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Report on

Magnetic Flaw Detector

Stationary Pickup, Eddy Current Detector

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ABSTRACT

An equipment suitable for the location of surface or submerged flaws in nonmagnetic metals is described. A predetermined pattern of electrical eddy currents is induced in a perfect test sample by alternating magnetic fields. Sensitive pickup coils properly disposed in relation to the eddy currents measure only the departures of the eddy-current pattern from the pattern in the perfect sample. The departures are indicated on a meter or may be recorded. Performance data are given for a universal type of search unit especially adapted for general surveys.

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INTRODUCTION

Authorization

1. This problem was authorized by Bureau of Aeronautics Project 170-40 of 25 November 1939.

Statement of Problem

2. During the last decade several admirable methods have been developed for the nondestructive testing of metallic objects. These methods are principally of use in testing magnetic materials or in castings where the extent of the flaw is comparable to the dimensions of the article under test. The limitations of the various methods have been reviewed by others[1], and we will, therefore, not discuss them at length here. The production of nonferrous-metal sheets, castings, and fabricated units has increased rapidly in recent years, and it has become important to devise a method especially suitable for this type of inspection. Moreover, some of the stainless steels are being widely used and because they are essentially nonmagnetic, they too, require methods of test similar to those used in the testing of copper or aluminum. A nondestructive test is desired for the location of flaws in these kinds of materials.

Known Facts Bearing on the Problem

3. If a difference of electrical potential is applied between two points in a conductor an electrical current will flow. The distribution of this electrical current will be affected by changes of conductivity along its path. Flaws contained in material through which the current flows will in general cause a different distribution of electric current than would occur in a similar piece of material that contained no flaw. Thus a study of the current distribution in an electrical conductor can be used as a means of flaw detection.

4. Such a procedure employing steady electric currents has been successful in geophysical prospecting where reproducible contacts and potentials are possible. However, because of the difficulties in securing such contacts with movable search equipment, the current-distribution method employing steady currents or potentials has been largely discarded as a testing device. The difficulties just outlined may be avoided and the principal advantages of the electric-current-distribution method may be preserved if a constantly changing current is induced in the test sample by suitable alternating magnetic fields.

5. It has long been known that a changing magnetic field adjacent to a metallic conductor induces in that conductor a system of currents which depends upon the geometry, the electrical conductivity of the metal, the frequency, and the magnetic intensity of the exciting source.

The depth of penetration of the current induced in the metallic object depends upon the frequency of the alternating magnetic field selected for operation. The lower the frequency of the exciting magnetic field the greater will be the depth of penetration of the induced eddy current. Thus, in the design of equipment one selects the frequency of operation on the basis of the type of flaw to be located. The present investigation has proceeded along two general directions. First, the development of equipment to operate at low commercial frequencies and designed to locate flaws which may or may not underlie a substantial thickness of solid homogeneous metal; second, the development of equipment to operate at a frequency of some thousands of cycles per second for the detection of very small surface flaws. The detecting equipment for both methods is the same in principle but the techniques adopted in carrying out the measurement of the magnitude of the flaws are considerably different. The apparatus described in this report will be operated at a fairly low frequency (60 cycles per second).

6. The theoretical aspects of the penetration of magnetic fields and electric currents into a simple conducting body is not very clear-cut at the present time. An examination of the problem has been carried forward by W. Lyons[2] who has worked out a satisfactory calculation for the shielding due to spheres and cylinders at frequencies exceeding 1000 cycles. Because of the difficult geometry involved in the present equipment and the much lower frequency employed, the change of current density and phase do not check well with Lyons' results. For this reason we prefer to outline only the experimental facts as deduced from measurement. It should be mentioned in passing that the pickup device which we have employed has shown some saturation at the exciting currents used and therefore the observational data may be subject to correction before it is compared with a theory.

METHODS AND APPARATUS

The Pickup Unit and the Theory of Its Operation

7. The principle of flaw detection to be described rests on the fact that a given geometrical arrangement of an alternating magnetic field adjacent to a metallic body induces a systematic pattern of electric currents within the metal which can be easily reproduced and analyzed by appropriate magnetic pickups. The simplest form of the principle employed may be best understood by reference to Figure 1. Imagine an electro-magnet excited by alternating current in coil 13. A slot, 14, is cut in the pickup unit to reduce eddy currents in the unit. The path for the alternating magnetic flux is along the inner cylinder, across the air gap 2-1 or 5-6, through the outer cylinder, and connecting washer, 8-9. These parts are constructed of iron with good magnetic properties. If the permeability of the inner cylinder, 2-5, is large compared to air, then the space within this cylinder will be nearly free of magnetic flux. Parts 3 and 4 are two

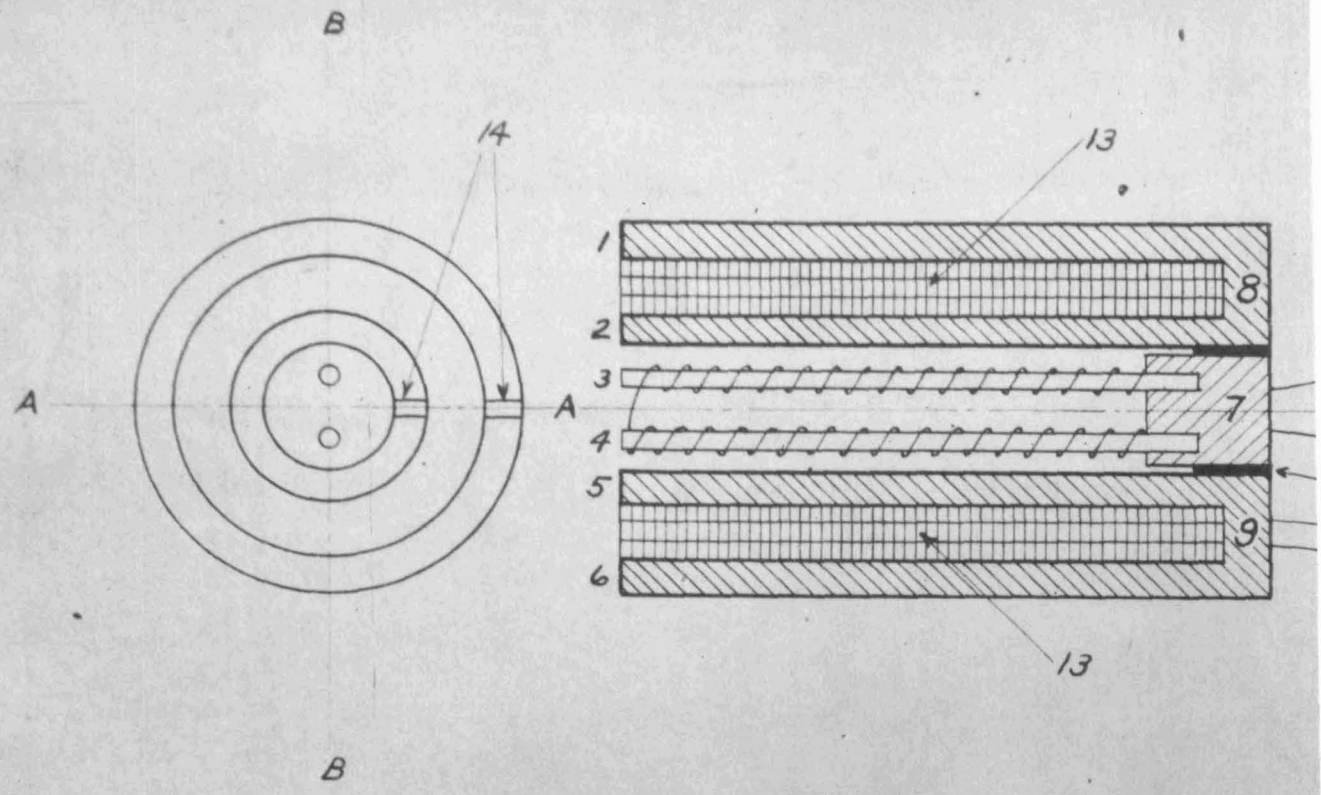

FIG. 1 PICKUP UNIT

(See opposite page for Fig. 1)

