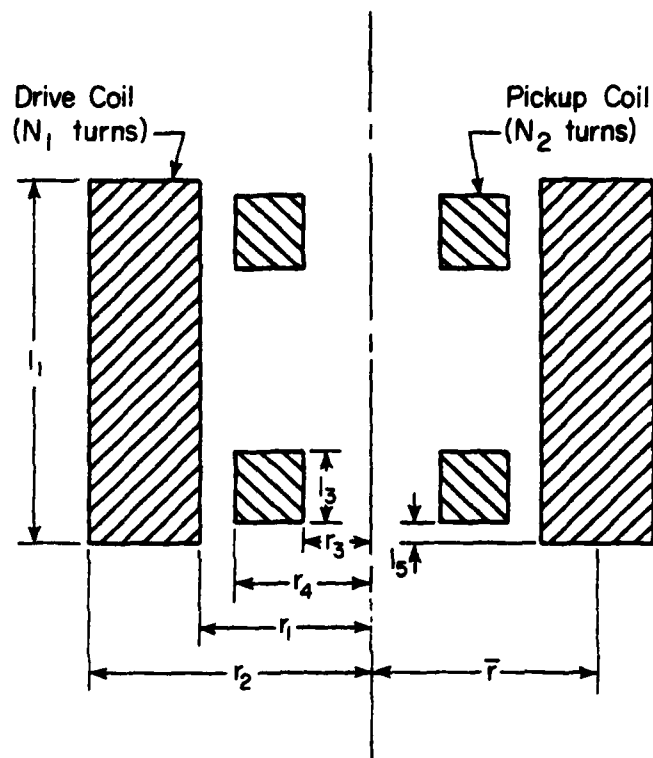


FIGURE 2. CROSS-SECTIONAL VIEW OF A REFLECTION COIL

- d. electromagnetic character of drive coil (number of winding turns, N_1 ; 1 parameter)
- e. electromagnetic character of pickup coils (number of winding turns, N_2 ; 1 parameter)

Thus, there are nine different parameters that control the design of reflection coils, all of which may be varied more or less independently. Compare this with a parametric coil, which has four parameters (three dimensional and one electromagnetic), and it can be seen that parametric coils are, by far, simpler to design.

5. Fortunately, Dodd, who promulgated the use of reflection coils, has also done a great deal to simplify their design. He has examined, in detail, the interdependency of the various parameters to come up with one basic design which depends most strongly on only one parameter, the drive coil mean radius, denoted as $\bar{r}$ in Figure 2. In general, smaller coils are used for low penetration, high frequency, and high resolution, and large coils are for deep penetration, low frequency, and reduced resolution.

C. PHASE-SENSITIVE DETECTION. Reflection coils are typically used with phase-sensitive detection schemes. Advantages and disadvantages of this approach are now considered.

1. Any sinusoid can be characterized by three parameters, one of which is frequency. The other two parameters are the magnitude of the signal and its phase lead or lag relative to some reference voltage. These will be called A and ϕ respectively. These two parameters may, in turn, be related to two others, commonly called the inphase and quadrature, designated x and y respectively. The transformation between these two sets of parameters is given by

$$\begin{aligned} x &= A \cos \phi \\ y &= A \sin \phi \\ \phi &= \tan^{-1} \left(\frac{y}{x} \right) \\ A &= (x^2 + y^2)^{1/2} \end{aligned} \tag{1}$$

Detection schemes may be devised which measure either of the two sets. These measurements are usually made independently of each other, though, since the electronic circuitry necessary for the above transformation is more complex than the circuitry which measures either set. Circuits which measure ϕ are called phase-sensitive instruments, and those which measure x and y are called vector voltmeters. Measurements of the magnitude A are rather trivial, and will not be discussed.

2. Since there are two sets of parameters which describe the eddy current response, the question arises as to which should be used. The answer to this question depends not only on the material parameter being measured, but also on whether the eddy current system being used balances out certain constant (or almost constant) voltages which appear across the pickup coil.

3. The voltage across the pickup can be separated into two parts, as illustrated in Figure 3: the voltage due to the mutual inductance between the drive and pickup coil (self-inductance in parametric coils) and the voltage due to the presence of the test material. All systems provide a means of nulling or balancing out the first of these two voltages; some internally through a balance network, and some externally through the coil configuration. Typically, parametric coils are balanced internally and transformer coils externally, though this is not necessarily so.

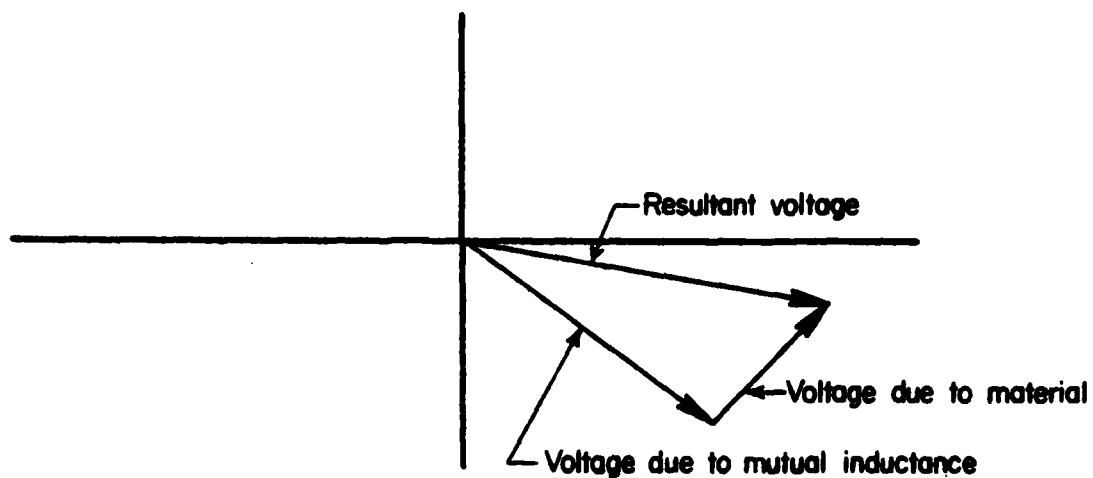
4. The remaining voltage, then, is due to the presence of the material and is determined by the bulk material properties (resistivity, conductivity, and geometry). This, too, can be divided into two parts: one due to the nominal material properties, and the other due to a change in one or more of these properties. This is illustrated in Figure 4, where the sinusoid due to the nominal material characteristics is the vector A, and that due to a change is the vector B. In an unbalanced system, the two add, giving a resultant vector A. In a balanced system, A is eliminated, leaving B. In general, phase-sensitive instruments do not allow this kind of balancing, while vector-voltmeter-based systems do.

5. The output of a phase-sensitive detector is a dc voltage proportional to ϕ , so it is limited to something corresponding to $\pm 180^\circ$, which means that 0.02° is about 1 millivolt on a ± 10 -volt full scale range. Phase measurements, then, have a limited dynamic range regardless of the amplitude of the sinusoid being measured. However, they also have a limited sensitivity. It is not difficult to show that the change in phase angle $\Delta\phi$, due to the presence of the vector B, is

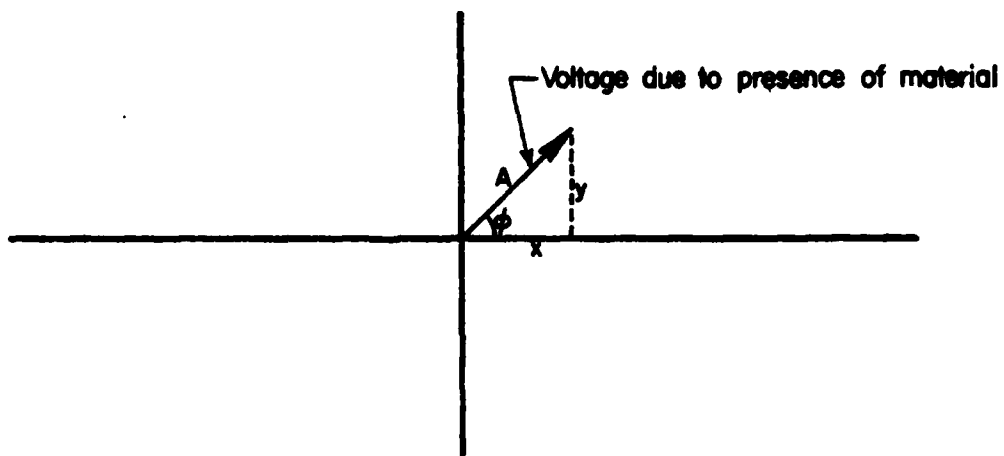
$$\Delta\phi = \tan^{-1} \left(\frac{\sin\theta}{\frac{A}{B} + \cos\theta} \right) \quad (2)$$

where A, B, θ , and $\Delta\phi$ are defined in Figure 4. A/B ratios of a thousand or more are not unrealistic, which means that $\Delta\phi$ is limited to $\pm 0.06^\circ$, depending on θ . On the other hand, phase-sensitive instruments can be made more insensitive to liftoff variations than can vector-voltmeters, though a demonstration of this is beyond the scope of this discussion.

6. The conclusion is that phase-sensitive detectors and vector voltmeters are both useful under different test situations. Phase-sensitive instruments are good for measuring bulk properties, surface and slightly subsurface defects where A/B is smaller, and when sensitivity to liftoff is of concern. Vector-voltmeters, on the other hand, are best for detecting the smaller volume flaws and flaws further into the material where A/B is large. There is, of course, no well defined delineation between the two, and there is much overlap in their useful test applications.

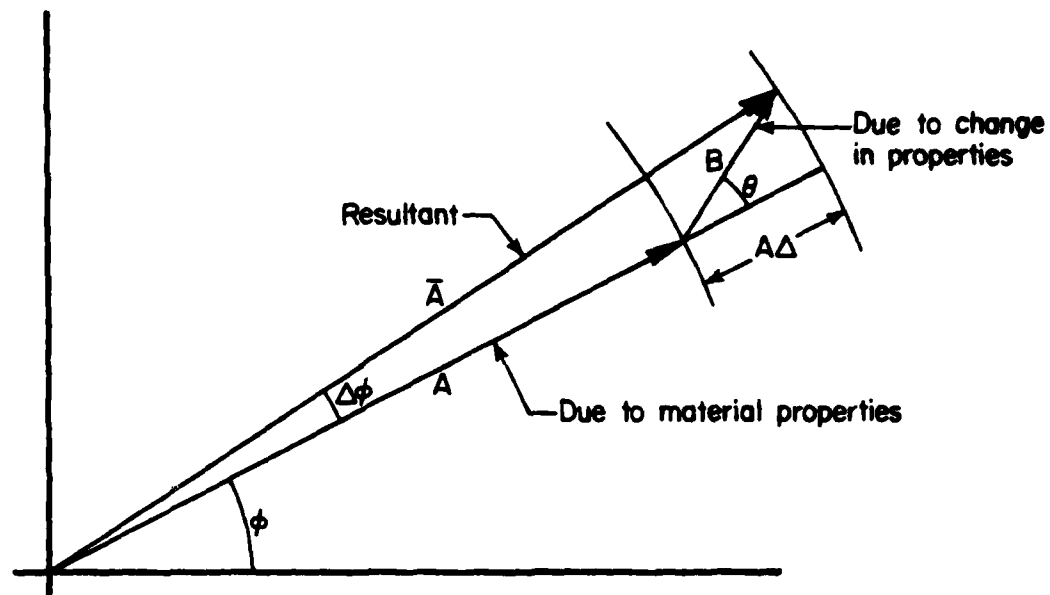


a) Before mutual inductance is balanced out

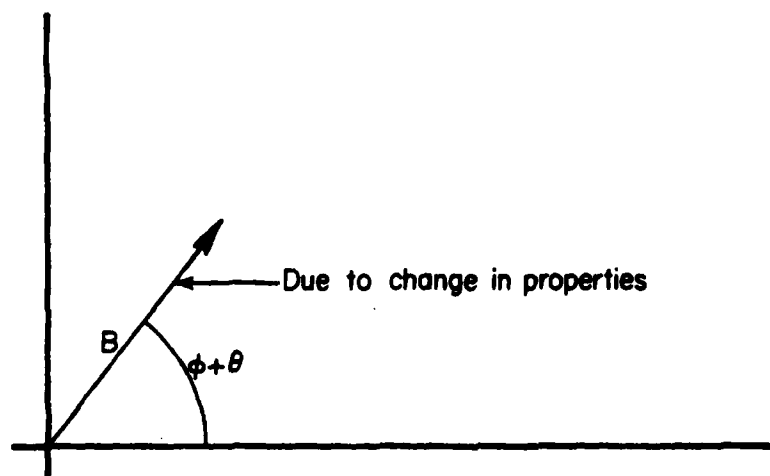


b) After mutual inductance is balanced out

FIGURE 3. VECTOR REPRESENTATION OF MUTUAL INDUCTANCE VOLTAGE ACROSS AN EDDY CURRENT COIL



a) In an unbalanced system



b) In a balanced system

FIGURE 4. VECTOR REPRESENTATION OF VOLTAGE DUE TO A TEST ARTICLE NEAR AN EDDY CURRENT COIL

III. EDDY CURRENT TEST OPTIMIZATION USING COMPUTER MODELING

A. INITIAL CONDITIONS.

1. The computer program used to model the airframe corrosion problem is a modified version of C. V. Dodd's program MULTIT. The modifications were made to simplify the data input routines, and to decrease the execution time of the integration subroutines by approximately 15 percent. The program is designed to analyze thickness changes in any given layer in a multilayer conducting medium.

2. As shown in the previous section, Dodd has eliminated much of the tedium in designing reflection coils, channeling the present effort into selecting only two test parameters, the coil mean radius and the test frequency. These are determined solely by the dimensional and electromagnetic properties of the test samples under consideration.

3. In general, there are two parameters which characterize any layer of the multilayer system (assuming that all layers are nonmagnetic); these are thickness and conductivity. Since the materials under consideration may be divided into three parts (that is the skin, the structural member, and the sealant/air gap* or corrosion products between the two), there are six parameter variations which should be investigated to completely describe the given problem. Actually there are only five, since the conductivity of air, sealant, and corrosion products is zero, for all practical purposes. A proper investigation of all permissible variations was beyond the scope of this project; hence, only certain variations were allowed, which, it was thought, would indicate the method of solution necessary for any variation of the above parameters.

4. The following assumptions were made:

- a. The thickness of the skin was 0.050 inch, and did not vary.
- b. The thickness of the structural member was 0.250 inch, and did not vary, except when corrosion was present.
- c. The resistivity of the skin was the same as that of the structural member, neither of which varied. This resistivity was set at 5.0 ohm-cm, a nominal value for aluminum.
- d. Corrosion of the structural member at the faying surface effectively increased the thickness of the air or sealant gap by the thickness of the corrosion products, while decreasing the thickness of the structural member by the same amount.

* The terms sealant thickness and air-gap thickness are used interchangeably, since, from an eddy current testing standpoint, they are equivalent.

- e. Corrosion of the structural member on the side away from the faying surface decreased the thickness of the structural member, but did not change the thickness of the air or sealant gap.

5. During the course of this project, ten cases were analyzed, as detailed in Table I. OSSC, outer surface corrosion, is taken to be at the structural member faying surface; and ISSC, inner surface corrosion, refers to corrosion of the structural member away from the faying surface. These ten cases can be divided into four categories:

- a. The nominal structure (case 1)
- b. Corrosion on the inner surface of the structural member (cases 2, 3, and 4)
- c. Corrosion on the outer surface of the structural member (cases 5, 6, and 7)
- d. Changes to the sealant or air gap, an extraneous variable (cases 8, 9, 10).

A pictorial representation of the four categories is shown in Figure 5.

TABLE 1. GEOMETRIES OF THE COMPUTER-ANALYZED CASES

Case	Thickness (In.)			Defect Type
	Member	Sealant	Skin	
1	0.250	0.005	0.050	Nominal Structure
2	0.2375	0.005	0.050	5% Corrosion - ISSC
3	0.225	0.005	0.050	10% Corrosion - ISSC
4	0.200	0.005	0.050	20% Corrosion - ISSC
5	0.2375	0.175	0.050	5% Corrosion - OSSC
6	0.225	0.030	0.050	10% Corrosion - OSSC
7	0.200	0.055	0.050	20% Corrosion - OSSC
8	0.250	0.175	0.050	Sealant Thickness Change Equivalent To: 5% Corrosion
9	0.250	0.030	0.050	
10	0.250	0.055	0.050	

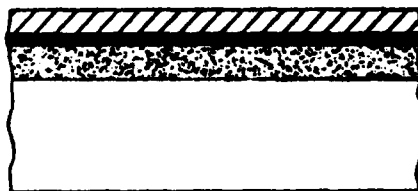
6. Existing computer models, including the one used here, have certain limitations on the size of modeled defects, such as corrosion, due to the mathematical complexity of modeling electromagnetic phenomena. Presently, flaw sizes must be limited to either very large volume or very small volume, as related to the size of the inspection coil. Large volume analysis was selected in this



Category A
Nominal Structure



Category B
Inner Surface Corrosion



Category C
Outer Surface Corrosion



Category D
Extraneous Variable (Air Gap)

Key



Skin



Structural Member



Sealant / Air Gap



Corroded Region

FIGURE 5. PICTORIAL REPRESENTATION OF THE VARIOUS CORROSION CATEGORIES

project, and it was assumed that the trends predicted by the large volume analysis would accurately follow the trends of intermediate-sized flaws. For the most part, this assumption was shown to be true.

B. RESULTS OF THE ANALYTIC STUDIES. This section contains the results of the computer modeling for the various categories detailed in the previous section. In particular, it is shown how extraneous variables, such as changes in the air-gap thickness, may be discriminated from corrosion at the outer surface by using multiple inspection frequencies.

1. DETECTION AND CHARACTERIZATION OF CORROSION - ISSC.

- a. Cases 2, 3, and 4 of category B were examined to determine the relationship between eddy current phase angle and test frequency for different depths of corrosion. The results of the computer analysis are shown in Figure 6. Only one coil was analyzed for this case, the 300A, at frequencies ranging from 100 Hz to 1000 Hz. The various corrosion depths are indicated as a percentage of the structural member thickness. The trends to be noted from these results are:
 - (1) As frequency decreases, sensitivity increases, then decreases, indicating a point of maximum sensitivity at about 200 Hz.
 - (2) Phase roll-off with frequency appears to drop faster at the high frequencies than the low; that is, it is better to be below the maximum than above it.
 - (3) The frequency chosen for this coil appears to relate well with skin depth δ , since δ at 200 Hz is about 0.31 inch.
- b. In most eddy current testing, it is as important to characterize flaws as it is to detect them; in this case, one should be able to give a figure for the remaining thickness after corrosion. Apparently this is possible, since there is a monotonically increasing relationship between phase angle and corrosion depth (see Figure 7). However, it must be remembered that this derived relationship is for large volume flaws, and that smaller volume flaws will give smaller phase angles, at the same depth, than large volume flaws. Thus, any practical calibration curves must measure phase angles for corroded regions of different areas as well as different depths.
- c. Phase angle, rather than magnitude of the eddy current signal, is used as the discriminating signal for two reasons. First, it is directly relatable to the thickness of the test piece, and second, it can be made relatively insensitive to liftoff effect, depending on the coil size, frequency, and instrumentation used. The magnitude of the eddy current signal, on the other hand, is almost directly proportional to liftoff, and cannot be compensated for liftoff variations.

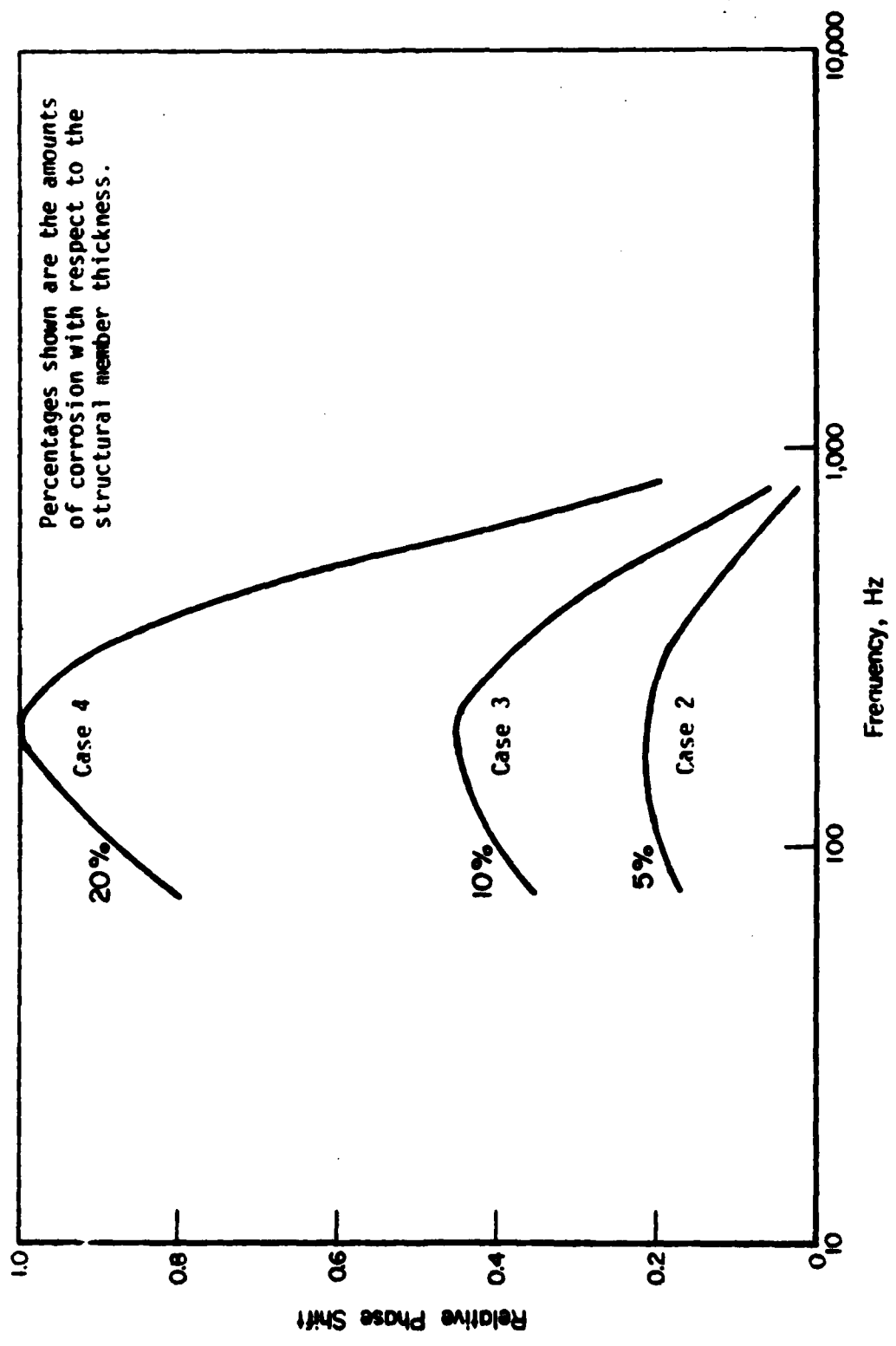


FIGURE 6. DEFECT SENSITIVITY FACTOR VERSUS FREQUENCY FOR INNER SURFACE CORROSION (300A COIL)

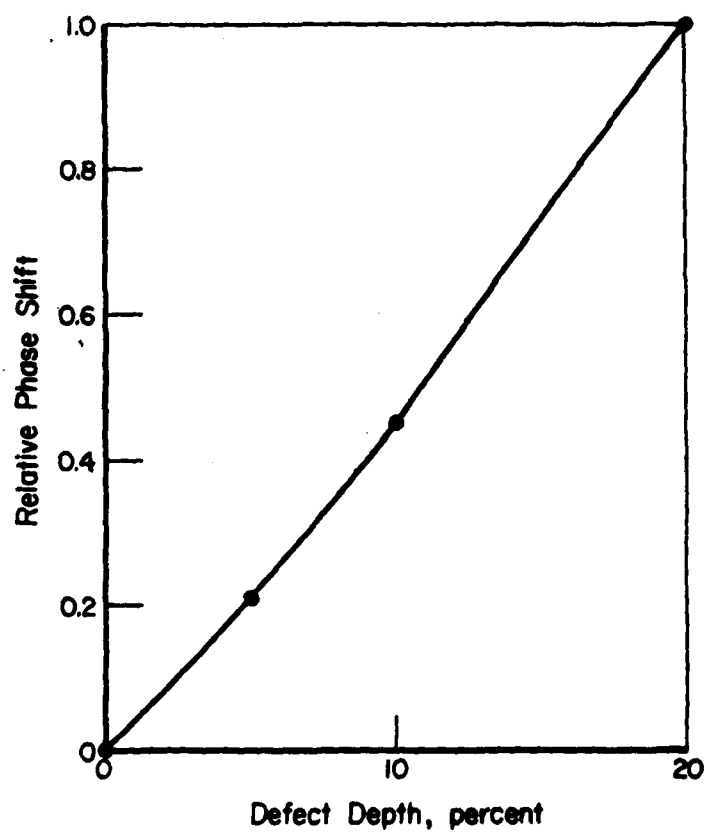


FIGURE 7. EDDY CURRENT PHASE ANGLE VERSUS DEFECT DEPTH (200 Hz)

2. DETECTION AND CHARACTERIZATION OF CORROSION - OSSC. Cases 5, 6 and 7 of category C (refer to Figure 5) were examined to determine the relationship between eddy current phase angle and test frequency for different depths of corrosion on the outer surface of the structural member. Two coils were used in this analysis: the 300A at frequencies ranging from 100 Hz to 5 kHz, and the 150A at frequencies ranging from 100 Hz to 10 kHz. The resulting data for the 300A is shown in Figure 8, and that for the 150A is shown in Figure 9. The trends to be noted are:

- a. As frequency decreases, the sensitivity increases then decreases, pointing out a region of maximum sensitivity at about 2 kHz, for both coils.
- b. Again, phase rolloff is higher for higher frequencies, indicating that it is better to be too low in frequency than too high.
- c. Optimum test frequency correlates well with skin depth δ since δ at 2 kHz = 0.10 inch, just over the thickness of the aircraft skin.

Again, it appears that flaw characterization, as well as detection, is possible as long as flaw area is taken into account. Computer-generated calibration curves for both coils are shown in Figure 10.

3. DETECTION AND CHARACTERIZATION OF SEALANT THICKNESS CHANGES. The primary detection mechanism of OSSC is through the separation of the skin from noncorroded metal of the structural member. Obviously, then, any phenomena which causes a change in this separation will be interpreted as OSSC, even though it may not be. Naturally occurring changes in the sealant or air-gap thickness must somehow be discriminated against. To do this, cases 8, 9, and 10 of category D were analyzed with the computer modeling programs, using both the 300A and 150A coils, at frequencies ranging from 100 Hz to 10 kHz. The resulting phase angle change versus frequency, with air-gap thickness as a parameter, are superimposed on the previous Figures 8 and 9 in Figures 11 and 12. The important points to note are listed below:

- a. At high frequency (above 1 kHz), there is essentially no difference between equivalent sealant thickness changes and corrosion of the outer surface.
- b. As frequency decreases, the phase-angle rolloff for sealant thickness changes is larger than for equivalent corrosion of the outer surface, thus allowing discrimination between sealant thickness changes and corrosion.
- c. The rolloff is larger for the larger coil, indicating that such discrimination could be more easily performed with the 300A than the 150A. This is due to the decreased penetration capabilities of smaller coils.

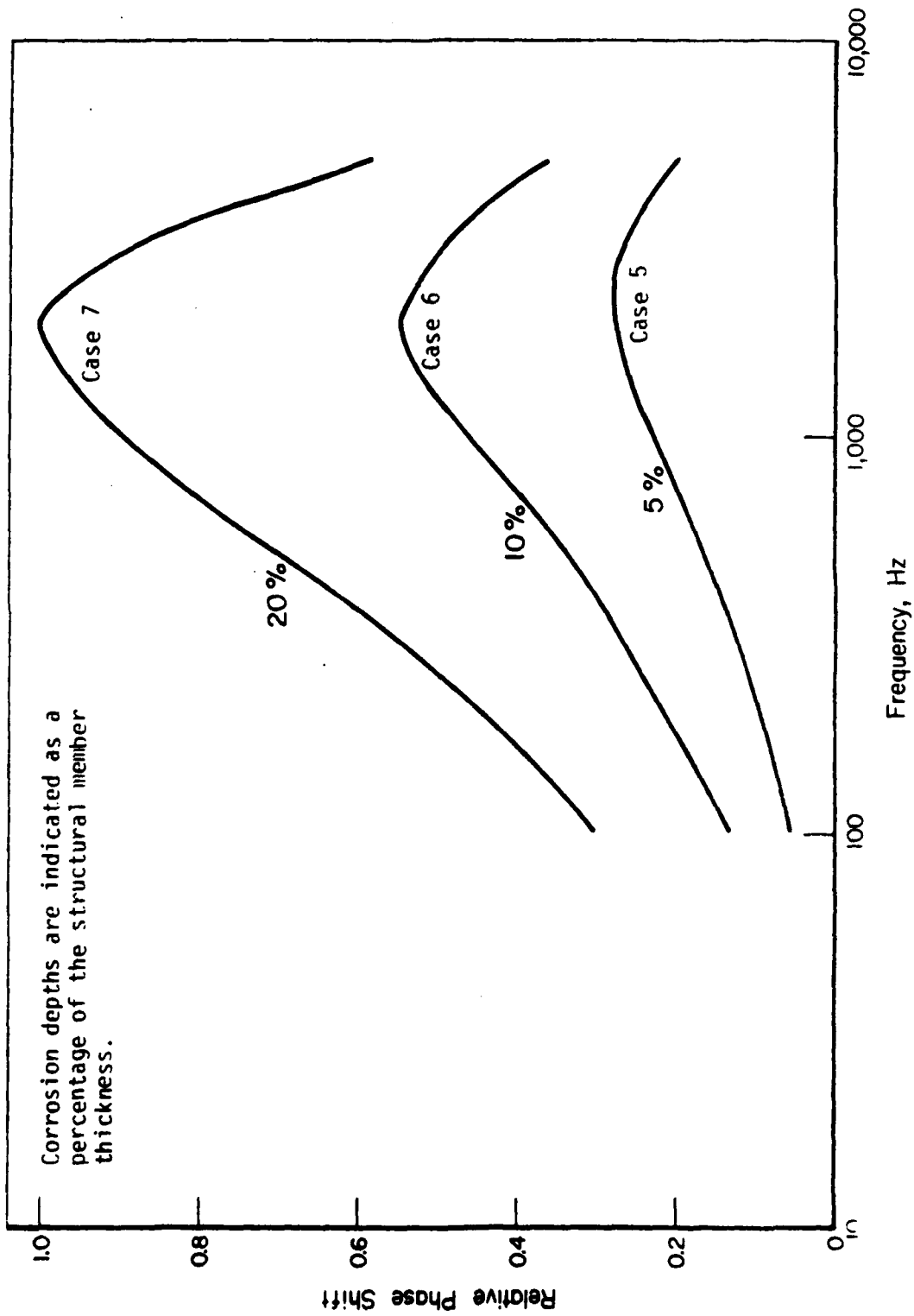


FIGURE 8. OUTER SURFACE DEFECT SENSITIVITY FACTOR VERSUS TEST FREQUENCY FOR DIFFERENT CORROSION DEPTHS (300A COIL)

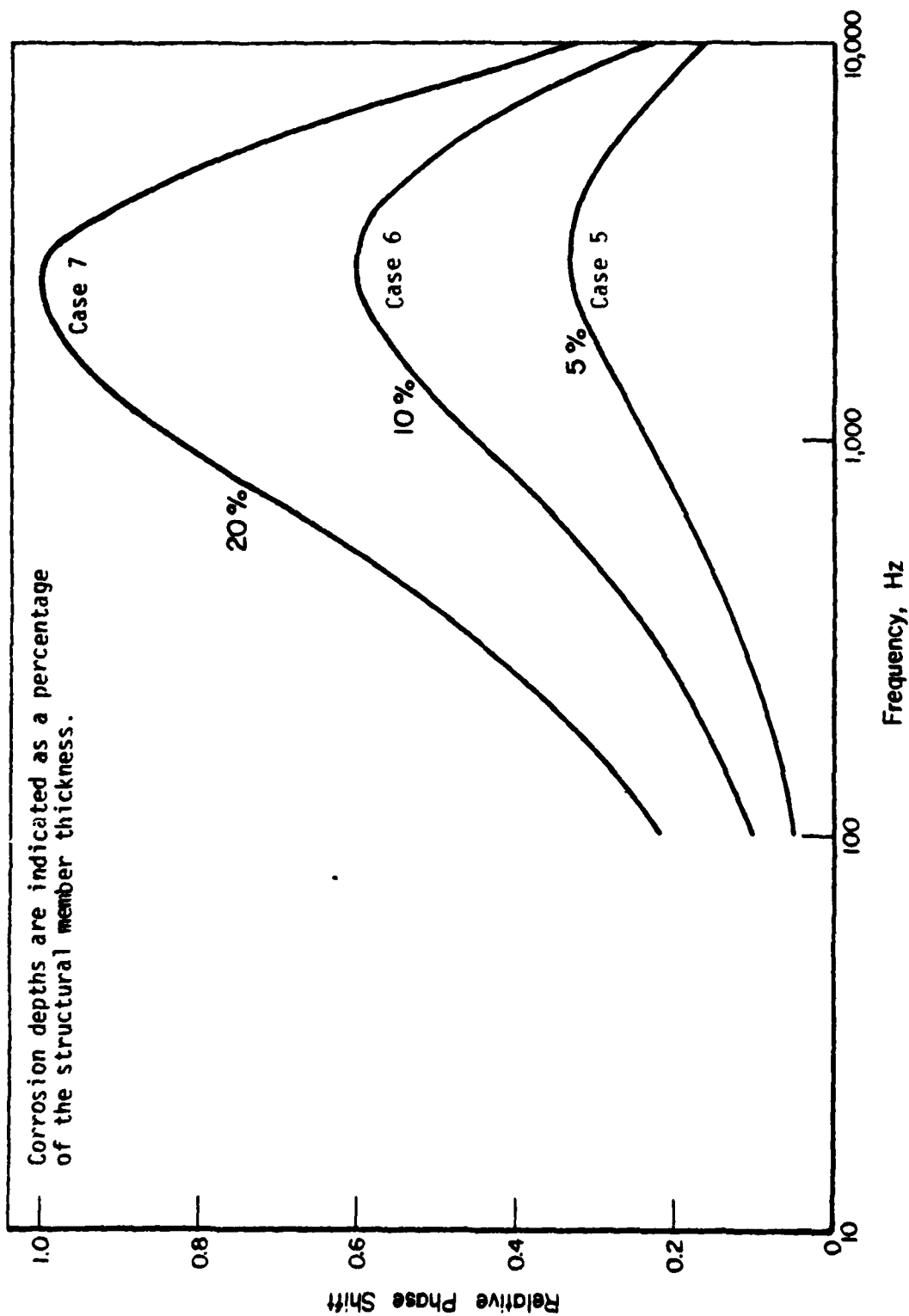


FIGURE 9. OUTER SURFACE DEFECT SENSITIVITY FACTOR VERSUS TEST FREQUENCY FOR DIFFERENT CORROSION DEPTHS (150A COIL)

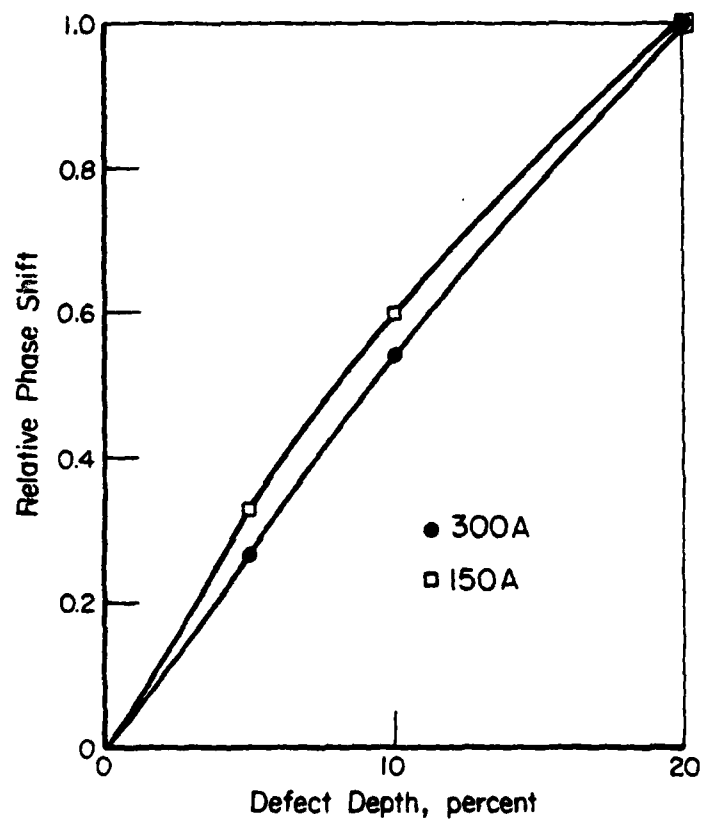


FIGURE 10. EDDY CURRENT PHASE ANGLE VERSUS OUTER SURFACE DEFECT DEPTH (2 kHz)