Figure 1. Pickup Unit

small magnetic rods on which are wound about 7500 turns of wire. This is called the pickup coil. With part 7 these rods form a long horseshoe magnetic path, the reluctance of which is small compared with the reluctance across the air gap 3-4. Part 12 is a small brass cylinder that serves to isolate parts 3-4-7 from the exciting magnetic field and so helps to preserve a field free space within the inner cylinder. An equal number of turns are wound on rods 3 and 4. The coils on these rods are so connected that flux changing in the same direction within these rods induce opposing potentials. Thus the resulting potential from both coils can be balanced to zero even though some of the exciting magnetic field traverses the rods. If there is a difference of magnetic potential between 3 and 4, (a magnetic field tangential to the face of the pickup unit) magnetic flux will go through the two rods in opposite directions and voltages induced in the two parts of the pickup coil due to a change of this flux will be additive. For a given frequency flux change the resultant voltage across the pickup coil terminals, 10, will be a measure of the difference of magnetic potential between 3 and 4 (or of the tangential component of the magnetic field). Anything that disturbs the symmetry of the exciting magnetic field with respect to a plane (A-A of Figure 1), through the axis of the pickup unit and perpendicular to a plane containing rods 3 and 4, will cause a magnetic difference of potential between 3 and 4. Therefore, anything that disturbs the exciting magnetic field on one side of plane A-A differently than the other side will result in a voltage across the terminals of the pickup coil.

8. If this pickup unit is placed pole down upon a homogeneous sheet of electrically conducting metal, then the sheet of metal will act like a short circuited turn of a transformer and systems of circular electrical eddy currents will be induced as is shown in Figure 2a. Now suppose that a hairline crack develops in the homogeneous metal plate under the axis of the exciting electromagnet. The current cannot traverse this flaw and the circular current systems are broken up to be replaced by current systems similar to c in Figure 2. These eddy currents produce magnetic fields in the usual manner.

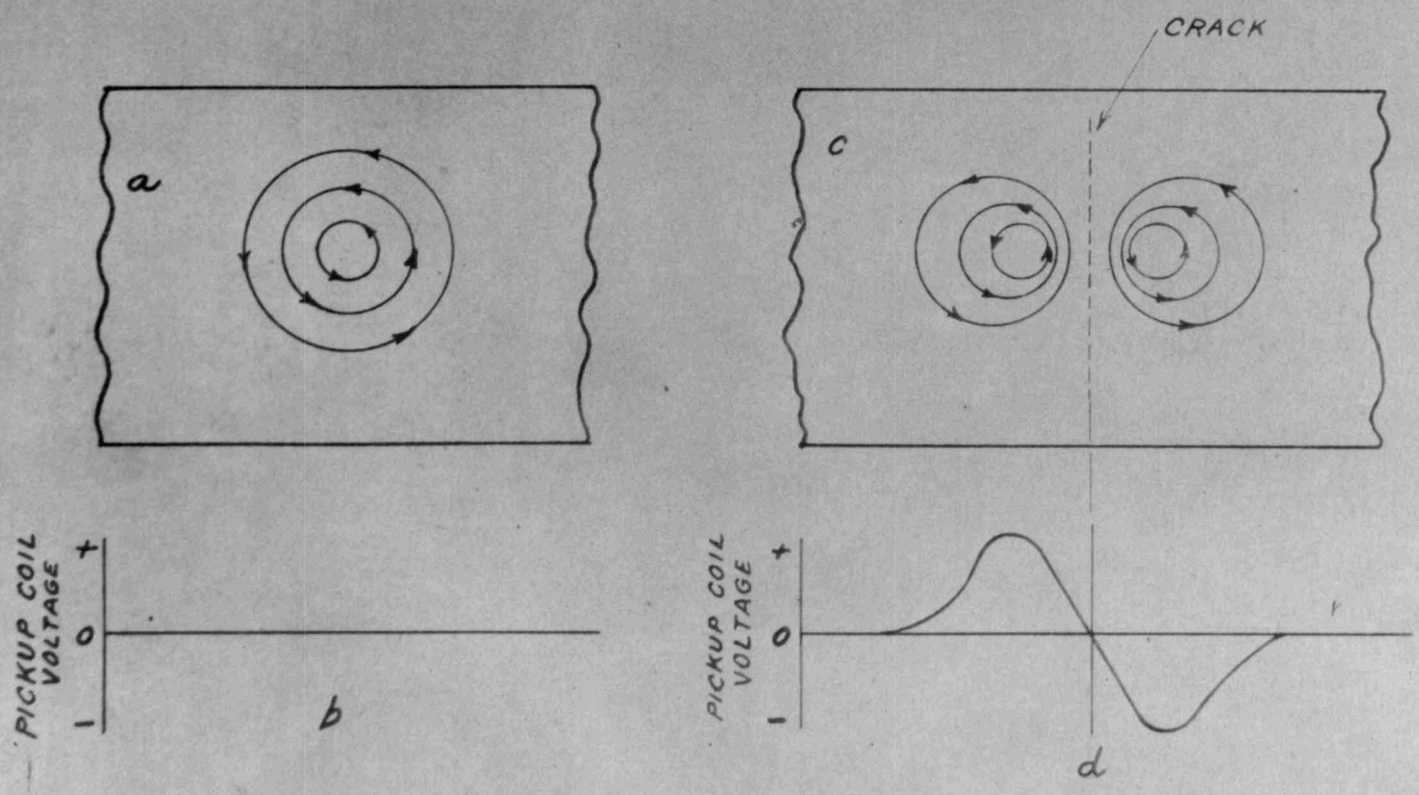

FIG. 2 EDDY CURRENTS INDUCED IN A HOMOGENEOUS METALLIC PLATE BY THE PICKUP UNIT

(See opposite page for Fig. 2)

Figure 2 Eddy Currents Induced in a Homogeneous Metallic Plate by the Pickup Unit

9. If the pickup unit is moved about on plate a of Figure 2, without approaching too closely the edges of the plate, no voltage will be generated in the pickup coil as the magnetic disturbance caused by the eddy currents are symmetrical not only with respect to plane A-A (see Figure 1) but with respect to the axis of the pickup unit. If the pickup unit is moved across plate c, with plane A-A kept parallel to the crack, then as the crack is approached the magnetic disturbance caused by the eddy currents will not be symmetrical with respect to plane A-A, and a pickup coil voltage as illustrated in Figure 2d will result. When plane A-A is directly over the crack the magnetic disturbances or both sides of the plane will be the same and there will be zero pickup coil voltage. When plane A-A moves from one side of the crack to the other the direction of pickup coil voltage will be reversed.