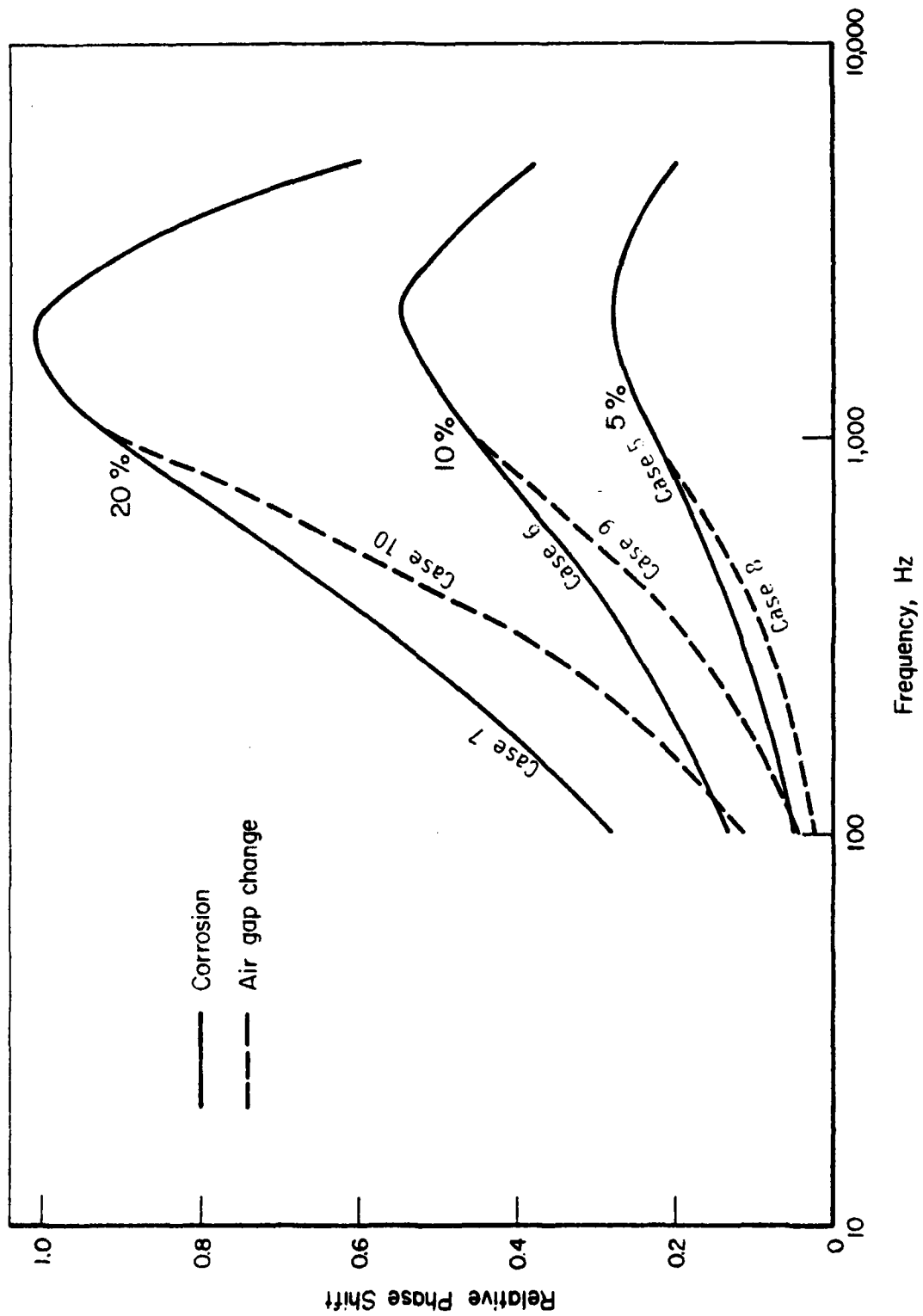


FIGURE 11. SENSITIVITY FACTOR VERSUS FREQUENCY FOR AIR-GAP THICKNESS CHANGES (300A COIL)

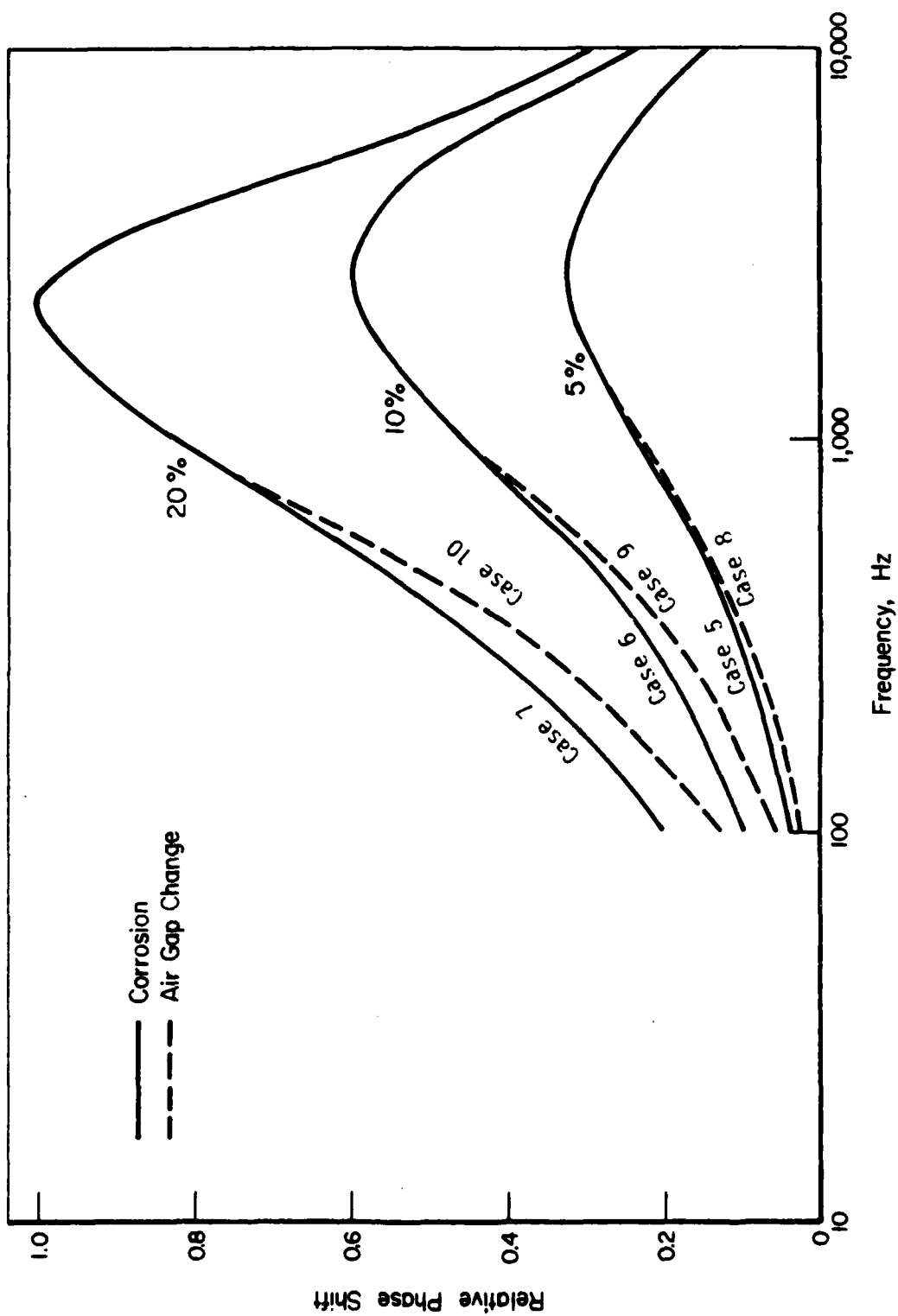


FIGURE 12. SENSITIVITY FACTOR VERSUS FREQUENCY FOR AIR-GAP THICKNESS CHANGES (150A COIL)

C. TEST IMPLEMENTATION.

1. It is now possible to envision an eddy current system that could perform the necessary inspection and its application. The system itself would necessarily be a dual-frequency system, where the test coil is excited by two frequencies simultaneously. The exact frequencies used would depend upon the thickness of the various metallic members, and if the results presented above are generalized to any structure, the high frequency is determined essentially by the skin thickness, and the low frequency is determined by the combined skin and structural member thickness. For the case examined here, with a 0.05-inch-thick skin and 0.25-inch-thick structural member, the selected frequencies are about 2000 Hz and 200 Hz respectively. Each half of the dual-frequency system would be identical, except for frequency selection, and would consist of a phase-sensitive indicator (probably a meter), a balance control (to set the initial phase reading to zero), and a liftoff compensation null (to reduce the effect of liftoff on the measured phase). Such instruments presently exist as single-frequency instruments; the modifications necessary to make a dual system are rather straightforward.

2. Three calibration curves are required. The first is an extension of Figure 7, and gives the relationship between phase angle (at 200 Hz) and depth of corrosion on the inner surface, as shown in Figure 13. As indicated above, the size of the corroded area is important, and several curves, labeled A1, A2, A3, etc., are shown to emphasize this point. The second set of curves, Figure 14, is an extension of Figure 10, in the same manner as Figure 13 is an extension of Figure 7. Again, various lateral extents of corrosion should be considered in deriving this calibration curve.

3. The last set of curves, Figure 15, is necessary for distinguishing corrosion from sealant thickness changes and is derived from Figure 11 in the following manner. For the three corrosion depths, the phase-angle change at 2 kHz is plotted along the abscissa, and the phase-angle change at 200 Hz is plotted along the ordinate, as shown in Figure 15, to obtain the curve labeled "outer surface corrosion". Similarly, the phase angle change for air-gap or sealant-thickness changes at 200 Hz is plotted versus phase-angle change at 2 kHz to obtain the curve labeled "air-gap change". A third curve is drawn between the two and is labeled "decision curve". Testing then proceeds as described in the following paragraph.

4. Call the low-frequency phase indicator meter A, and the high-frequency indicator meter B. The operator continues testing until meter A registers an indication (either or both meters may be equipped with audible alarms, if desired). He then notices whether meter B also registers an indication. If not, the indication is due to corrosion on the far side of the structural member, and the operator records the indication. If meter B also registers, then the operator must decide whether the indication is due to corrosion of the outer surface, or an air-gap change. This is done by locating the phase angle at 200 Hz versus the phase angle at 2000 Hz of the indication on Figure 15. If the indication lies above the decision curve, it is due to corrosion on the outer surface, and the operator records the indication. If it is below the decision line, it is due to an air-gap thickness change, and the operator continues testing until meter A again responds to an indication. This decision process, which is rather simple in form, is depicted in Figure 16. The applicability to computer-based decision processing is rather obvious.

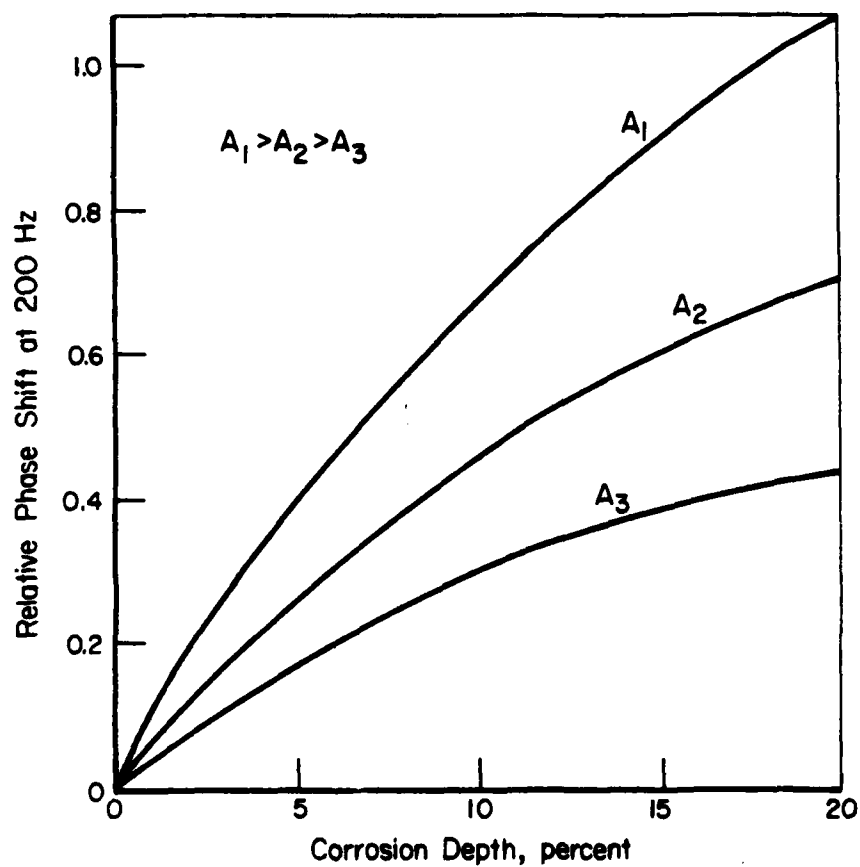


FIGURE 13. PHASE SHIFT VERSUS CORROSION DEPTH FOR VARIOUS SIZES OF INNER SURFACE CORROSION

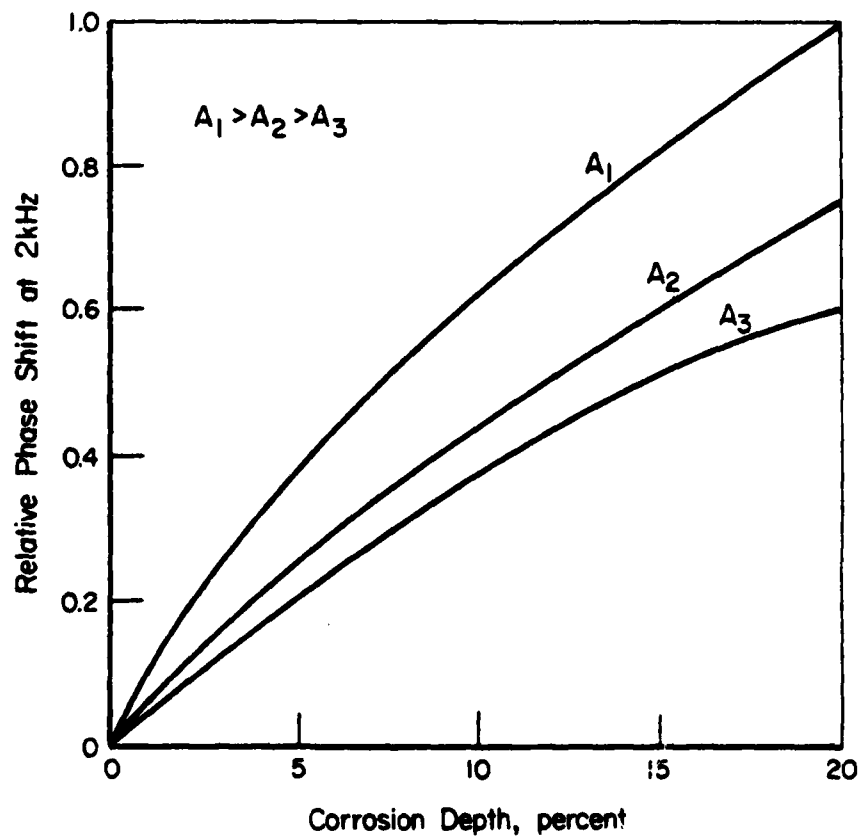


FIGURE 14. PHASE SHIFT VERSUS CORROSION DEPTH FOR VARIOUS SIZES OF OUTER SURFACE CORROSION

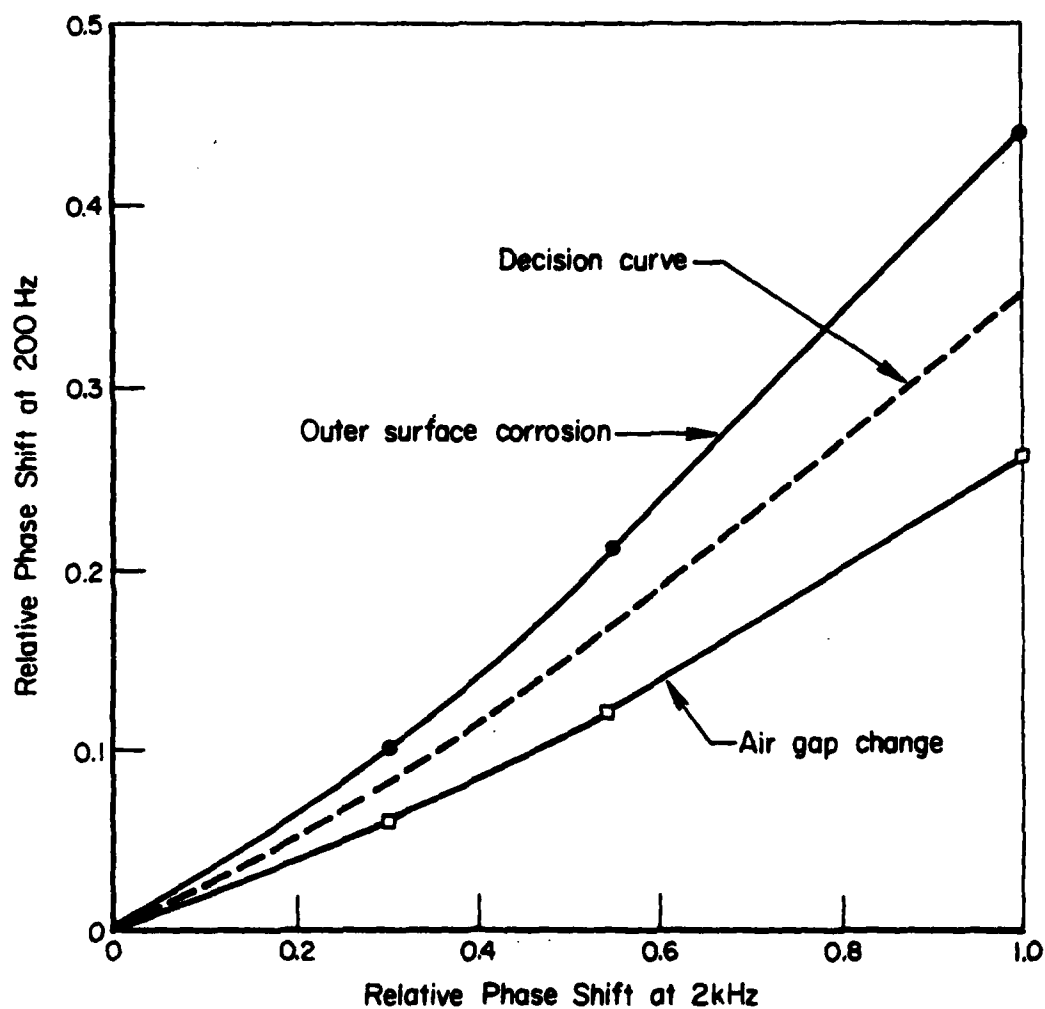


FIGURE 15. DECISION CURVE FOR SEPARATING OUTER SURFACE CORROSION FROM AIR-GAP CHANGES

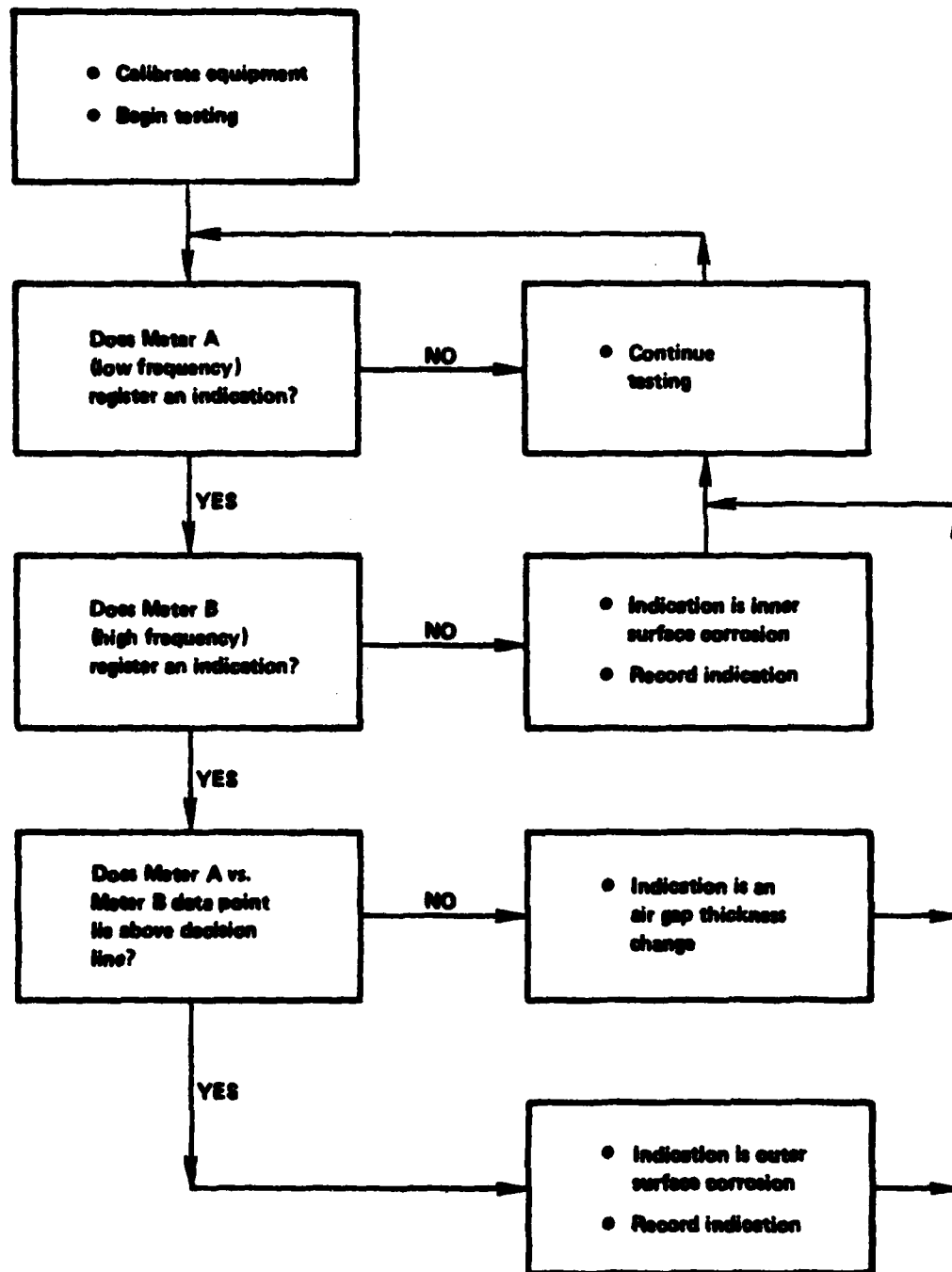


FIGURE 16. EDDY CURRENT CORROSION TESTING DECISION ALGORITHM

IV. EXPERIMENTAL VERIFICATION OF THE ANALYTICAL MODEL

Analytical models are useful because they allow the designer to examine a large variety of test situations with relative ease and speed. The accuracy of any model is suspect, however, because all models, by their very nature, must include assumptions which may or may not be physically justifiable, and because the accuracy of computer calculations is sometimes low. Dodd, the developer of the models used in this study, has verified his results in a few applications, some simple and others more complex. The following is intended as a verification of the models in a somewhat complex test situation.

A. TEST SAMPLES. Two general types of test samples were used in this study. The first type was to test the detection and characterization of simulated OSSC and ISSC, and the second was used to test the results for sealant thickness changes versus outer surface corrosion. The first test sample is depicted in Figure 17, and consisted of a 0.25-inch piece of aluminum (7075-T6) with thirteen 0.5-inch-diameter flat-bottom holes milled into the top and bottom surfaces of the plate to simulate corrosion. As shown, nine holes were in areas away from edges or other discontinuities. A row of fastener holes was also present in the plate and some simulated corrosion areas were placed near these fastener holes to examine the effect of edges on the detection of corrosion. After manufacture, a skin (0.050 inch of 6061-T0) was glued to the sample. The second type of test sample is shown in Figure 18. There were actually five samples of this type made, one of which was a balance sample, fabricated from a 0.25-inch-thick piece and a 0.050-inch-thick piece of 6061-T0. Two of the four samples contained a large area of simulated corrosion; the remaining two had mylar placed between the two aluminum pieces to simulate a sealant or air-gap thickness change comparable to the corrosion depths of the first two samples.

B. INSTRUMENTATION.

1. Two eddy-current instruments were used for the experimental studies. The first was a Tennelec EC 501, which is based upon Dodd's work. The Tennelec is also designed to use the reflection coils, with an operating frequency which varies from 500 Hz to 2 MHz, in 1-2-5 steps. Since the low-frequency end was still too high for some of the required measurements, the EC 501 was supplemented with a Super Halec, sold by Halo Instruments. The frequency range of this instrument is from 10 Hz to 9.9 kHz, depending on the coil size, though the usable range appears to be from 70 Hz up. Transformer coils are also used with this instrument, but are different from the reflection coils designed by Dodd. For the purposes of this report, it was assumed that the predictions generated for the Tennelec-Dodd reflection coils would also hold true, at least in principle, for the Super Halec. That is to say, it was expected that the general trends in the data would be similar, though the numerical values would be different.

2. Both instruments are of the phase-sensitive type; that is, both measure the phase of the voltage induced in the pickup coil, relative to some reference voltage. However, in both instruments, the output is only proportional to phase changes, with the constant of proportionality being different and unknown for both. Thus, all data, both in this section and the

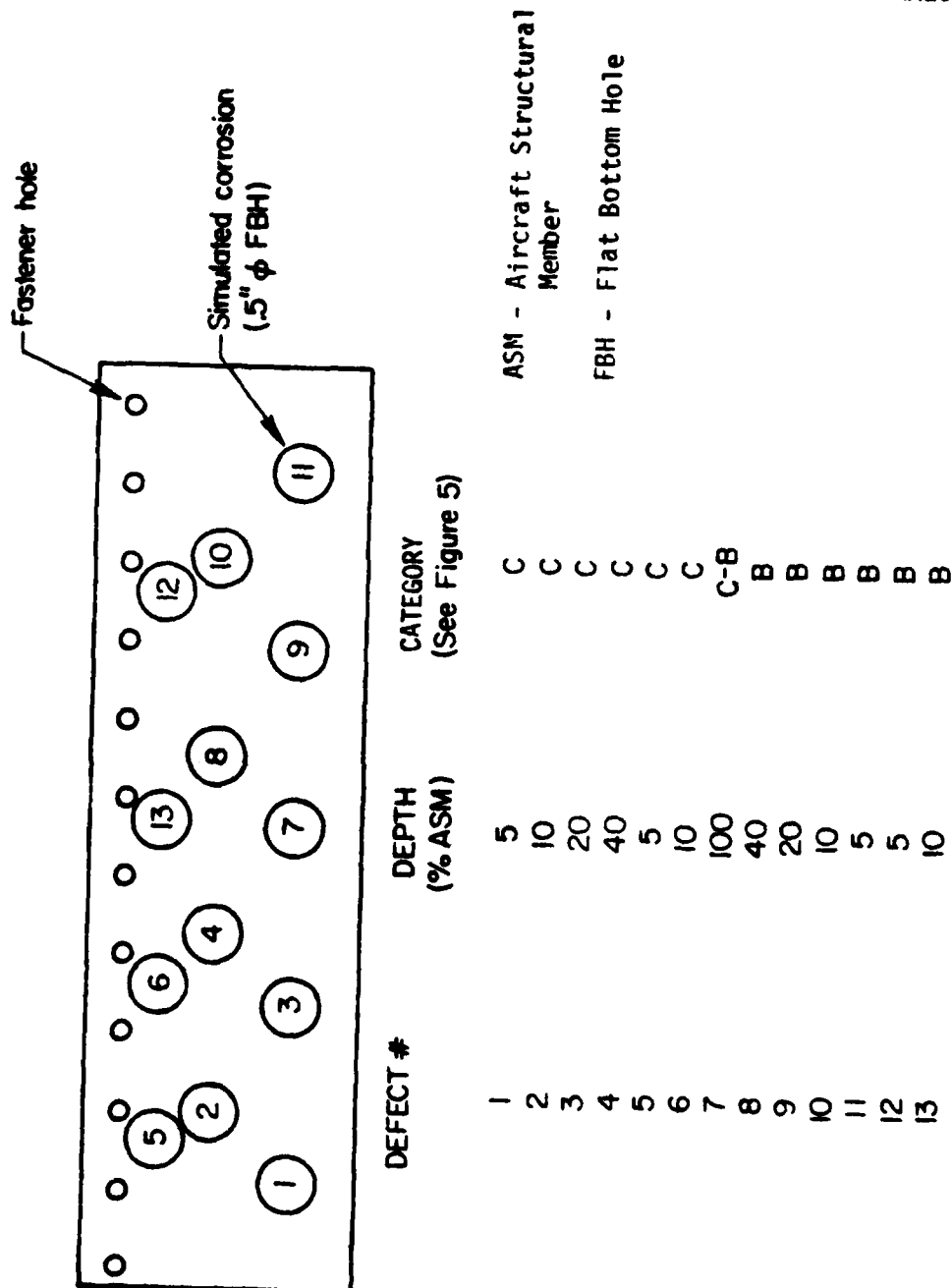


FIGURE 17. TEST PANEL CONFIGURATION

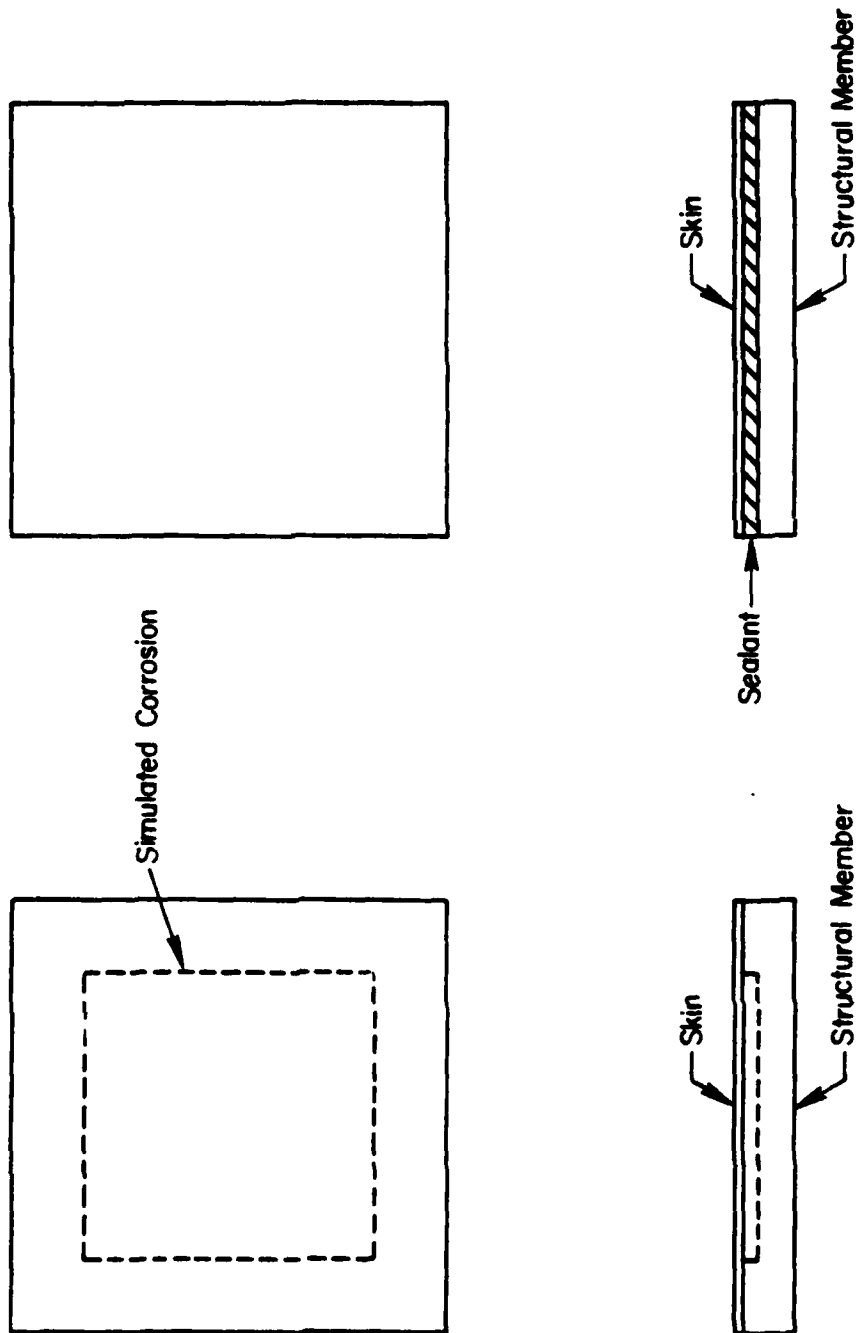


FIGURE 18. TEST PANEL CONFIGURATION - SEALANT THICKNESS CHANGES IN COMBINATION WITH SIMULATED CORROSION

previous section, were normalized to 1 by dividing the output for a given frequency and test situation by the maximum obtained during that series of tests.

C. RESULTS.

1. A sample panel of the type in Figure 17 was used with both instruments to examine the relationship between phase angle and frequency, for various corrosion depths on the outer surface of the structural member. For both instruments, the test coil was scanned across the plate until a maximum phase change was noted. The plate contained corrosion depths deeper than 20 percent, as noted in Figure 17, but only depths of 5 percent, 10 percent, and 20 percent were modeled; thus, only these depths are shown in Figure 19. Also shown in this figure are the computer-generated plots, for comparison. Note that the predicted results agree very well with the experimental data.

2. The same sample was used with the Super Halec only, since the Tennelec did not have a low enough frequency response to examine the relationship between phase change and inspection frequency for various depth corrosion areas on the inner surface of the structural member. The results, along with the computer-generated curves, appear in Figure 20. In general, the agreement between the two is good, though the agreement at the lower frequencies is not as good. This may be attributed to two major factors: firstly, large volume defects were analyzed, but small volume defects were made in the test sample; and secondly, the coil type used was not exactly like the coil type analyzed.

3. To directly compare the frequency response for near-side corrosion with sealant thickness changes, the areal extent of the two must be the same. It is more difficult to accurately fabricate small area sealant thickness changes, hence the second type of sample, Figure 18, was made with large area corrosion/sealant thickness. The Super Halec was used in this test since the lowest frequency of the Tennelec was again too high for this work.

4. The experimental results are shown in Figure 21; however, the predicted values are not shown, in this case, because the numerical agreement was poor. Note, though, that the trends are well predicted.