10. It is important to note the effect of the orientation of plane A-A with respect to a flaw. If the pickup unit should be moved across the crack, with plane A-A perpendicular to the crack, the magnetic disturbances on both sides of the plane would remain the same, regardless of position, and there would be zero pickup voltage generated. In looking for flaws it will be necessary, therefore, to scan the piece in two directions, preferably at right angles to each other, in order that it may be certain that the pickup unit has not moved across a flaw in such a manner as to have balanced magnetic disturbances on either side of the plane A-A.

11. It is evident from an examination of the currents induced in the metallic sample and the resulting pickup coil voltages of Figure 2c and d that it is most essential that the electrical indicator,

cooperating with the pickup unit, shall be phase-sensitive, i.e., it is essential that the indicating electrical meter reverse direction when the phase of the alternating current from the pickup coil reverses, for it is only by such means that the exact position of the flaw is easily determined. A non-phase-sensitive pickup would, upon movement across the flaw, show a minimum potential between two maxima, and this might easily be misinterpreted. In the present apparatus the pickup coil is made phase-sensitive by the adoption of some type of synchronous mechanical rectifier which is arranged to rectify the alternating current picked up by the detector coil.

The Electrical Circuit

12. The circuit diagram and panel controls are shown in Plates 1 and 2. Power is obtained by connecting to a 110 volt supply operating at any commercial frequency (not D.C.) and closing the input switch. A current of 1/8 or 1/4 ampere can be supplied to the exciting coil, E, of the pickup unit by opening or closing switch S2. The sensitivity of the pickup unit is nearly directly proportional to the exciting current up to about 1/2 ampere.

13. A Western Electric polarized relay R, is used as a mechanical rectifier. The time of transit for the armature can be made very short (1/5000 second) and the relay can be made to operate up to 500 cycles per second. The current from the pickup coil, P, is passed through the rectifier to the D.C. measuring instruments.

14. In case there is a current from the pickup coil when the pickup unit is placed against a homogeneous metal or held for air the "zero adjuster," R_2, should be moved until the meter reads zero. This provides a very small voltage across R_4 that can be made to buck the voltage generated in P.

15. Circuit constants have been adjusted so that the rectification takes place at the part of the cycle required for best sensitivity. The resistances R_7 and R_8 make up a constant impedance shunt so that the resistance of the output circuit is constant regardless of the sensitivity used. With galvanometer and micrometer resistances, as shown in Plate 1, either may be used without changing the circuit resistance. Switch S_3 allows the sensitivity of the meter in use to be changed by a factor of ten. S_4 puts either the microammeter or galvanometer in the circuit.

EXPERIMENTS AND RESULTS

Description of Experiments

16. The amount of pickup coil current has been determined as the pickup unit has scanned flat plates of various thickness and containing artificially placed flaws at known positions. The curves shown are for

an orientation of the pickup unit with respect to the flaw, such that maximum current is obtained (See paragraphs 9 and 10).

17. A flaw is referred to as "total flaw" when it penetrates completely through a plate containing it. The flaws constructed have been made straight and perpendicular to the surfaces of plates containing them.

Curves and Plots of Data

18. The maximum pickup coil current caused by a total flaw in materials of various thicknesses is shown in plate 4. Plate 5 illustrates the current caused by total flaws of varying length in plates of a given thickness. These curves show, as expected, that the indicator current increases quite linearly for increases in size for total flaws of small thicknesses (up to 1/8 inch) or short lengths up to 3/4 inch.

19. It may be seen from the curves of Plate 6 that the materials studied give indications which are greatest for copper, less for aluminum, still less for duralumin, and quite small for lead and 18-8 stainless steel. Hence the indications are in the same relative order as are the electrical conductivities of the metals. It is illuminating to compare Plate 6 with somewhat similar curves of Plates 7 and 8 which were obtained with the same type of total flaw as employed in Plate 6, but in these figures an overlying sheet of solid metal equal in thickness to the flaw was placed over it. It may be seen from these curves that the position of the flaw is as readily determined as when there was no solid metal above it, but that the intensity of the induced field is reduced by a considerable factor. It is interesting to note also that the relative response of lead in relation to copper is greatly increased when the flaw is submerged under solid metal. This change in relative response is obviously due to the larger currents circulating in the overlying metal when the conductivity of this metal is large. If a flaw is deeply submerged under highly conducting metal, shielding electric currents induced in the surface layers produce counter-magnetic fields that reduce the field deep in the metal. Therefore, at the depth of such a flaw, relatively small currents may flow. The magnitude of these surface shielding currents increases as the conductivity and frequency increases and hence one may reduce their effect by employing a suitably low frequency. Thus for a given metal one may select a frequency which will be sufficiently penetrating to reach any presumed defect. The curves of Plate 9 show how the indicator currents decrease at various frequencies as the thickness of the overlying solid metal increases. It should be clear from these curves that if one is to locate a flaw under 1/2 in. of solid duralumin, one must employ a very low frequency or else use a very sensitive pickup unit.

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CONCLUSIONS AND RECOMMENDATIONS

Facts Established

20. Flaws or cracks in metallic conductors that have an area, or a component of area, extending perpendicularly to the surface will under certain conditions be indicated by the flaw detector. The conditions under which the flaw detector may not locate a flaw of the type specified above are:

(a) The flaw is too deeply covered by solid metal (see Plate 9). For the apparatus described in this report a flaw 3/4 inch long and 1/8 inch deep covered by 3/8 inch duralumin is just detectable.

(b) The flaw, or component of the flaw perpendicular to the surface, is too small (Plates 4, 5, 6 and 9).

(c) The surface of the metal is too rough or has too small a radius of curvature. Special jigs or pickup coils must be used for surfaces having a short (less than 12 inches) radius of curvature.

(d) The orientation of the pickup unit during scanning (see paragraphs 8 and 9) has been such that flaw is not indicated. The scanning must be performed in two directions to eliminate this possibility.

21. Flaws that run parallel to the surface of a conductor are not detectable unless of considerable width.

22. The greater the conductivity of a metal the greater will be the indicator current due to a surface flaw.

23. The greater the conductivity of a metal the more rapidly will the indications due to a flaw disappear as its depth below the surface increases. This is due to the greater shielding effect of the better conductor.

24. The lower the frequency of the exciting current the greater can be depth below the surface at which a flaw can be detected.

SUMMARY AND DISCUSSION

Conditions under which the Flaw Detector will not be useful.

25. In order that a flaw may be detectable it is necessary that it be located in such a manner that it will disturb the eddy current flow set up by the exciting field. With the pickup unit as described in this report the induced eddy currents will in general flow in planes

APPENDIX I

Instructions for Operation

The flaw detector apparatus consists of four essential parts (See Plates 1, 2 and 3).

1 - the pickup unit
2 - the mechanical rectifier
3 - the current indicators
4 - the zero adjustor

To make the flaw detector ready for operation the following procedure may be followed:

1 - Connect the pickup unit to its cable and connect the cable to its connection on the panel.

2 - Connect the galvanometer to its connection on the panel. (Always have galvanometer short circuited when it is moved.)

3 - Throw switch S_4 to "M" side. The letters M and G stand for microammeter and galvanometer, respectively.