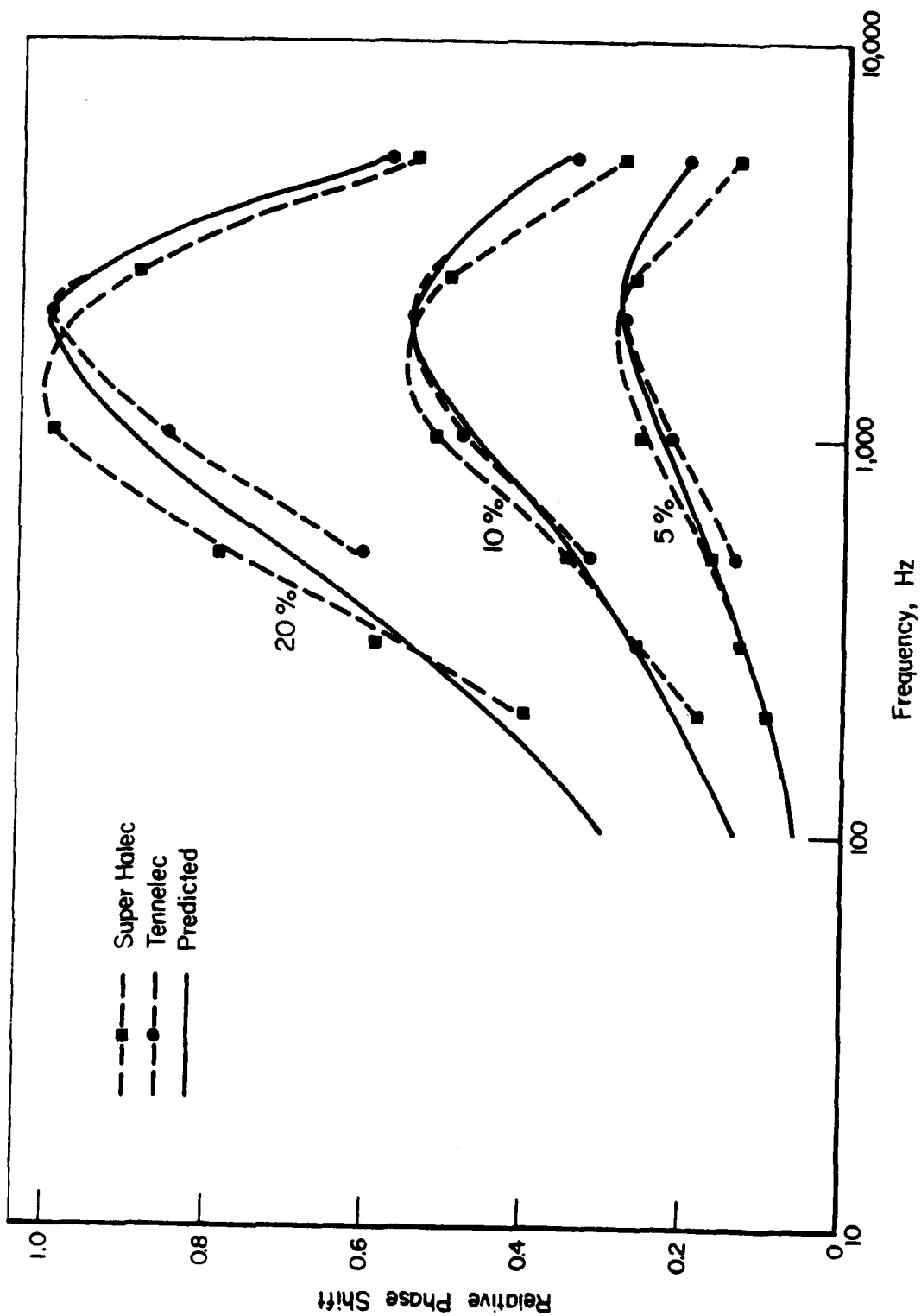


FIGURE 19. EXPERIMENTAL DATA FOR OUTER SURFACE DEFECTS

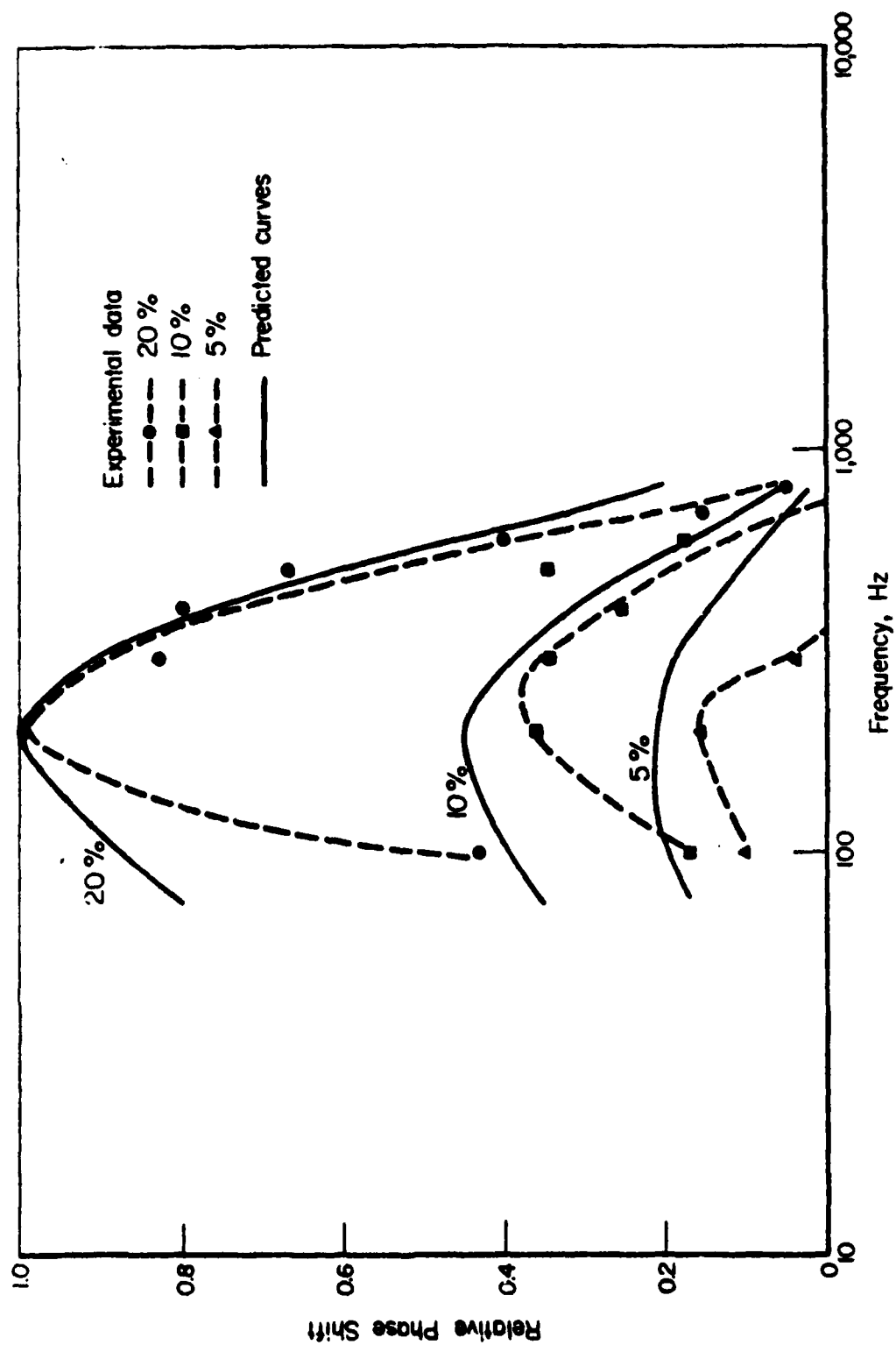


FIGURE 20. EXPERIMENTAL DATA FOR INNER SURFACE CORROSION

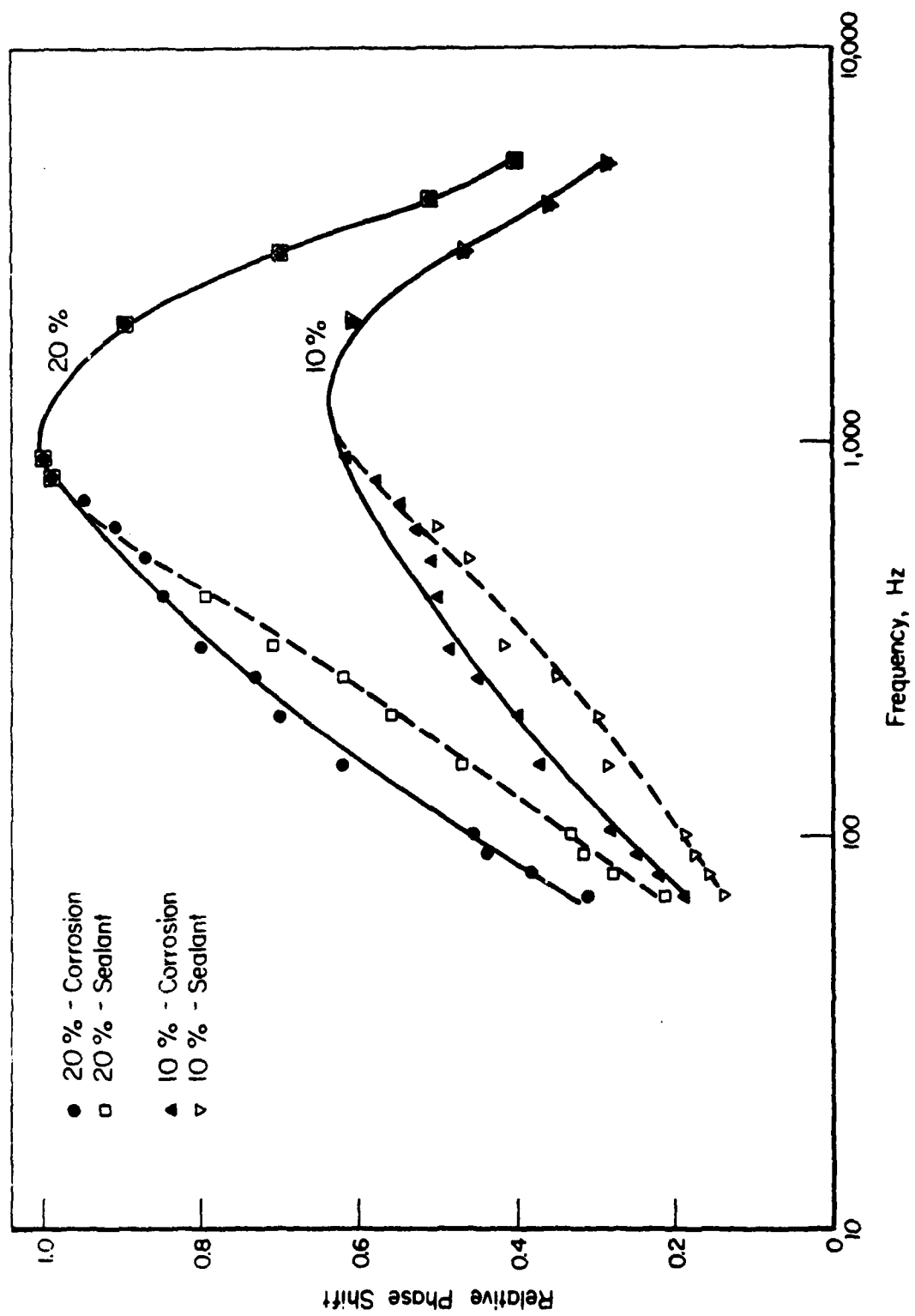


FIGURE 21. EXPERIMENTAL CHARACTERIZATION OF AIR-GAP/SEALANT THICKNESS CHANGES

APPENDIX A

COMPUTER PROGRAMS FOR MULTIT, EDTRFC, AND UTILITY SUBROUTINES

	<u>Page</u>
MULTIT	A-2
EDTRFC	A-23
UTILITY SUBROUTINES.	A-28

INTRODUCTION

The following is a collection of the programs used in the computer modeling of thickness measurements of multilayered structures. The original reference for MULTIT by C. V. Dodd, et al, is contained in the report ORNL-4384 from Oak Ridge National Laboratory entitled "Some Eddy-Current Problems and Their Integral Solutions."

The appendix is divided into three parts: the first contains a slightly modified version of MULTIT, with the associated subroutines, the second is a program EDTRFC (Edit Reflection Coil) which sets up data files for various reflection coils and test object parameters used by MULTIT, and the third is a set of utility subroutines used by both programs for setting up a file structure and for allowing interaction between the computer and the operator. The latter two sections, though written entirely by staff members of the Fabrication and Quality Assurance Section of Battelle Columbus Laboratories for purposes other than this project, are not considered proprietary.

Since these programs were designed for use on our computer system, it is not advisable for some other persons to directly copy them for use in their (different) computer system, and this should be used for informational purposes only. Any person requiring reasonable additional information should contact the staff at BCL for more details.

NAEC-92-143

MULTIT

FORTRAN IV

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C..
C.. MULTIT.FOR
C.. WRITTEN BY C. V. DODD
C.. ORNL--APRIL, 1973
C..
C.. MODIFIED BY D. T. MAYFORD
C.. BCL--DECEMBER, 1978
C..
C.. THIS PROGRAM EVALUATES THE SENSITIVITY TO A THICKNESS
C.. VARIATION IN ANY GIVEN LAYER OF A MULTI-LAYERED
C.. MATERIAL
C..

0001 COMPLEX BETA0,BETA1,BETA,V,V97,TR,GAMMA,MUT,DRIVER
0002 COMPLEX PICKUP
0003 REAL L2,L3,L4,L5,L6,L7,M,N3,N4,MATL
0004 DIMENSION T(10),U(10),RHO(10),M(10),BETA(10)
0005 DIMENSION V(2,2),V97(2,2),TR(2,2),GAMMA(3),DRIVER(3,5)
0006 DIMENSION PICKUP(3,5),RL(5),THAG(3,5),PHASE(3,5)
0007 DIMENSION SHIFT(3,5),MUT(3,5)
0008 DIMENSION COIL(13), AMP(6), MATL(10,3), ITITL(20), VERB(5)
0009 EQUIVALENCE (K1,COIL(1)),(R0,AMP(1))
      $ (T(1),MATL(1,1)),(U(1),MATL(1,2)),(RHO(1),MATL(1,3))
0010 COMMON X,Z,Q1,PI
0011 COMMON /B1/ BETA0,BETA1
0012 COMMON /B2/ R1,R2,R3,R4,L2,L3,L4,L5,L6,N3,N4,
      $ R6,R7,R0,R9,C6,C7,V0,G5,W,F,R5
0013 COMMON /B3/ MUT,DRIVER,PICKUP,AIR1,AIR2
0014 COMMON /B4/ GAGE,XIN,XOUT,XLEN,TURNS,N1A,J1,
      $ PERLAY,XLAY
0015 DATA VERB/'COIL','ATT','DRFT','STRT','EXIT'/
0016 PI = 3.1415926536
0017 RAD = 180./PI
0018 5 JKL = 0

C..
C.. ENTER COIL PARAMETERS
C..

0019 CALL ATTIN(2,1,0,ICUR)
0020 READ(2) ITITL,COIL
0021 CALL CLOSE(2)
0022 R5 = (R1+R2)*0.5
0023 DO 10 I=1,9
0024 10 COIL(I) = COIL(I)/R5
0025 TYPE 20, ITITL
0026 20 FORMAT(1X,20A2/)
0027 CALL ATTIN(2,2,0,ICUR)
0028 READ(2) ITITL, N9, MATL
0029 CALL CLOSE(2)
0030 TYPE 20, ITITL
0031 TYPE 21
0032 21 FORMAT('ENTER LAYER NO. WITH THICKNESS VAR.: ')
0033 ACCEPT 22,N9
0034 22 FORMAT(I2)
0035 N9 = N9+1
0036 CALL ATTIN(2,3,0,ICUR)

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0037      READ(2) ITITL, AMF
0038      CALL CLOSE(2)
0039      TYPE 20, ITITL
0040      TYPE 23
0041      23 FORMAT('ENTER OPERATING FREQ.: ')
0042      ACCEPT 24, F
0043      24 FORMAT(F10.0)
0044      T9 = .05
0045      IF(N9.LT.3.OR.N8.GE.N9.OR.N8.EQ.1)GO TO 1110
0047      L7 = L3-2.0*(L4+L5)
0048      105 W = 2.0*PI*F
0049      IF(JKL.NE.0) GO TO 115
0051      TYPE 110
0052      110 FORMAT('  N',13X,'THICK.(IN)',4X,'R(M-OMM CM)',3X,
$           'M,SIGMA',10X,'U')
0053      115 DO 150 I= 1,N9
0054      IF(RHO(I).GT.1.0E9) GO TO 120
0056      M(I) = 0.5094*U(I)*F*R5/R5/RHO(I)
0057      GO TO 125
0058      120 M(I) = 0.0
0059      125 IF(JKL.NE.0) GO TO 150
0061      130 TYPE 140,I ,T(I),RHO(I),M(I),U(I)
0062      140 FORMAT(' ',12,12X,1PE12.5,2X,E12.5,2X,E12.5,2X,0PF6.2)
0063      150 CONTINUE
0064      T(N9)= 0.0
0065      T0 = T(N8)
0066      T9 = 0.05
0067      IF(JKL.NE.0)GO TO 205
0069      TVAR = 100.0*T9
C..
C..      PRINT OUT SYSTEM PARAMETERS
0070      TYPE 155,N8,TVAR
0071      155 FORMAT(' THICKNESS VARIATION OF',I3,'TH LAYER IS +- '
$           ,F6.2,'X')
0072      TYPE 570
0073      TYPE 160,R1,R2,L3
0074      160 FORMAT(' R1=',F8.5,3X,'R2=',F8.5,3X,'DRIVER LENGTH=',F8.5)
0075      TYPE 170,R3,R4,L4
0076      170 FORMAT(' R3=',F8.5,3X,'R4=',F8.5,3X,'PICKUP LENGTH=',F8.5)
0077      TYPE 180,R5,F
0078      180 FORMAT(' COIL MEAN RADIUS=',F8.5,' INCHES',3X,
$           'OPERATING FREQUENCY=',1PE12.5)
0079      TYPE 190,L5
0080      190 FORMAT(' PICKUP RECESSED',F8.5)
0081      TYPE 200,L6,L2
0082      200 FORMAT(' MIN LIFT-OFF=',F8.5,3X,'LIFT-OFF INCREMENT=',F8.5)
C..
C..      INTEGRATION BEGINS HERE. THE MUTUAL, DRIVER, AND
C..      PICKUP INDUCTANCES, ALONG WITH THEIR AIR VALUES ARE CALCULATED
C..
0083      205 S1 = 0.01
0084      S2 = 5.0
0085      B1 = 0.0
0086      B2 = S2

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0087      DO 207 I=1,3
0088      DO 207 J=1,5
0089      MU1(I,J) = (0.0, 0.0)
0090      DRIVER(I,J) = (0.0, 0.0)
0091      207 PICKUP(I,J) = (0.0, 0.0)
0092      AIR1 = 0.0
0093      AIR2 = 0.0
0094      210 I1 = (B2-B1)/S1
0095      X = B1-S1/2.0
0096      DO 490 IIX=1,I1
0097      X = X+S1
0098      TEST = X*L3
0099      IF(TEST.GT.20.0) GO TO 220
0101      W3 = EXP(-TEST)
0102      GO TO 230
0103      220 W3 = 0.0
0104      230 W8 = 1.0-W3
0105      TEST = X*L4
0106      IF(TEST.GT.20.0) GO TO 240
0108      W4 = EXP(-TEST)
0109      GO TO 250
0110      240 W4 = 0.0
0111      250 W9 = 1.0-W4
0112      TEST = X*L7
0113      IF(TEST.GT.20.0) GO TO 260
0115      W7 = EXP(-TEST)
0116      GO TO 270
0117      260 W7 = 0.0
0118      270 W5 = EXP(-X*L5)
0119      W0 = 1.0-W7*W4
0120      TEST = X*L6
0121      IF(TEST.GT.20.0) GO TO 485
0123      W6 = EXP(-2.0*TEST)
0124      Z = X*R2
0125      Q1 = R2
C.. SUBROUTINE BESSEL EVALUATES THE INTEGRAL OF X*J1(X)
0126      CALL BESSEL(VAL2)
0127      Z = X*R1
0128      Q1 = R1
0129      CALL BESSEL(VAL1)
0130      Z = X*R4
0131      Q1 = R4
0132      CALL BESSEL(VAL4)
0133      Z = X*R3
0134      Q1 = R3
0135      CALL BESSEL(VAL3)
0136      S3 = S1*(VAL2-VAL1)*(VAL4-VAL3)
0137      S4 = S1*(VAL2-VAL1)*(VAL2-VAL1)
0138      S5 = S1*(VAL4-VAL3)*(VAL4-VAL3)
0139      A5 = W6*W5*W8*W9*W0*W3
0140      A6 = W6*W8*W8*W5
0141      A7 = W6*W5*W5*W9*W9*W0*W0*W3
0142      IF(X.GT.30.0) GO TO 485
C.. THE LOWEST SIGNIFICANT LAYER, N7, IS DETERMINED

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0144      QSUM = 0.0
0145      N = N9
0146      TEST = XXX*1.0E-5
0147      280 IF(M(N).LT.TEST) GO TO 290
0149      BETA(N) = CSQRT(CMPLX(XXX,M(N)))/U(N)
0150      GO TO 300
0151      290 BETA(N) = CMPLX(X,0.0)
0152      300 QSUM = QSUM+REAL(BETA(N))*T(N)/R5
0153      IF(QSUM.GT.20.0.OR.N.EQ.1) GO TO 310
0155      N = N-1
0156      GO TO 280
0157      310 N7 = N
      C.. THE MATRIX ELEMENTS V(N7+1,N7)L,2 (L=1,2) ARE
      C.. CALCULATED
0158      V(1,2) = BETA(N+1)-BETA(N)
0159      V(2,2) = BETA(N+1)+BETA(N)
      C.. THE TOTAL MATRIX V(N9,N7) IS CALCULATED BETWEEN HERE
      C.. AND LINE 430. THE GAMMA FACTOR IS JUST THE RATIO
      C.. V(N9,N7)1,2/V(N9,N7)(2,2. SUBROUTINE XFORM CALCULATES
      C.. THE TRANSFORMATION MATRIX T(M+1,M)I,J AND SUBROUTINE
      C.. MATRIX THEN CALCULATES V(K,L)I,J
0160      IF(N8.EQ.(N7+1)) GO TO 360
0162      BETA0 = BETA(N7+1)
0163      N6 = N8
0164      IF(N8.GT.(N7+1)) GO TO 340
0166      N6 = N9
0167      340 IDX1 = N7+2
0168      IF(IDX1.GT.N6) GO TO 355
0170      DO 350 N=IDX1,N6
0171      BETA1 = BETA(N)
0172      CALL XFORM(N,TR,R5,U,T)
0173      JUMP = 1
0174      CALL MATRIX(JUMP,V,TR)
0175      350 BETA0 = BETA1
0176      355 IF(N8.LT.(N7+1)) GO TO 410
0178      360 V97(1,2) = V(1,2)
0179      V97(2,2) = V(2,2)
0180      IF(N8.EQ.(N9-1)) GO TO 400
0182      N = N8+2
0183      BETA0 = BETA(N8+1)
0184      BETA1 = BETA(N)
0185      CALL XFORM(N,TR,R5,U,T)
0186      DO 370 I=1,2
0187      DO 370 J=1,2
0188      370 V(I,J) = TR(I,J)
0189      IF(N8.EQ.(N9-2)) GO TO 390
0191      BETA0 = BETA(N8+2)
0192      IDX1 = N8+3
0193      IF(IDX1.GT.N9) GO TO 390
0195      DO 380 N=IDX1,N9
0196      BETA1 = BETA(N)
0197      CALL XFORM(N,TR,R5,U,T)
0198      JUMP = 0
0199      CALL MATRIX(JUMP,V,TR)

```

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```

0200 380 BETA0 = BETA1
0201 390 V97(1,1) = V(1,2)
0202 V97(2,1) = V(2,2)
0203 400 N = NB+1
0204 BETA0 = BETA(NB)
0205 BETA1 = BETA(N)
0206 410 DO 430 I=1,3
0207 IF(NB.LT.(N7+1))GO TO 430
0208 AI = I
0210 T(N-1) = T0*(1.0+(AI-2.0)*T9)
0211 CALL XFORM(N,TR,R5,U,T)
0212 V(1,2) = V97(1,2)
0213 V(2,2) = V97(2,2)
0214 JUMP = 1
0215 CALL MATRIX(JUMP,V,TR)
0216 IF(NB.EQ.(N9-1)) GO TO 430
0218 DO 420 J=1,2
0219 TR(J,1) = V(J,1)
0220 420 TR(J,2) = V97(J,1)
0221 JUMP = 1
0222 CALL MATRIX(JUMP,V,TR)
0223 430 GAMMA(1) = V(1,2)/V(2,2)
0224 T(NB) = T0
0225 RL(1) = 1.0
0226 TEST = X*L2
0227 IF (TEST.GT.20.0) GO TO 440
0229 W2 = EXP(-2.0*TEST)
0230 GO TO 450
0231 440 W2 = 0.0
0232 450 DO 470 K=2,5
0233 AK = K
0234 TEST = AK*X*L2
0235 IF(TEST.GT.20.0) GO TO 460
0237 RL(K) = W2*RL(K-1)
0238 GO TO 470
0239 460 RL(K) = 0.0
0240 470 CONTINUE
0241 DO 480 J=1,3
0242 DO 480 K=1,5
0243 MUT(J,K) = MUT(J,K)+GAMMA(J)*RL(K)*A5
0244 DRIVER(J,K) = DRIVER(J,K)+GAMMA(J)*RL(K)*A6
0245 480 PICKUP(J,K) = PICKUP(J,K)+GAMMA(J)*RL(K)*A7
0246 485 AIR1 = AIR1+2.0*S4*(X*L3-W8)
0247 AIR2 = AIR2+S5*(4.0*(X*L4-W9)-2.0*W7*W9*W9)
0248 490 CONTINUE
0249 B1 = B2
0250 B2 = B2+S2
0251 S1 = 0.05
0252 IF(X.LT.9.0) GO TO 210
0254 S1 = 0.1
0255 IF(X.LT.29.0) GO TO 210
0257 S1 = 0.2
0258 IF (X.LT.39.0) GO TO 210
0260 S1 = 0.5

```

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0261      IF(X.LT.79.0) GO TO 210
C..      THE INTEGRATION ENDS HERE
0263      IF(JAL.NE.0) GO TO 880
C..
C..      NEXT, THE INDUCTANCES, VOLTAGES, AND PHASE SHIFTS
C..      ARE CALCULATED AND PRINTED
0265      500 CALL CIRCT(TMAG,PHASE,Q0,T1,T2)
0266      CALL PHASET(TMAG,PHASE,SHIFT,V1,SET)
0267      TYPE 510
0268      510 FORMAT(' DRIVER RES',4X,'INDUCTANCE',4X,
$      'ND TURNS',6X,'SHUNT CAP',5X,'NOR IM PT')
0269      Q1 = Q0*T1*T1*AIR1/W
0270      Q2 = (REAL(DRIVER(2,3))+AIR1)/AIR1
0271      Q3 = Q0*T2*T2*AIR2/W
0272      Q4 = (REAL(PICKUP(2,3))+AIR2)/AIR2
0273      TYPE 520,R6,Q1,N3,C6,Q2
0274      520 FORMAT(' ',1PE12.5,2X,E12.5,2X,OPF8.1,6X,1PE12.5,
$      2X,OPF9.6)
0275      TYPE 530
0276      530 FORMAT(' PICKUP RES',4X,'INDUCTANCE',4X,'ND TURNS',6X,
$      'SHUNT CAP',5X,'NOR IM PT')
0277      TYPE 520,R7,Q3,N4,C7,Q4
0278      TYPE 540
0279      540 FORMAT(' DRIVING VOLT',2X,'SERIES RES',4X,
$      'AMP GAIN',6X,'INPUT IMP')
0280      TYPE 550,V0,R0,G5,R9
0281      550 FORMAT(' ',F5.1,9X,1PE12.5,2X,OPF8.1,6X,1PE12.5)
0282      TYPE 560,V1
0283      560 FORMAT(' DISCRIMINATOR VOLTAGE=',1PE12.5)
0284      TYPE 570
0285      RL(1)=L6
0286      570 FORMAT(' ')
0287      DO 580 I=2,5
0288      RL(I) = L2+RL(I-1)
0289      TYPE 590,RL
0290      590 FORMAT(' ',4(F6.3,8X),F6.3)
0291      TYPE 570
0292      DO 600 I=1,3
0293      TYPE 610,(TMAG(I,J),J=1,5)
0294      TYPE 610,(PHASE(I,J),J=1,5)
0295      TYPE 610,(SHIFT(I,J),J=1,5)
0296      TYPE 570
0297      600 CONTINUE
0298      610 FORMAT(1X,4(1PE12.5,2X),E12.5)
0299      CALL SENS(SHIFT,RAD,SEN)
C..
C..      THE USER NEXT SELECTS ONE OF FIVE POSSIBILITIES
C..
0300      620 CALL COMAND(VERB,5,N5,'COMMAND: ')
0301      GO TO (650,780,860,5,1110),N5
C..
C..      THE FIRST POSSIBILITY ALLOWS THE USER TO ALTER THE
C..      COIL DESIGN BY INPUTTING THE REQUESTED INTEGER DATA
0302      650 TYPE 660

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0303 660 FORMAT(' DRIVER WIRE GAGE, TURNS, PICKUP WIRE GAGE, TURNS')
0304 TYPE 570
0305 ACCEPT 670, N1A, N2A, N3A, N4A
0306 670 FORMAT(A14)
0307 IF(N1A*N2A.EQ.0) GO TO 680
0309 GAGE = N1A
0310 XIN = R1*R5
0311 XOUT = R2*R5
0312 XLEN = L3*R5
0313 TURNS = N2A
0314 N3 = N2A
0315 N1A = -1
0316 J1 = 1
0317 CALL GAGER(R6)
0318 GO TO 700
0319 680 IF(N1A.EQ.0) GO TO 690
0321 GAGE = N1A
0322 XIN = R1*R5
0323 XOUT = R2*R5
0324 XLEN = L3*R5
0325 J1 = 1
0326 CALL GAGER(R6)
0327 N3 = TURNS
0328 GO TO 700
0329 690 IF(N2A.EQ.0) GO TO 720
0331 N3 = N2A
0332 TURNS = N2A
0333 XIN = R1*R5
0334 XOUT = R2*R5
0335 XLEN = L3*R5
0336 J1 = 0
0337 CALL GAGER(R6)
0338 700 TYPE 710, TURNS, GAGE, PERLAY, XLAY, R6
0339 710 FORMAT(' DRIVER', F6.1, ' TURNS OF ', F5.1, ' WIRE',
      & F5.1, ' / LAYER', F5.1, ' LAYERS', 1PE12.5, ' OHMS')
0340 720 IF(N3A*N4A.EQ.0) GO TO 730
0342 GAGE = N3A
0343 TURNS = N4A
0344 N4 = N4A
0345 XIN = R3*R5
0346 XOUT = R4*R5
0347 XLEN = L4*R5
0348 J1 = 1
0349 CALL GAGER(R7)
0350 R7 = 2.0*R7
0351 GO TO 750
0352 730 IF(N3A.EQ.0) GO TO 740
0354 GAGE = N3A
0355 XIN = R3*R5
0356 XOUT = R4*R5
0357 XLEN = L4*R5
0358 J1 = 1
0359 CALL GAGER(R7)
0360 R7 = 2.0*R7

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0361      N4 = TURNS
0362      GO TO 750
0363 740 IF(N4A.EQ.0) GO TO 770
0365      N4 = N4A
0366      TURNS = N4A
0367      XIN = R3/R5
0368      XOUT = R4/R5
0369      XLEN = L4/R5
0370      J1 = 0
0371      CALL GAGER(R7)
0372      R7 = 2.0/R7
0373 750 TYPE 760,TURNS,GAGE,PERLAY,XLAY,R7
0374 760 FORMAT(' PICKUP',F6.1,' TURNS EA',F5.1,'WIRE',
$           F5.1,'/LAYER',F5.1,'LAYERS',1PE12.5,'OHMS')
0375 770 GO TO 500

C..
C.. THE SECOND POSSIBILITY ALLOWS THE USER TO ALTER THE
C.. ATTENUATOR DESIGN BY INPUTTING THE DATA REQUESTED IN
C.. E FIELD FORMAT
0376 780 TYPE 790
0377 790 FORMAT(' DRIVER SERIES RES, SHUNT CAP, PICKUP SHUNT RES,
$           SHUNT CAP')
0378      TYPE 570
0379      ACCEPT 800,F1,F2,F3,P4
0380 800 FORMAT(4F10.0)
0381      IF(P1.EQ.0.0) GO TO 810
0383      R0 = P1
0384 810 IF(P2.EQ.0.0) GO TO 820
0386      C6 = P2
0387 820 IF(P3.EQ.0.0) GO TO 830
0389      R9 = P3
0390 830 IF(P4.EQ.0.0) GO TO 840
0392      C7 = P4
0393 840 Q5 = 1.0/(W*SQRT(Q1*Q2*C6))
0394      Q6 = SQRT(Q1*Q2/C6)
0395      Q7 = R0/(W*Q1*Q2)
0396      Q8 = 1.0/(W*SQRT(Q3*Q4*C7))
0397      Q9 = SQRT(Q3*Q4/C7)
0398      Q10 = R9/(W*Q3*Q4)
0399      TYPE 850,Q5,Q6,Q7
0400 850 FORMAT(' DVR CKT',1PE12.5,' BELOW RES',1PE12.5,
$           ' OPT RES',1PE12.5,' RES/REACT.')
0401      TYPE 855,Q8,Q9,Q10
0402 855 FORMAT(' P-U CKT',1PE12.5,' BELOW RES',1PE12.5,
$           ' OPT RES',1PE12.5,' RES/REACT.')
0403      GO TO 500

C..
C.. THE THIRD POSSIBILITY ALLOWS THE USER TO EXAMINE THE
C.. EFFECT OF DRIFTS ON THE CIRCUIT
0404 860 TYPE 870
0405 870 FORMAT(' SYSTEM DRIFT VARIATIONS')
0406      DR1 = 0.01
0407      DR2 = 0.01
0408      DR3 = 0.01

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0409      DR4 = 0.01
0410      DR5 = 0.01
0411      DR6 = 0.01
0412      DR7 = 0.01
0413      DR8 = 0.01
0414      DR9 = 0.01
0415      GO TO 890
0416      880 CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
0417      GO TO (1070,1100),JKL
0418      890 TYPE 900
0419      900 FORMAT(' X VARIATION',3X,' PARAMETER VAR',1X,
      $ ' RADIANS',7X,' DEGREES',7X,' % OF RANGE')
0420      IF(DR1.EQ.0.0) GO TO 930
0422      R6 = R6*(1.0+DR1)
0423      DR100 = 100.0*DR1
0424      TYPE 920,DR100
0425      920 FORMAT(' ',F4.1,10X,' DRIVER RES  ')
0426      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
0427      R6 = R6/(1.0+DR1)
0428      930 IF(DR2.EQ.0.0) GO TO 950
0430      R7 = R7*(1.0+DR2)
0431      DR100 = 100.0*DR2
0432      TYPE 940,DR100
0433      940 FORMAT(' ',F4.1,10X,' PICKUP RES  ')
0434      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
0435      R7 = R7/(1.0+DR2)
0436      950 IF(DR3.EQ.0.0) GO TO 970
0438      C6 = C6*(1.0+DR3)
0439      DR100 = 100.0*DR3
0440      TYPE 960,DR100
0441      960 FORMAT(' ',F4.1,10X,' DVR SHUNT CAP')
0442      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
0443      C6 = C6/(1.0+DR3)
0444      970 IF(DR4.EQ.0.0) GO TO 990
0446      C7 = C7*(1.0+DR4)
0447      DR100 = 100.0*DR4
0448      TYPE 980,DR100
0449      980 FORMAT(' ',F4.1,10X,' P-U SHUNT CAP')
0450      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
0451      C7 = C7/(1.0+DR4)
0452      990 IF(DR5.EQ.0.0) GO TO 1010
0454      R0 = R0*(1.0+DR5)
0455      DR100 = 100.0*DR5
0456      TYPE 1000,DR100
0457      1000 FORMAT(' ',F4.1,10X,' SERIES RES  ')
0458      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
0459      R0 = R0/(1.0+DR5)
0460      1010 IF(DR6.EQ.0.0) GO TO 1030
0462      R9 = R9*(1.0+DR6)
0463      DR100 = 100.0*DR6
0464      TYPE 1020,DR100
0465      1020 FORMAT(' ',F4.1,10X,' AMP INPUT RES')
0466      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
0467      R9 = R9/(1.0+DR6)

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```
0468 1030 IF(DR7.EQ.0.0) GO TO 1050
0470      V0 = V0*(1.0+DR7)
0471      DR100 = 100.*DR7
0472      TYPE 1040,DR100
0473 1040 FORMAT(' ',F4.1,10X,'APPLIED VOLT ')
0474      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
0475      V0 = V0/(1.0+DR7)
0476 1050 IF(DR8.EQ.0.0) GO TO 1080
0478      F = F*(1.0+DR8)
0479      DR100 = 100.*DR8
0480      TYPE 1060,DR100
0481 1060 FORMAT(' ',F4.1,10X,'FREQUENCY ')
0482      JKL = 1
0483      GO TO 105
0484 1070 F = F/(1.0+DR8)
0485      JKL = 0
0486 1080 IF(DR9.EQ.0) GO TO 620
0488      R5 = R5*(1.0+DR9)
0489      DR100 = 100.*DR9
0490      TYPE 1090,DR100
0491 1090 FORMAT(' ',F4.1,10X,'MEAN RADIUS ')
0492      JKL = 2
0493      GO TO 105
0494 1100 R5 = R5/(1.0+DR9)
0495      JKL = 0
0496      GO TO 620

C..
C.. THE FOURTH POSSIBILITY RETURNS TO PROGRAM START
C..
C.. THE FIFTH POSSIBILTY ENDS ALL CALCULATIONS
C..
0497 1110 CALL EXIT
0498      END
```

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```

0001      SUBROUTINE BESSEL (VAL)
0002      COMMON X, Z, Q1, F1
0003      IF (Z.GT.5.0) GO TO 1510
0004      L = 2.0*Z+3.0
0005      F1 = 0.5*Q1*Q1*Q1
0006      VAL = F1/3.0
0007      DO 1500 I = 1, L
0008      AI = I
0009      F1 = -F1*0.25*Z*Z/(AI*AI+AI)
0010      1500 VAL = VAL+F1/(2.0*AI+3.0)
0011      GO TO 1520
0012      1510 Z1 = 1./Z
0013      X0 = (((-188.1357*Z1+109.1142)*Z1-23.79333)*Z1+2.050931)*Z1
0014      X0 = ((X0-0.1730503)*Z1+0.7034845)*Z1-0.064109E-3
0015      X1 = (((-5.817517*Z1+2.105874)*Z1-.6896196)*Z1+.4952024)*Z1
0016      X1 = (X1-0.187344E-2)*Z1+0.7979095
0017      VAL = (1.0-SQRT(Z))*(X1*CD5(Z-F1/4.)-X0*SIN(Z-F1/4.)))/(X*X*X)
0018      1520 RETURN
0019      END
0020