4 - Throw the instrument sensitivity switch, S_3, to the "L" side. (The instrument sensitivity is increased by a factor of 10 by changing this switch from "L" to "H".)

5 - Throw the coil sensitivity switch S_2 to the "L" side. (One eighth of an ampere goes through the pickup unit exciting coil when this switch is on the "L" side and 1/4 ampere when it is on the "H" side. This changes the sensitivity by approximately a factor of two.)

6 - Plug in to 110 volts A.C. where indicated and close the input switch S_1. The pilot light should indicate when the power is applied.

7 - With the pickup unit placed face down on a homogeneous part of a metal to be scanned, turn the zero adjustor R_2, until no current is indicated.

8 - Increase the sensitivity as desired and make suitable changes of the zero adjustor. There may be some variations of galvanometer readings at high sensitivity due mainly to the mechanical rectifier. The velocity of scanning should not be more than one inch per second with the microammeter in the circuit and for careful work with the galvanometer in the circuit the velocity should not be more than 1/2 inch per second.

Care must be taken to hold the face of the pickup unit in good contact with the metal being scanned as rocking or lifting of one edge of the pickup unit will cause spurious indicator readings.

The Characteristic Curve Due to a Crack-Like Flaw

The pickup unit should be held so that the slot (See Figure 1 or Plate 2) is toward the person holding it, and the direction of motion should be from left to right in a plane containing the flat sides of the plug connection of the pickup unit. If this is done a positive deflection (to the right) of the microammeter will result when the flaw is being approached. This current will reach its maximum when the axis of the pickup unit is approximately 1/8 inch from the flaw, it will return to zero when the axis is directly over the flaw, and it will swing to a negative maximum when approximately 1/8 inch beyond the flaw. This type curve is shown in the figure below.

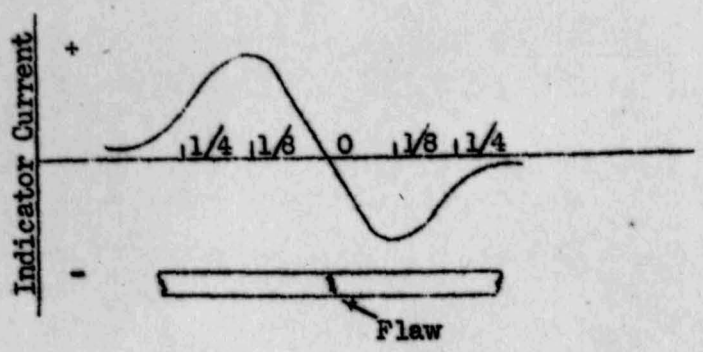

Figure 1 - Characteristic Curve Due to a Crack-like Flaw

The galvanometer should be so connected that it will swing in the same direction as the microammeter. Variations of indicator current that are not of the type indicated by Figure 1 above are not due to crack-like flaws. They may be due to surface irregularities, large flaws, edge effects, rocking of the pickup unit, or many other causes. A curve of the characteristic type enables flaws of this type to be located in spite of other variations.

The Mechanical Rectifier

It is not expected that the contact in the mechanical rectifier shall need attention. If, however, the variations in galvanometer

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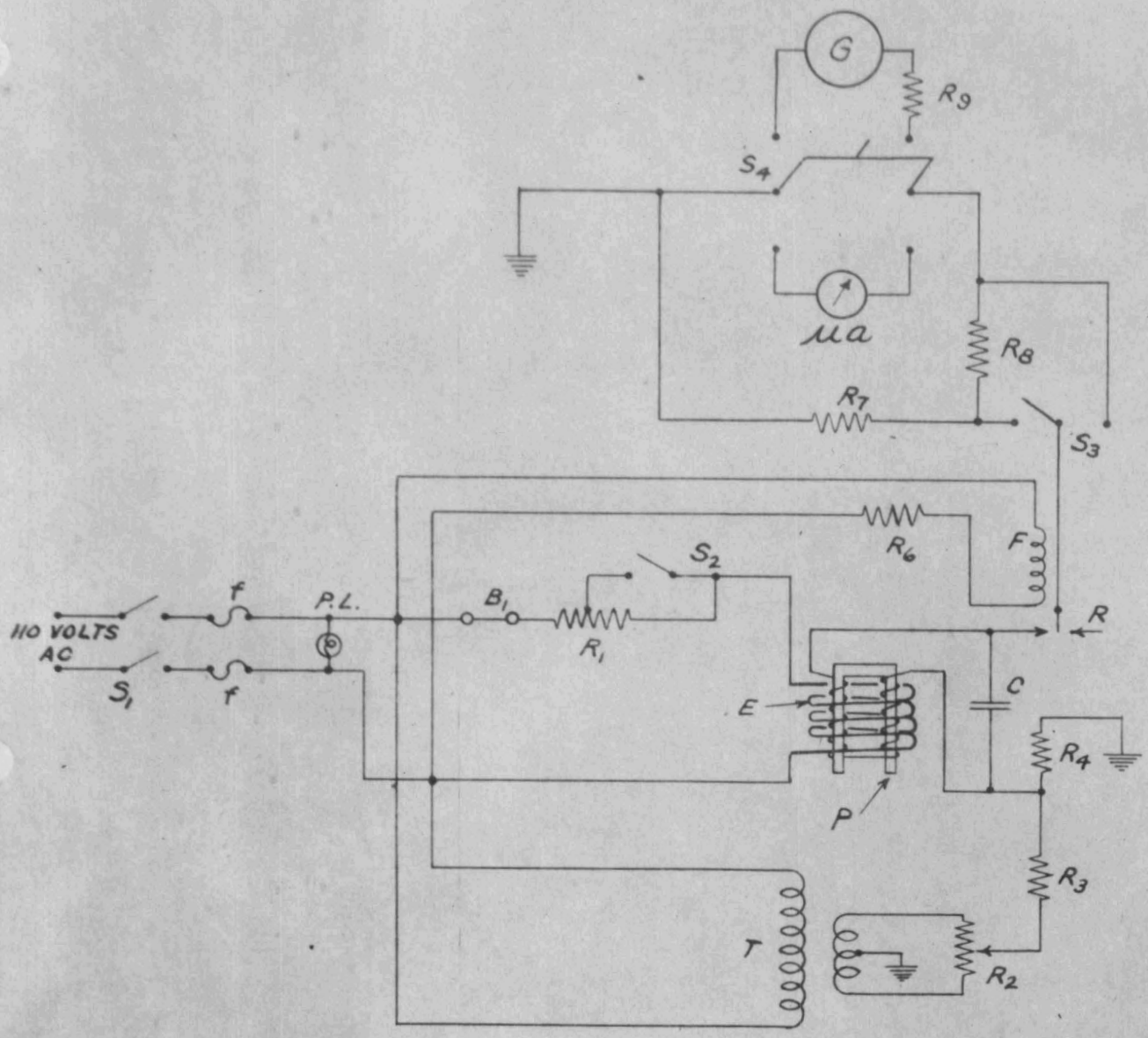
readings at high sensitivity becomes large, causes such as line voltage variations or poor contacts have been eliminated, the contacts of the rectifier should be cleaned. The point of rectification is determined to a large extent by the position of the rectifier contact points. As the sensitivity of the instrument depends upon this point of rectification care should be taken that the contacts be returned to their original positions.