```

```
0001 SUBROUTINE XFORM(N, TR, R5, U, T)
0002 COMMON/R1/BETA0, BETA1
0003 COMPLEX BETA0, BETA1, EX, TR
0004 DIMENSION EX(2), U(10), T(10), TR(2, 2)
0005 EX(1) = CEXP(-BETA0*U(N-1)*T(N-1)/R5)
0006 EX(2) = 1.0/EX(1)
0007 DO 1610 I = 1, 2
0008 DO 1610 J=1, 2
0009 K = I+J
0010 IF(K.EQ.3) GO TO 1600
0012 TR(I, J) = (BETA1+BETA0)*EX(J)
0013 GO TO 1610
0014 1600 TR(I, J) = (BETA1-BETA0)*EX(J)
0015 1610 CONTINUE
0016 RETURN
0017 END
```

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```
0001      SUBROUTINE MATRIX(JUMP, V, TR)
0002      COMPLEX V, Q, TR
0003      DIMENSION Q(2, 2), V(2, 2), TR(2, 2)
0004      IF(JUMP.EQ.1) GO TO 1720
0005      DO 1700 I=1, 2
0006      1700      Q(I, 1) = V(I, 1)
0007      DO 1710 I=1, 2
0008      1710      V(I, 1) = (0.0, 0.0)
0009      DO 1710 J=1, 2
0010      1710      V(I, 1) = V(I, 1)+TR(I, J)*Q(J, 1)
0011      1720      DO 1730 I=1, 2
0012      1730      Q(I, 2) = V(I, 2)
0013      DO 1740 I=1, 2
0014      1740      V(I, 2) = (0.0, 0.0)
0015      DO 1740 J=1, 2
0016      1740      V(I, 2) = V(I, 2)+TR(I, J)*Q(J, 2)
0017      RETURN
0018      END
0019
```

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0001      SUBROUTINE CIRCT(THAG, PHASE, Q0, T1, T2)
0002      COMPLEX MUT, DRIVER, PICKUP, Z1, Z2, Z3, Z4, Z5, Z6, Z7
0003      COMPLEX DENOM, TNUM, VOLT
0004      COMMON /B2/ R1, R2, R3, R4, L2, L3, L4, L5, L6, N3, N4,
      *      R6, R7, R0, R9, C6, C7, V0, G5, W, F, R5
0005      COMMON /B3/ MUT, DRIVER, PICKUP, AIR1, AIR2
0006      DIMENSION MUT(3, 5), DRIVER(3, 5), PICKUP(3, 5)
0007      DIMENSION THAG(3, 5), PHASE(3, 5)
0008      REAL L3, L4, N3, N4, L2, L5, L6
0009      T1 = N3/((R2-R1)*L3)
0010      T2 = N4/((R4-R3)*L4)
0011      Q0 = 6.300475204E-7*F*R5
0012      Z1 = CMPLX(W*C6*R0, -1.0)
0013      Z2 = CMPLX(W*C7*R9, -1.0)
0014      Z3 = CMPLX(0.0, -R0)
0015      Z4 = CMPLX(0.0, -R9)
0016      DO 1800 I=1, 3
0017      DO 1800 J=1, 5
0018      Z5 = Q0*T1*T2*MUT(I, J)
0019      Z6 = Q0*T1*T1*(0.0, 1.0)*(DRIVER(I, J)+AIR1)
0020      Z7 = Q0*T2*T2*(0.0, 1.0)*(PICKUP(I, J)+AIR2)
0021      DENOM = Z1*Z2*Z5*Z5+(Z1*(Z6+R6)+Z3)*(Z2*(Z7+R7)+Z4)
0022      TNUM = V0*R9*G5*(0.0, -1.0)*Z5
0023      VOLT = TNUM/DENOM
0024      THAG(I, J) = CABS(VOLT)
0025      1800 PHASE(I, J) = ATAN2(AIMAG(VOLT), REAL(VOLT))
0026      RETURN
0027      END

```

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```
0001 SUBROUTINE PHASET(A, B, C, V1, O3)
0002 DIMENSION A(3, 5), B(3, 5), C(3, 5)
0003 O1 = A(2, 5)*SIN(B(2, 5))-A(2, 1)*SIN(B(2, 1))
0004 O2 = -(A(2, 5)*COS(B(2, 5))-A(2, 1)*COS(B(2, 1)))
0005 O3 = ATAN2(O1, O2)
0006 V1 = A(2, 1)*SIN(O3+B(2, 1))
0007 DO 1900 I=1, 3
0008 DO 1900 J=1, 5
0009 1900 C(I, J) = O3-ATAN2(V1, SQRT(A(I, J)*A(I, J)-V1*V1))+B(I, J)
0010 RETURN
0011 END
```

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```
0001      SUBROUTINE SENS(TH, RAD, TH1)
0002      DIMENSION TH(3, 5)
0003      TH9 = TH(1, 1)
0004      TH0 = TH(1, 1)
0005      DO 2010 I=2, 5
0006      IF(TH(1, I).LT.TH9) GO TO 2000
0008      TH9 = TH(1, I)
0009 2000 IF(TH(1, I).GT.TH0) GO TO 2010
0011      TH0 = TH(1, I)
0012 2010 CONTINUE
0013      TH1 = (TH(1, 1)+TH(1, 2)+TH(1, 3)+TH(1, 4)+TH(1, 5))/5.0
0014      TH1 = TH1-(TH(3, 1)+TH(3, 2)+TH(3, 3)+TH(3, 4)+TH(3, 5))/5.
0015      XLO = TH9-TH0
0016      PERCT = 100.*XLO/TH1
0017      DEGR1 = TH1*RAD
0018      DEGR2 = XLO*RAD
0019      TYPE 2020, TH1, XLO, PERCT
0020 2020 FORMAT(' PHASE SHIFT=', 1PE12.5, 2X, 'LIFTOFF='
      $      , E12.5, 2X, 'X=', E12.5)
0021      TYPE 2030, DEGR1, DEGR2
0022 2030 FORMAT(' DEGREE:', 1PE13.5, 5X, E13.5)
0023      RETURN
0024      END
```

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```
0001      SUBROUTINE GAGER(RES)
0002      COMMON/B4/G, D1, D2, RLN, T5, N1A, J1, D, E
0003      PI = 3.1415926536
0004      IF(J1.EQ.1) GO TO 2120
0005      N1A = -1
0006      D3 = 0.95*SQRT((D2-D1)*RLN/T5)
0007      X2 = 1.0371E-5/(D3*D3)
0008      Q = 40.0
0009      2100 G = 40.+10.*(ALOG(X2)-ALOG(.9989+.017*(Q/10.-1.)))/2.30259
0010      IF(ABS(Q-G).LT.1.E-4) GO TO 2110
0011      Q = G
0012      GO TO 2100
0013      2110 IG = G
0014      G = IG
0015      2120 X2 = (.9989+.017*(G/10.-1.))*10.**((G/10.-4.))
0016      D3 = SQRT(1.0371E-5/X2)
0017      IF(G.GT.40.) GO TO 2130
0018      X3 = (.460655*ALOG(D3*1.E3)-.43444)*1.E-3
0019      GO TO 2140
0020      2130 X3 = (98.02228*D3+2.56791E-2)*1.E-3
0021      2140 ID = (RLN/(D3+X3))
0022      D = ID
0023      IE = (D2-D1)/(D3+X3)
0024      E = IE
0025      IF(N1A.EQ.-1) GO TO 2150
0026      T5 = D*E
0027      2150 RES = T5*X2*(D2+D1)*PI/12.0
0028      RETURN
0029      END
```

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```
0001      SUBROUTINE CIRCT1(TH1, V1, TH, RAD, SEN)
0002      DIMENSION TH(3, 5), THAG(3, 5), PHASE(3, 5)
0003      CALL CIRCT(THAG, PHASE, Q0, T1, T2)
0004      Q1 = 0.0
0005      DO 2200 I=1, 3
0006      DO 2200 J=1, 5
0007      Q2 = TH1-ATAN2(V1, SQRT(THAG(I, J)**2-V1**2))
          $      +PHASE(I, J)-TH(I, J)
0008      IF(ABS(Q1).GT.ABS(Q2)) GO TO 2200
0010      Q1 = Q2
0011 2200 CONTINUE
0012      Q2NEW = RAD*Q1
0013      Q3 = 100.*Q1/SEN
0014      TYPE 2210, Q1, Q2NEW, Q3
0015 2210 FORMAT('+', 1X, 2(1PE12.5, 2X), 1PE12.5)
0016      RETURN
0017      END
```

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```
0001      SUBROUTINE BESS1(VAL)
0002      COMMON X, Z, Q1, FI
0003      IF(Z.GT.5.0) GO TO 1510
0005      L = 2.0*Z+3.0
0006      F1 = 0.5*Z*Q1*Q1
0007      VAL = F1/3.0
0008      DO 1500 I = 1, L
0009      AI = I
0010      F1 = -F1*0.25*Z*Z/(AI*AI+AI)
0011 1500 VAL = VAL+F1/(2.0*AI+3.0)
0012      GO TO 1520
0013 1510 Z1 = 1./Z
0014      X0 = (((-188.1357*Z1+109.1142)*Z1-23.79333)*Z1+2.050931)*Z1
0015      X0 = ((X0-0.1730503)*Z1+0.7034845)*Z1-0.064109E-3
0016      X1 = (((-5.817517*Z1+2.105874)*Z1-.6896196)*Z1+.4952024)*Z1
0017      X1 = (X1-0.187344E-2)*Z1+0.7979095
0018      VAL = (1.0-SQRT(Z))*(X1*COS(Z-FI/4.)-X0*SIN(Z-FI/4.))/(X*X)
0019 1520 RETURN
0020      END
```

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FORTKAM IV

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```
0001      SUBROUTINE RFCDS1
0002      COMMON /C2/ Z, R
0003      IF(Z .GT. 3) GO TO 100
0005      Z2 = Z**2
0006      Q1 = (((2.1E-11*Z2-5.38E-9)*Z2+6.757E-7)*Z2-5.48443E-5)*Z2
0007      Q1 = ((Q1+2.60415E-3)*Z2-6.25E-2)*Z2+.5
0008      R = Z*Q1
0009      RETURN
0010 100    Z1 = 1./Z
0011      Q3 = (((-.14604057*Z1+.27617679)*Z1-.20210391)*Z1+4.61835E-3)*Z1
0012      Q3 = ((Q3+.14937)*Z1+4.68E-6)*Z1+.79788456
0013      Q4 = (((-.21262014*Z1+.19397232)*Z1+6.022188E-2)*Z1
          $ -1.7222733E-1)*Z1
0014      Q4 = ((Q4+5.085E-4)*Z1+.37498836)*Z1-2.35619449+Z
0015      R = Q3*COS(Q4)/SQRT(Z)
0016      RETURN
0017      END
```

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EDTRFC

```

C.. PROGRAM EDTRFC.FOR
C..
C.. ALLOWS INPUT PARAMETERS FOR MULTILAYERED
C.. REFLECTION COIL PROGRAMS TO BE CHANGED
C..
C.. D. T. HAYFORD & CHIP WILSON
C.. BATTELLE COLUMBUS LABORATORIES 12-19-78
C..

0001 REAL*4 MATL
0002 LOGICAL*1 IANS, YES
0003 DIMENSION COIL(13), AMP(6), MATL(10, 3), ITITL(20)
0004 DIMENSION VERB(8), VERB1(6), VERB2(14), VERB3(5),
      $ VERB4(7)
0005 DATA VERB/'COIL', 'MATL', 'AMP', 'EXIT', 5*'EXIT'/
0006 DATA VERB1/'SAVE', 'CHNG', 'LIST', 'HELP', 'RET', 'EXIT'/
0007 DATA VERB2/'R1', 'R2', 'R3', 'R4', 'L2', 'L3',
      $ 'L4', 'L5', 'L6', 'N3', 'N4', 'RES1', 'RES2', 'NONE'/
0008 DATA VERB3/'T', 'MU', 'RHO', 'NUM', 'NONE'/
0009 DATA VERB4/'RES3', 'RES4', 'CAP3', 'CAP4', 'VOUT', 'GAIN', 'NONE'/
0010 DATA YES/'Y'/
0011 10 CALL COMAND(VERB, 8, IFILE, 'ENTER FILE TYPE: ')
0012 GO TO (100, 200, 300, 400) IFILE

C..
C.. 'COIL'--INPUT COIL PARAMETERS
C..
0013 100 CALL ATTIN(2, IFILE, 0, ICUR)
C.. READ THE FILE
0014 READ(2) ITITL, COIL
0015 CALL CLOSE(2)

C..
C.. GET NEXT COMMAND
0016 110 CALL COMAND(VERB1, 6, J, 'COMMAND: ')
0017 GO TO (120, 130, 140, 150, 160, 400) J

C..
C.. 'SAVE'--WRITE THE COIL PARAMETERS OT TO DISK
0018 120 CALL ATTOUT(2, IFILE, 0, ICUR)
0019 CALL TITLE(ITITL)
0020 WRITE(2) ITITL, COIL
0021 CALL CLOSE(2)
0022 GO TO 110

C..
C.. 'CHNG'--CHANGE THE COIL PARAMETERS
0023 130 K = 1
0024 CALL COMAND(VERB2, 14, J, 'ITEM: ')
0025 IF(J.EQ. 14) K = 2
0026 GO TO (135, 110) K
0027 135 TYPE 136, COIL(J)
0028 136 FORMAT(' OLD VALUE: ', 1PE12.5/'$NEW VALUE: ')
0029 ACCEPT 137, COIL(J)
0030 137 FORMAT(F10.0)
0031 GO TO 130

C..
C.. 'LIST'--LIST PRESENT COIL FILE
0033 140 TYPE 141, ITITL, COIL

```

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```

0034 141 FORMAT(1X, 20A2//T10, 'R1 = ', F7.4, T25, 'R2 = ',
      1 F7.4/T10, 'R3 = ', F7.4, T25, 'R4 = ', F7.4/
      2 T10, 'L2 = ', F7.4, T25, 'L3 = ', F7.4/T10, 'L4 = ',
      3 F7.4, T25, 'L5 = ', F7.4/T10, 'L6 = ', F7.4/T10, 'N3 = ',
      4 F7.1, T25, 'N4 = ', F7.1/T8, 'RES1 = ', F7.1, T23,
      5 'RES2 = ', F7.1//)
0035 GO TO 110
      C..
      C.. 'HELP'---GIVE A LIST OF VARIABLE NAMES
0036 150 TYPE 151
0037 151 FORMAT(' R1 = DRIVER COIL INNER RADIUS'//
      $ ' R2 = DRIVER COIL OUTER RADIUS'//
      $ ' R3 = PICKUP COIL INNER RADIUS'//
      $ ' R4 = PICKUP COIL OUTER RADIUS'//
      $ ' L2 = LIFTOFF INCREMENT'//
      $ ' L3 = DRIVER COIL LENGTH'//
      $ ' L4 = PICKUP COIL LENGTH'//
      $ ' L5 = PICKUP COIL RECESS'//
      $ ' L6 = MINIMUM LIFTOFF'//
      $ ' N3 = NO. OF TURNS-DRIVER'//
      $ ' N4 = NO. OF TURNS-PICKUP'//
      $ ' RES1 = RESISTANCE OF DRIVER'//
      $ ' RES2 = RESISTANCE OF PICKUP'///)
0038 GO TO 110
      C..
      C.. 'RET'---RETURN TO PROGRAM BEGINNING
0039 160 GO TO 10
      C..
      C.. 'MATL'---INPUT MATERIAL PARAMETERS
      C..
0040 200 CALL ATTIN(2, IFILE, 0, ICUR)
      C.. READ THE FILE
0041 READ(2) ITITL, NUM, MATL
0042 CALL CLOSE(2)
      C..
      C.. GET THE NEXT COMMAND
0043 210 CALL COMAND(VERB1, 6, J, 'COMMAND: ')
0044 GO TO (220, 230, 240, 250, 160, 400) J
      C..
      C.. 'SAVE'---WRITE MATERIAL PARAMETERS OUT TO DISK
0045 220 CALL ATTOUT(2, IFILE, 0, ICUR)
0046 CALL TITLE(ITITL)
0047 WRITE(2) ITITL, NUM, MATL
0048 CALL CLOSE(2)
0049 GO TO 210
      C..
      C.. 'CHNG'---CHANGE MATERIAL PARAMETERS
0050 230 CALL COMAND(VERB3, 5, J, 'ITEM: ')
0051 GO TO (231, 231, 231, 235, 210) J
0052 231 TYPE 232
0053 232 FORMAT('%LAYER NO.: ')
0054 ACCEPT 233, K
0055 233 FORMAT(I2)
0056 K = K+1

```

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```

0057      IF(K .LT. 2 .OR. K .GT. NUM-1) GO TO 231
0059      TYPE 234, MATL(K, J)
0060      234 FORMAT(' OLD VALUE: ', 1PE12.5/' NEW VALUE: ')
0061      ACCEPT 137, MATL(K, J)
0062      GO TO 230
0063      235 TYPE 236, NUM - 2
0064      236 FORMAT(' OLD VALUE: ', 12/' NEW VALUE: ')
0065      ACCEPT 233, NUMDUM
0066      NUMDUM = NUMDUM + 2
0067      IF(NUMDUM .LT. 1 .OR. NUMDUM .GT. 10) GO TO 235
0069      NUM = NUMDUM
0070      IF (NUM .EQ. 10) GO TO 230
0072      DO 237 I=1, 3
0073      DO 237 J=NUM+1, 10
0074      237 MATL(J, I) = 0.
0075      MATL(1, 1) = 1.E10
0076      MATL(1, 2) = 1.
0077      MATL(1, 3) = 1.E10
0078      MATL(NUM, 1) = 1.
0079      MATL(NUM, 2) = 1.
0080      MATL(NUM, 3) = 1.E10
0081      GO TO 230
C..
C.. 'LIST'--LIST PRESENT MATERIAL FILE
0082      240 TYPE 241, ITITL, NUM, (J, ( MATL(J, I), I=1, 3), J=1, 10)
0083      241 FORMAT(1X, 20A2//' NO. OF LAYERS: ', I2//
$      T2, ' LAYER', T20, ' THICKNESS', T44, ' MU', T64, ' RHO'//
$      10(T4, I2, T20, 1PE10.4, T40, E10.4, T60, E10.4//)
0084      GO TO 210
C..
C.. 'HELP'--GIVE LIST OF INPUT PARAMETERS
0085      250 TYPE 251
0086      251 FORMAT(' LAYERS ARE NUMBERED FROM ONE TO 'NUM+2', STARTING'//
$      ' FROM THE BOTTOM. LAYER 1 IS ALWAYS AIR, WITH AN INFINITE'//
$      ' THICKNESS, AND LAYER 'NUM+2' IS AIR WITH A THICKNESS OF 1.'//
$      ' THE VARIABLES TO BE ENTERED ARE:'//
$      ' T = THICKNESS (IN INCHES)'//
$      ' MU = RELATIVE PERMEABILITY'//
$      ' RHO = RESISTIVITY (IN MU-OHM-CM)')
0087      GO TO 210
C..
C.. 'AMP' --INPUT AMPLIFIER PARAMETERS
C..
0088      300 CALL ATTIN(2, IFILE, 0, ICUR)
C.. READ THE FILE
0089      READ(2) ITITL, AMP
0090      CALL CLOSE(2)
C.. GET NEXT COMMAND
0091      310 CALL COMAND(VERB1, 6, J, 'COMMAND: ')
0092      GO TO (320, 330, 340, 350, 160, 400) J
C..
C.. 'SAVE'--WRITE AMPLIFIER PARAMETERS OUT TO DISK
0093      320 CALL ATTOUT(2, IFILE, 0, ICUR)
0094      CALL TITLE(ITITL)

```

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```

0095      WRITE(2) ITITL, AMP
0096      CALL CLOSE(2)
0097      GO TO 310
      C..
      C.. 'CHNG'--CHANGE AMPLIFIER PARAMETERS
0098      330 K = 1
0099      CALL COMAND(VERB4, 7, J, 'ITEM: ')
0100      IF (J.EQ. 7) K = 2
0102      GO TO (331, 310) K
0103      331 TYPE 234, AMP(J)
0104      ACCEPT 137, AMP(J)
0105      GO TO 330
      C..
      C.. 'LIST'--LIST PRESENT AMPLIFIER FILE
0106      340 TYPE 341, ITITL, AMP
0107      341 FORMAT(1X, 20A2//T10, 'RES3 = ', 1PE12.5/
          $      T10, 'RES4 = ', E12.5/T10, 'CAP3 = ', E12.5/
          $      T10, 'CAP4 = ', E12.5/T10, 'VOUT = ', E12.5/
          $      T10, 'GAIN = ', E12.5//)
0108      GO TO 310
      C..
      C.. 'HELP'--GIVE LIST OF VARIABLE NAMES
0109      350 TYPE 351
0110      351 FORMAT(' RES3 = DRIVER AMPLIFIER SERIES RES. (OHMS)//
          $      ' RES4 = PICKUP AMPLIFIER SERIES RES. (OHMS)//
          $      ' CAP3 = DRIVER CIRCUIT SHUNT CAP. (FARADS)//
          $      ' CAP4 = PICKUP CIRCUIT SHUNT CAP. (FARADS)//
          $      ' VOUT = DRIVER OUTPUT VOLTAGE (VOLTS)//
          $      ' GAIN = PICKUP AMPLIFIER GAIN'//)
0111      GO TO 310
      C..
      C.. 'EXIT'--EXIT THE PROGRAM
      C..
0112      400 TYPE 401
0113      401 FORMAT('ARE YOU SURE (Y/N)? ')
0114      ACCEPT 402, IANS
0115      402 FORMAT(A1)
0116      IF(IANS.EQ. YES) GO TO 410
0118      GO TO (110, 210, 310, 10) IFILE
0119      410 CALL EXIT
0120      END

```

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UTILITY SUBROUTINES

FORTRAN IV

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```

0001 SUBROUTINE ATTN(LUN, NENTRY, IFLAG, IOPEN)
      C..
      C.. THIS SUBROUTINE ATTACHES A FILE FOR INPUT BY
      C.. CHECKING THE FILE NAME DIRECTORY FOR THE FILENAME
      C.. AND DEFAULT SEQUENCE NUMBERS. EITHER THE DEFAULT
      C.. WILL BE USED OR THE OPERATOR WILL BE PROMPTED FOR
      C.. ONE.
      C..
      C.. INPUT PARAMETERS:
      C..
      C.. LUN -- LOGICAL UNIT NUMBER TO BE USED FOR
      C.. THE FILE TO BE ATTACHED.
      C..
      C.. NENTRY -- NUMBER FOR THE DIRECTORY ENTRY
      C.. TO BE OPENED.
      C..
      C.. IFLAG -- #0 PROMPT OPERATOR FOR SEQUENCE NO.
      C.. #1 USE DEFAULT VALUE
      C.. #GT. 0 USE IFLAG AS CURRENT FILE NUMBER
      C..
      C.. OUTPUT PARAMETERS
      C..
      C.. IOPEN -- SET EQUAL TO THE SEQUENCE NO.
      C.. OF THE FILE OPENED.
      C..
0002 LOGICAL*1 STRING(42)
0003 COMMON/FILNAM/ LUNUM, N, STRING, ICUR, INEXT, IAV
0004 LUNUM = LUN
0005 N = NENTRY
      C..
      C.. ATTACH THE FILE NAME DIRECTORY.
      C..
0006 10 CALL DIRDPN
0007 I = IFLAG
0008 IF(IFLAG) 100, 35, 50
      C..
      C.. USE CURRENT FILE SEQUENCE NUMBER?
      C..
0009 35 TYPE 40, (STRING(I), I=12, 14), ICUR
0010 40 FORMAT('OPEN ', 3A1, ' FILE #', I3, ' ? ')
0011 READ(5, 30, ERR=35) I
0012 30 FORMAT(I10)
0013 IF(I .LT. 0 .OR. I .GT. 999) GO TO 35
0015 IF(I .EQ. 0) I = ICUR
0017 50 ICUR = I
0018 CALL DIRCLO
0019 GO TO 140
0020 100 CALL CLOSE(LUNUM)
      C..
      C.. CHECK FOR EXISTENCE OF FILE
      C..
0021 140 IF(EXIST(STRING) .GT. 0) GO TO 150
0023 TYPE 65, (STRING(I), I=12, 14), ICUR
0024 65 FORMAT(' ', 3A1, ' FILE #', I3, ' NOT FOUND.')

```

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FORTRAN IV

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```
0025      C..      GO TO 10
        C..      OPEN THE FILE.
        C..
0026      150      IF(IFLAG .NE. 0) TYPE 60, (STRING(I), I=12, 14), ICUR
0028      60      FORMAT(' ', 3A1, ' FILE #', I3, ' OPENED.')
0029      CALL ASSIGN(LUNUM, STRING, 14, 'OLD')
0030      IOPEN = ICUR
0031      RETURN
0032      END
```

FORTRAN IV

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```

0001 SUBROUTINE ATTOUT(LUN, NENTRY, IFLAG, INEW)
      C..
      C.. THIS SUBROUTINE ATTACHES A FILE FOR OUTPUT
      C.. BY CHECKING THE FILE NAME DIRECTORY FOR THE
      C.. FILENAME AND THE NEXT AVAILABLE SEQUENCE
      C.. NUMBER; THEN, EITHER THE DEFAULT NUMBER WILL
      C.. BE USED OR THE OPERATOR WILL BE PROMPTED FOR
      C.. ONE.
      C..
      C.. INPUT:
      C..
      C.. LUN -- LOGICAL UNIT NUMBER FOR THE FILE
      C.. TO BE ATTACHED.
      C..
      C.. NENTRY -- THE DIRECTORY TO BE OPENED.
      C..
      C.. IFLAG -- =0 PROMPT OPERATOR FOR SEQ. NO.
      C..          =-1 USE NEXT AVAILABLE SEQ. NO.
      C..          .GT. 0 USE IFLAG AS FILE SEQ. NO.
      C.. OUTPUT:
      C..
      C.. INEW -- EQUAL TO THE SEQUENCE NO. OF FILE OPENED.
      C..
0002 LOGICAL*1 STRING(42)
0003 COMMON/FILNAM/ LUNUM, N, STRING, ICUR, INEXT, IAV
0004 LUNUM = LUN
0005 N = NENTRY
      C..
      C.. ATTACH THE FILE NAME DIRECTORY.
      C..
0006 CALL DIRDPN
0007 I = IFLAG
0008 IF(IFLAG) 100, 35, 50
      C..
      C.. USE NEXT SEQUENCE NUMBER?
      C..
0009 35 TYPE 40, (STRING(I), I=12, 14), INEXT
0010 40 FORMAT(' $SAVE AS ', 3A1, ' FILE #', I3, ' ? ')
0011 READ(5, 30, ERR=35) I
0012 30 FORMAT(I10)
0013 IF(I .LT. 0 .OR. I .GT. 999) GO TO 35
0015 50 ICUR = I
0016 IF((I .NE. 0) .AND. (I .NE. INEXT)) GO TO 140
      C..
      C.. USE NEXT AVAILABLE SEQUENCE NUMBER.
      C..
0018 100 ICUR = INEXT
0019 INEXT = INEXT + 1
      C..
      C.. CHECK FOR EXISTENCE OF FILE
      C..
0020 140 CALL DIRCLO
0021 IF(EXIST(STRING) .GE. 0) TYPE 45, (STRING(I), I=12, 14), ICUR
0023 45 FORMAT(' OLD ', 3A1, ' FILE #', I3, ' DELETED.')

```

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FORTRAN IV

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```
0024 IF(IFLAG .NE. 0) TYPE 60, (STRING(I), I=12, 14), ICUR
0026 60 FORMAT(' SAVE AS ', 3A1, ' FILE #', I3, '.')
0027 CALL ASSIGN(LUN, STRING, 14, 'NEW')
0028 INEW = ICUR
0029 RETURN
0030 END
```

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```

0001      SUBROUTINE DIROPN
          C..
          C..      THIS SUBROUTINE ATTACHES THE FILE NAME DIRECTORY,
          C..      LOOKS UP THE REQUESTED ENTRY, AND REPORTS THE
          C..      CURRENT AND NEXT SEQUENCE NUMBERS.
          C..
          C..      INPUT:
          C..
          C..      LUNUM -- LOGICAL UNIT NUMBER.
          C..
          C..      NENTRY -- DIRECTORY ENTRY TO BE OPENED.
          C..
          C..      OUTPUT:
          C..
          C..      STRING -- ARRAY CONTAINING THE FILE NAME.
          C..
          C..      ICUR -- CURRENT SEQUENCE NUMBER.
          C..
          C..      INEXT -- NEXT SEQUENCE NUMBER.
          C..
0002      LOGICAL*1 STRING(42), DUM1(3), DUM2(3)
          C..
0003      COMMON/FILNAM/ LUNUM, NENTRY, STRING, ICUR, INEXT, IAV
          C..
0004      EQUIVALENCE (DUM1(1), STRING(8)), (DUM2(1), STRING(16))
          C..
          C..      ATTACH THE FILE NAME DIRECTORY.
          C..
0005      CALL ASSIGN(LUNUM, 'DIR:RFCRFC.DIR', 14)
0006      DEFINE FILE LUNUM(4, 21, U, IAV)
0007      IAV = NENTRY + 1
          C..
          C..      READ IN THE REQUESTED ENTRY.
          C..
0008      READ(LUNUM'IAV) STRING
          C..
          C..      DETERMINE CURRENT AND NEXT AVAILABLE SEQ. NO.
          C..
0009      DECODE (3, 30, DUM1) ICUR
0010      DECODE (3, 30, DUM2) INEXT
0011      30  FORMAT(I3)
0012      RETURN
0013      END

```

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```

0001      SUBROUTINE DIRCLO
      C..
      C..      THIS SUBROUTINE UPDATES AND CLOSES THE FILE
      C..      NAME DIRECTORY.
      C..
      C..      INPUT:
      C..
      C..      LUNUM -- LOGICAL UNIT NUMBER.
      C..
      C..      NENTRY -- DIRECTORY ENTRY TO BE UPDATED.
      C..
      C..      STRING -- ARRAY CONTAINING THE FILENAME.
      C..
      C..      ICUR -- CURRENT SEQUENCE NUMBER.
      C..
0002      LOGICAL*1 STRING(42), DUM1(3), DUM2(3), DUM3, DUM4
      C..
0003      COMMON/FILNAM/ LUNUM, NENTRY, STRING, ICUR, INEXT, IAV
      C..
0004      EQUIVALENCE (DUM1(1), STRING(8)), (DUM2(1), STRING(16))
      C..
      C..
      C..      ENCODE ICUR AND INEXT INTO STRING
      C..
      C..
0005      DUM3 = STRING(11)
0006      ENCODE (3, 30, DUM1) ICUR
0007      STRING(11) = DUM3
      C..
0008      DUM3 = STRING(19)
0009      ENCODE (3, 30, DUM2) INEXT
0010      STRING(19) = DUM3
      C..
0011      30  FORMAT(I3)
      C..
      C..      CONVERT BLANKS TO ZEROS.
      C..
0012      IF (STRING(8) .EQ. '040') STRING(8) = '060
0014      IF (STRING(9) .EQ. '040') STRING(9) = '060
0016      IF (STRING(16) .EQ. '040') STRING(16) = '060
0018      IF (STRING(17) .EQ. '040') STRING(17) = '060
0020      IAV = NENTRY + 1
      C..
      C..      UPDATE DIRECTORY ENTRY AND CLOSE IT.
      C..
0021      WRITE(LUNUM, IAV) STRING
0022      CALL CLOSE(LUNUM)
0023      RETURN
0024      END

```

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```
0001      SUBROUTINE TITLE( ITITLE)
      C..
      C.. PROGRAMMED BY CHIP WILSON.
      C..
      C.. THIS SUBROUTINE LISTS THE 40 CHARACTER TITLE CONTAINED IN
      C.. ARRAY ITITLE, ASKS THE OPERATOR IF HE WANTS TO CHANGE IT,
      C.. AND RETURNS WITH EITHER THE OLD TITLE OR A NEW TITLE AS
      C.. ENTERED BY THE OPERATOR.
      C..
0002      LOGICAL*1 ITITLE(40), ANS
      C..
0003      TYPE 200, ITITLE
0004      200  FORMAT(' PRESENT TITLE: >', 40A1, '<', /, 'NEW TITLE (Y/N)? ')
0005      ACCEPT 210, ANS
0006      210  FORMAT( 40A1)
0007      IF( ANS .NE. '131) RETURN
0009      DO 300 J=1, 40
0010      300  ITITLE(J) = '040
0011      CALL MSGOUT('ENTER NEW TITLE: ')
0012      ACCEPT 210, ITITLE
0013      RETURN
0014      END
```

FORTRAN IV

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```

0001      SUBROUTINE COMAND(ARRAY, ISIZE, MATCH, PROMPT)
      C..
      C.. PROGRAMMED BY CHIP WILSON.
      C..
      C.. A FOUR CHARACTER COMMAND IS INPUT FROM THE
      C.. KEYBOARD AND A SEARCH IS MADE FOR A MATCH.
      C.. A NONAMBIGUOUS ABBREVIATION IS CONSIDERED A
      C.. VALID MATCH.
      C.. IF NO MATCH IS FOUND, ALL COMMANDS ARE LISTED OUT
      C.. AND THE ROUTINE WAITS FOR ANOTHER INPUT.
      C..
      C.. INPUT -
      C.. ARRAY -- ARRAY OF COMMANDS TO BE CHECKED.
      C.. ISIZE -- NUMBER OF COMMANDS TO BE CHECKED.
      C.. PROMPT -- CHARACTER STRING CONTAINING A PROMPTING
      C.. MESSAGE TERMINATED BY A NULL.
      C..
      C.. OUTPUT -
      C.. MATCH -- ARRAY SUBSCRIPT WHERE MATCH OCCURED.
      C..
0002      LOGICAL*1 PROMPT(1), LTRY(4), REPLY(4)
0003      EQUIVALENCE (TRY, LTRY(1)), (ANSWER, REPLY(1))
0004      DIMENSION ARRAY(1)
0005      3 DO 50 J=1,40
0006      IF(PROMPT(J) .EQ. 0) GO TO 5
0008      50 CONTINUE
0009      5 TYPE 4, (PROMPT(I), I=1, J)
0010      4 FORMAT(/, 'S', 40A1)
0011      READ(5, 110, ERR=3) ANSWER
0012      110 FORMAT(A4)
0013      IFIND = 0
0014      LETRS = 0
0015      DO 10 K=1, ISIZE
0016      TRY = ARRAY(K)
0017      DO 9 J=1, 4
0018      IF(REPLY(J) .NE. LTRY(J)) GO TO 20
0020      9 CONTINUE
0021      20 IF(J-1 - LETRS) 10,22,21
0022      21 IFIND = 0
0023      LETRS = J-1
0024      22 IFIND = IFIND + 1
0025      MATCH = K
0026      10 CONTINUE
0027      IF(IFIND.EQ.1.AND.(LETRS.EQ.4 .OR. REPLY(LETRS+1).EQ.'040')) RETURN
0029      TYPE 210, (ARRAY(I), I = 1, ISIZE)
0030      210 FORMAT ('+', 4( 10(A4:, ', '))/, ' ')
0031      GO TO 3
0032      END

```

FORTRAN IV

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```
0001      FUNCTION IEXIST(FNAME)
      C..
      C..      THIS FUNCTION PERFORMS A DIRECTORY LOOK UP
      C..      TO CHECK FOR THE EXISTENCE OF A FILE.
      C..
      C..      IEXIST = -1  ERROR.
      C..      = -2  FILE NOT FOUND.
      C..      .GE. 0  FILE FOUND.  IEXIST = NO. OF BLOCKS IN FILE.
      C..
      C..      FNAME = A 14-CHARACTER LOGICAL ARRAY CONTAINING THE FILE NAME
      C..      IN ASCII.  E.G. DEV:FLNAME.EXT
      C..
0002      INTEGER RAD50(4)
0003      LOGICAL*1 FNAME(1)
      C..
      C..      CONVERT FILENAME TO RADIX 50 FORMAT
0004      CALL IRAD50(3, FNAME(1), RAD50(1))
0005      CALL IRAD50(6, FNAME(5), RAD50(2))
0006      CALL IRAD50(3, FNAME(12), RAD50(4))
0007      IEXIST = -1
0008      ICHAN = IGETC()
0009      IF(ICHAN .LT. 0) RETURN
0011      IEXIST = LOOKUP(ICHAN, RAD50)
0012      CALL CLOSEC(ICHAN)
0013      CALL IFREEC(ICHAN)
0014      RETURN
0015      END
```

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FORTRAN IV

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```
0001      SUBROUTINE MSGOUT(MSG)
          C..
          C.. PROGRAMMED BY CHIP WILSON
          C..
          C.. THIS ROUTINE SENDS AN ASCII MESSAGE OUT TO THE
          C.. TERMINAL. THE LOGICAL*1 STRING, MSG, MUST BE
          C.. TERMINATED BY A NULL BYTE.
          C..
0002      LOGICAL*1 MSG(1)
          C..
0003      DO 10 J=1, 80
0004      IF ( MSG(J) .EQ. 0 ) RETURN
0006      5  IF ( ITTOUR(MSG(J)) .EQ. 1 ) GO TO 5
0008      10 CONTINUE
0009      RETURN
0010      END
```