CIRCUIT DIAGRAM

PLATE 1

PLATE 1
(Continued)

S_1 = Input switch

S_2 = "Coil Sensitivity" switch for changing exciting current

S_3 = "Instrument Sensitivity" switch for changing meter sensitivity

S_4 = Switch for selection of microammeter or galvanometer

f = One ampere fuses

P.L. = Pilot Light

B_1 = Internal binding posts for meter connections for measuring the exciting current

Gal. = External binding posts for galvanometer

P = Pickup Coil of Pickup Unit

F = Field coil of mechanical rectifier

R = Mechanical Rectifier, W. E. polarized type 209 FA

μa = Microammeter - Resistance = 120 ohms

T = Transformer - 2-1/2 volt secondary, center tapped

R_1 = 50 watt resistor tapped to give exciting current of 0.125 or 0.250 amperes. 910 ohms total.

R_2 = Clarostat 250 ohms = zero adjuster

R_3 = 50 ohms

R_4 = 2 ohms

R_6 = 25000 ohms

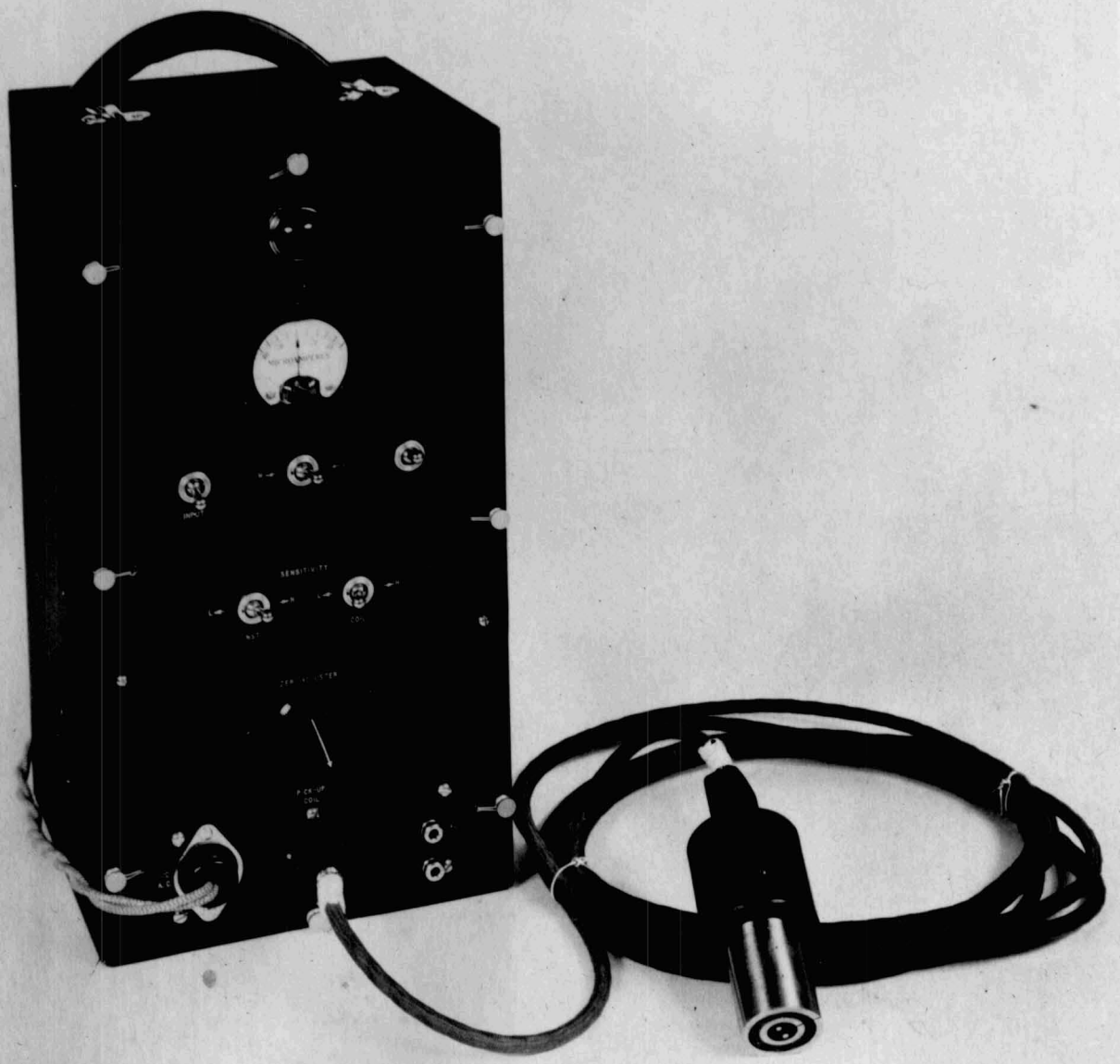
R_7 = 120 ohms

R_8 = 1080 ohms

R_9 = 20 ohms

Galvanometer Resistance = 98 ohms = G-M 2564C

C = 2 mfd. condenser



Flaw Detector Assembly

Plate 2

Internal View of Flaw Detector Assembly

Plate 3

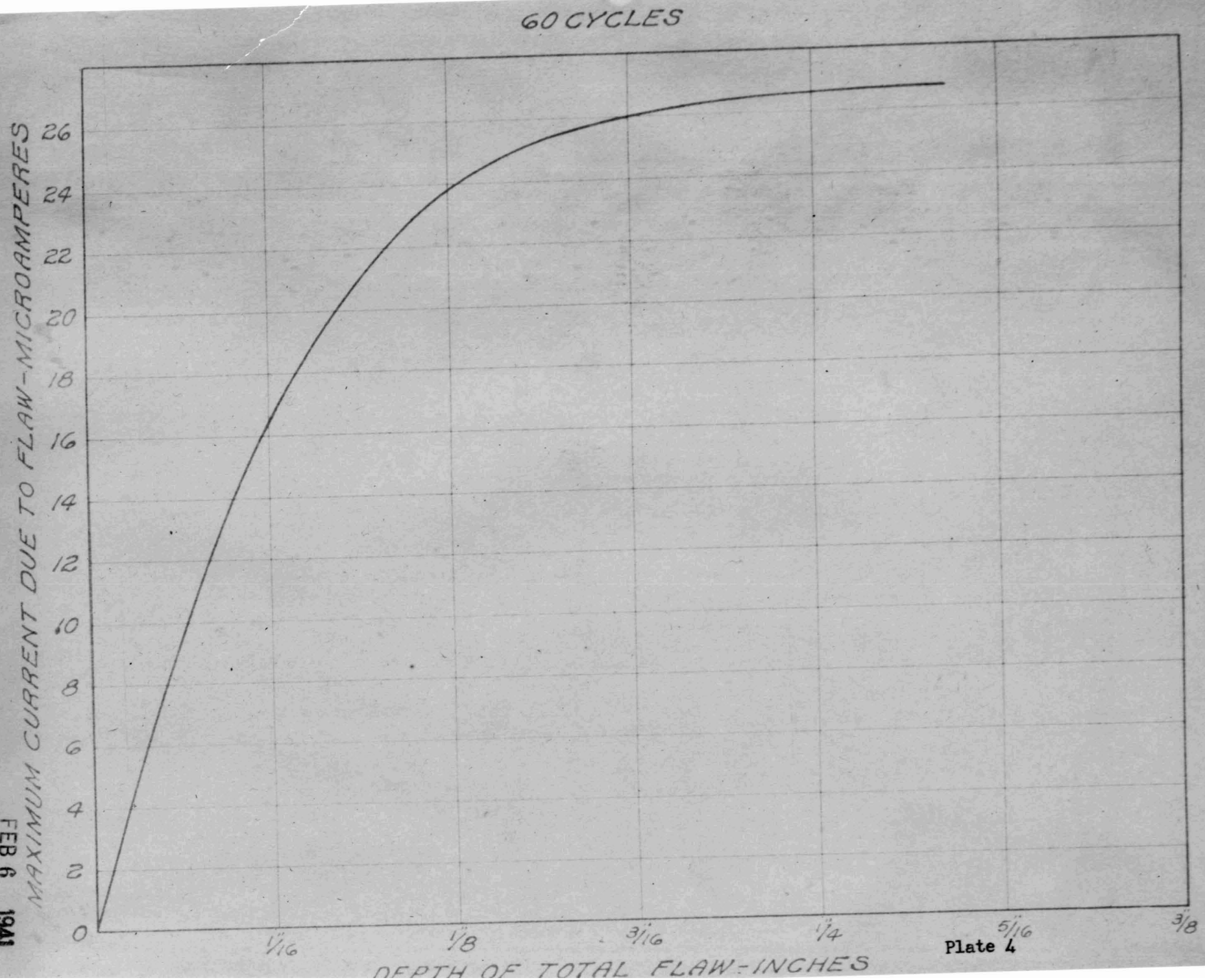


Plate 4

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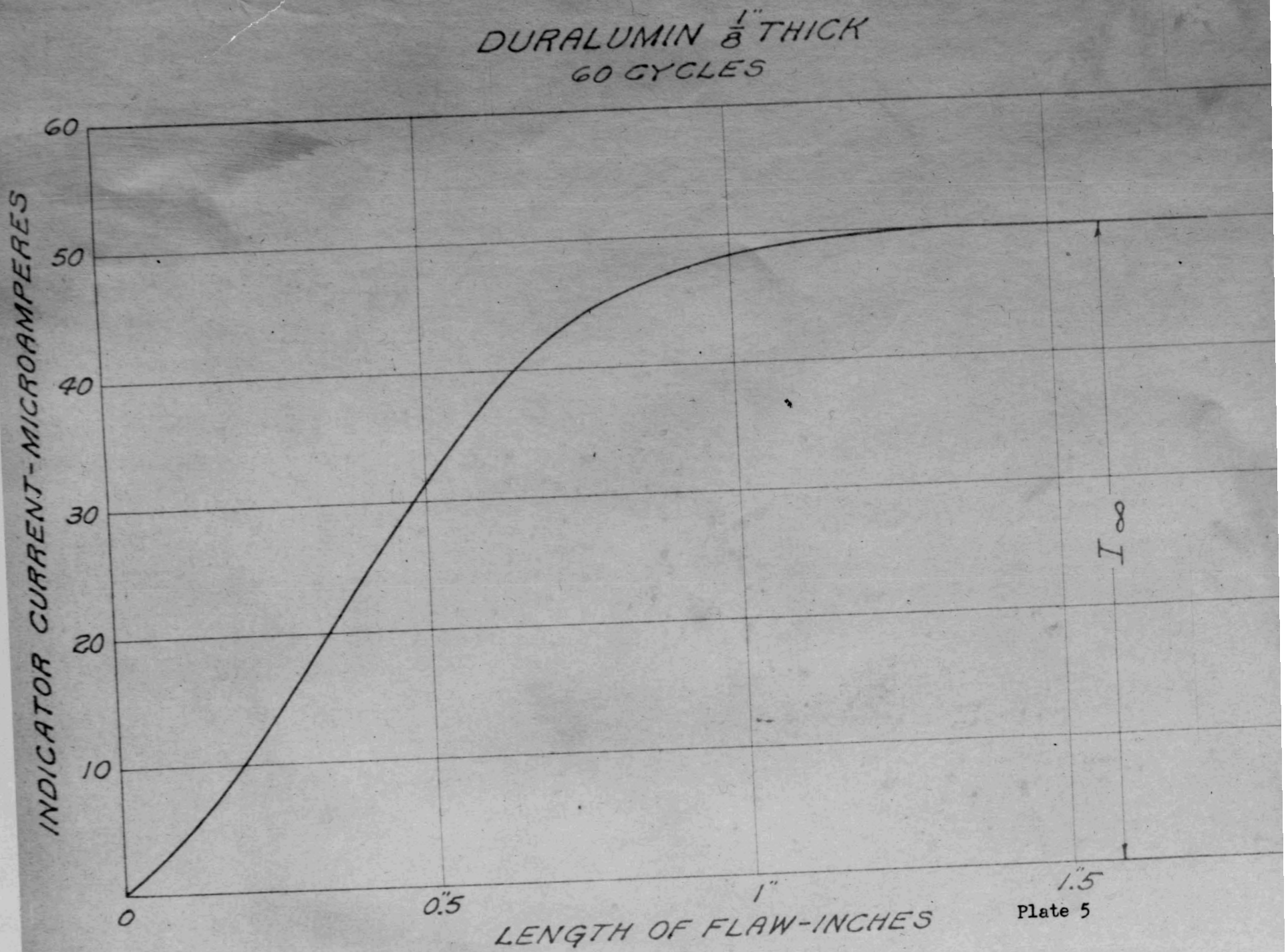
DURALUMIN 1/8" THICK
60 CYCLES
INDICATOR CURRENT-MICROAMPERES
60
50
40
30
20
10
0
0.5"
1"
1.5"
LENGTH OF FLAW-INCHES
I∞

Plate 5

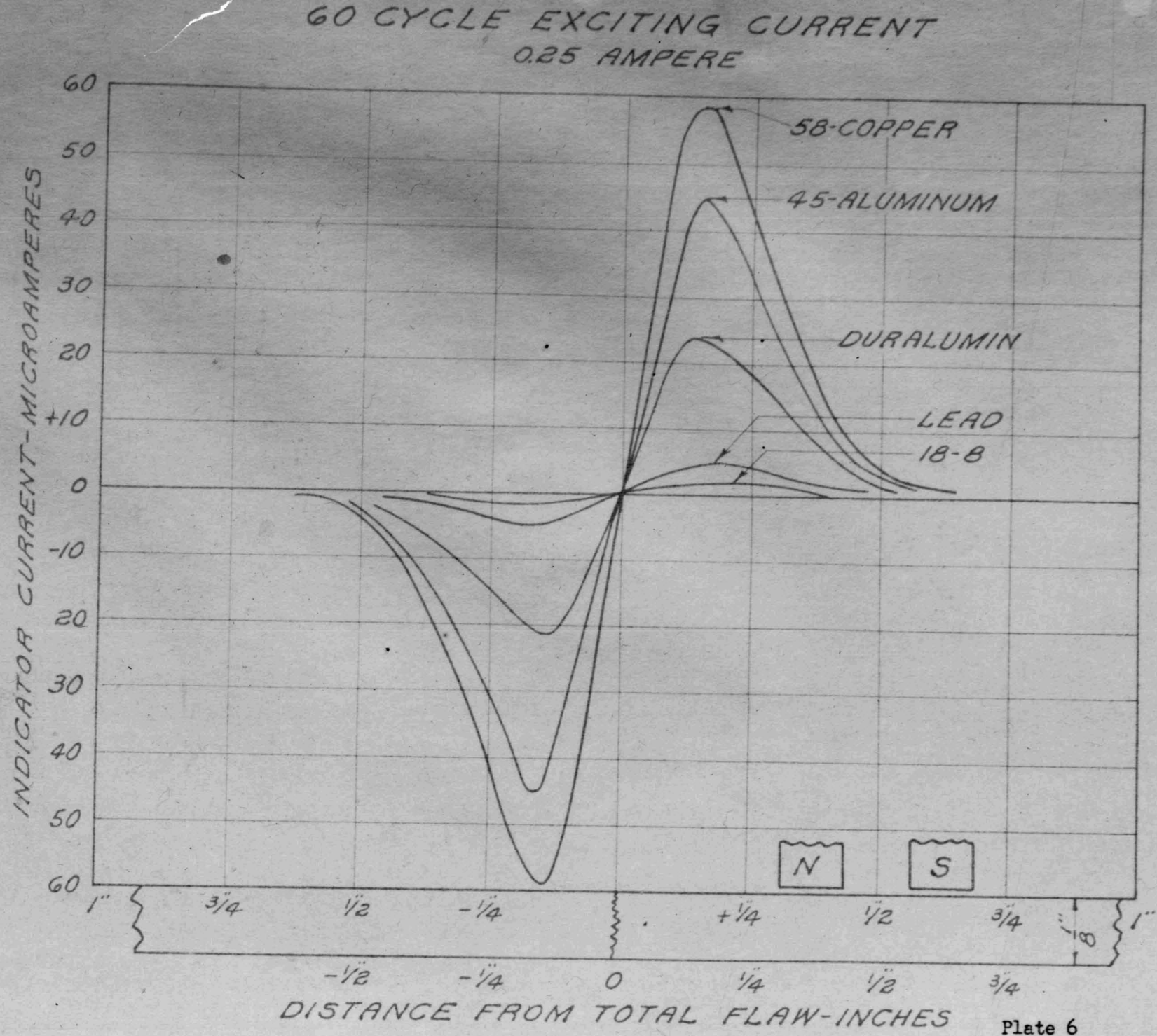

Plate 6

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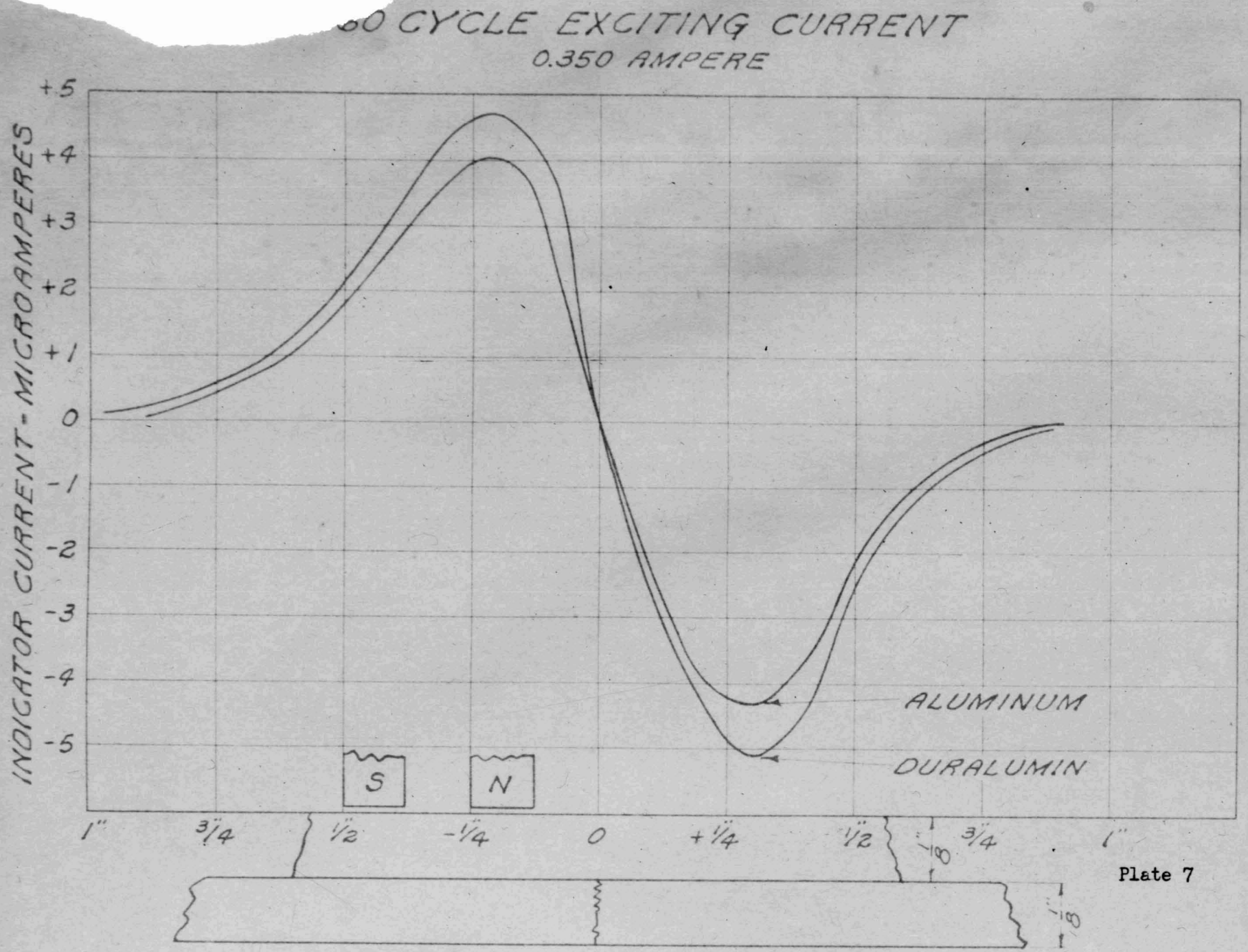
60 CYCLE EXCITING CURRENT
0.350 AMPERE
INDICATOR CURRENT - MICROAMPERES
+5
+4
+3
+2
+1
0
-1
-2
-3
-4
-5
ALUMINUM
DURALUMIN
S
N
1"
3/4
1/2
-1/4
0
+1/4
1/2
3/4
1"
1/8
1/8
DISTANCE FROM TOTAL FLAW UNDER SIMILAR HOMOGENEOUS METAL

Plate 7

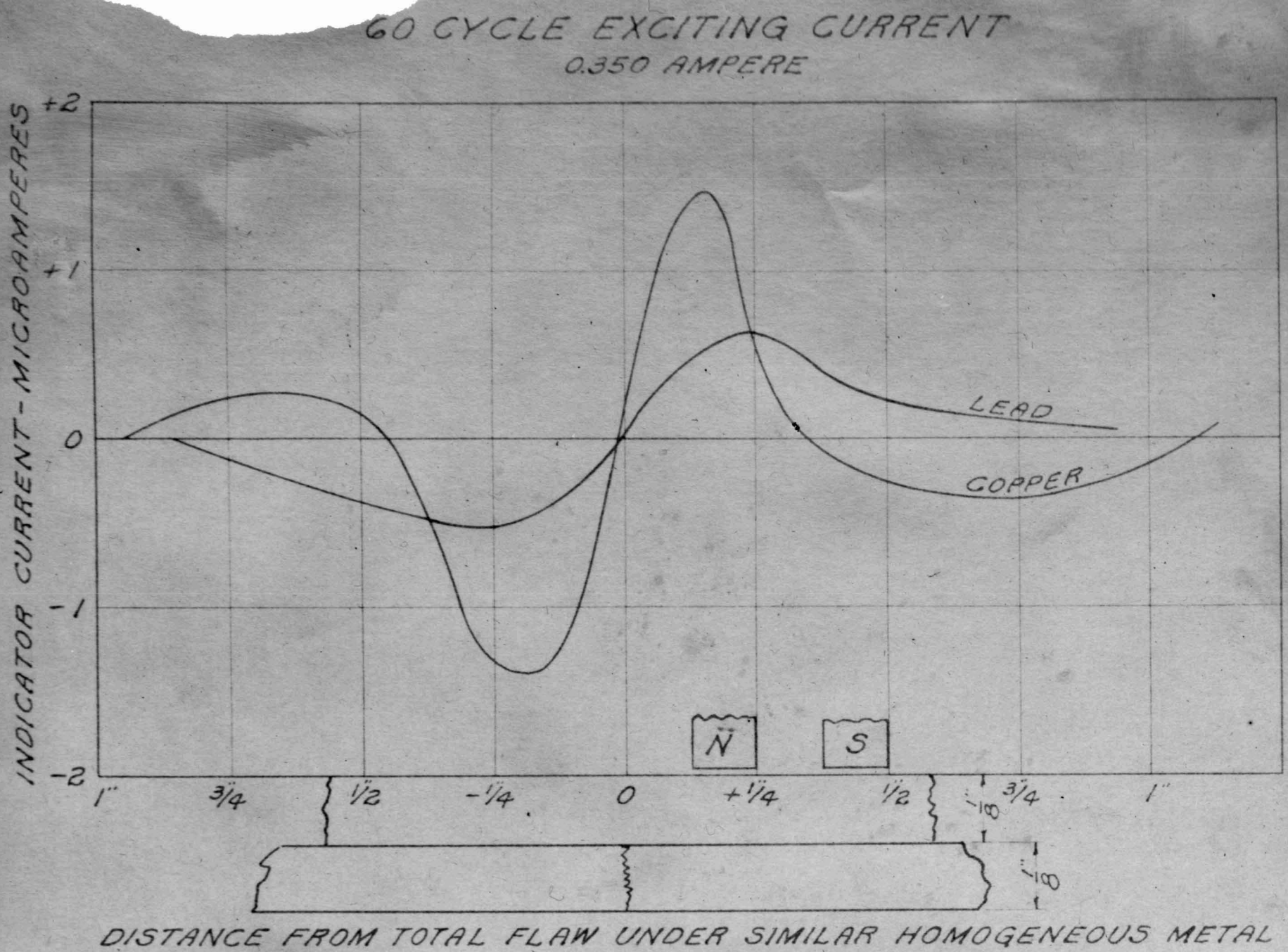

Plate 8

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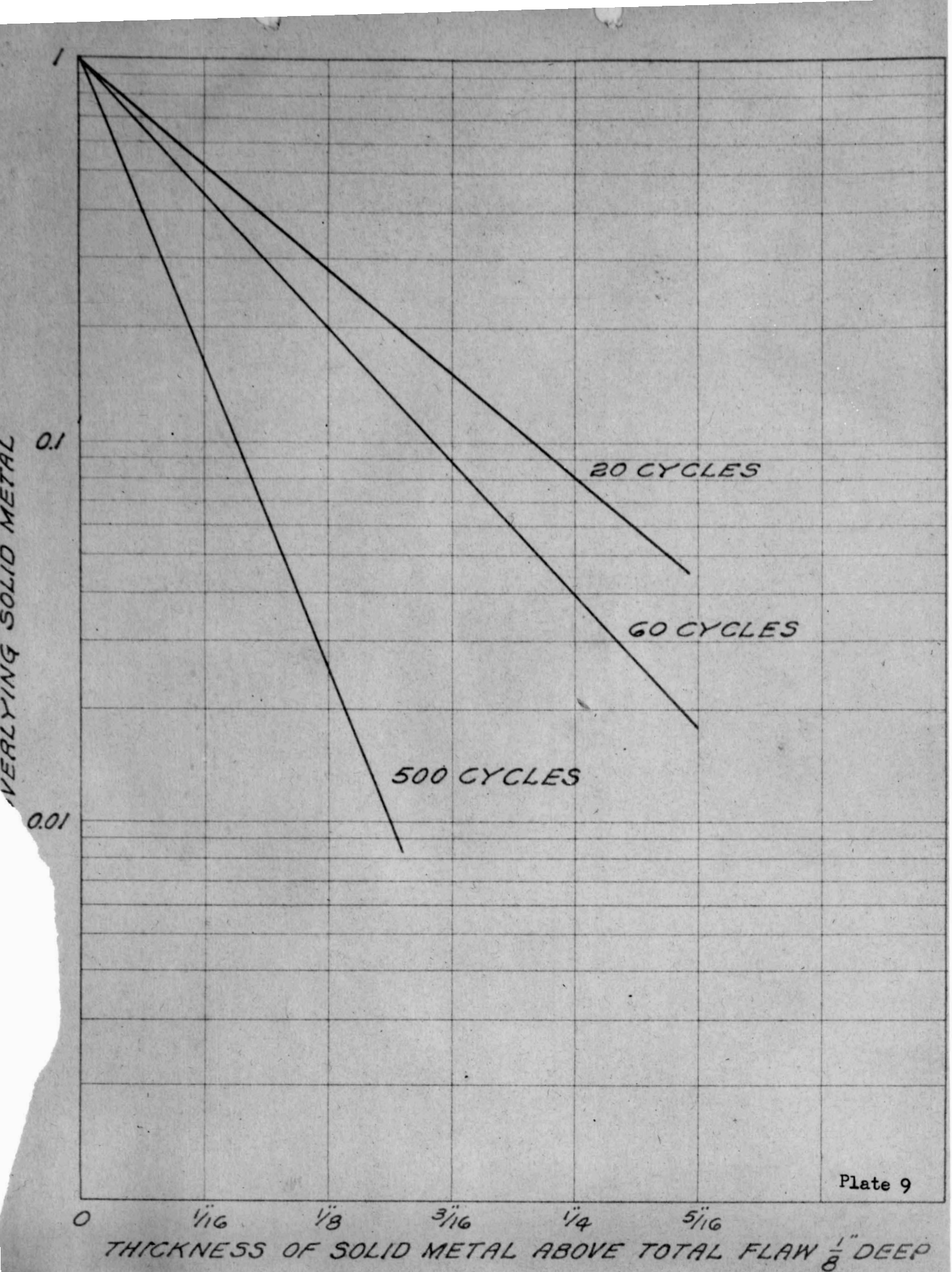
1
0.1
0.01
VERLYING SOLID METAL
20 CYCLES
60 CYCLES
500 CYCLES
0
1/16"
1/8"
3/16"
1/4"
5/16"
THICKNESS OF SOLID METAL ABOVE TOTAL FLAW 1/8" DEEP

Plate 9