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EDDY CURRENT INSPECTION METHODS: TRIP REPORT-THE DR. FORSTER INSTITUTE REUTLINGEN, GERMANY

by

R. C. McMillen
Engineering Research Laboratory
Engineering Department
Wilmington, Delaware

November 1953

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E. I. du Pont de Nemours & Co., Inc.
Explosives Department - Atomic Energy Division
Technical Division - Savannah River Laboratory

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ABSTRACT

Test instruments developed at the Dr. Förster Institute, Reutlingen, Germany, were considered for possible application to Savannah River nondestructive inspection problems involving stainless steel and aluminum tubing. None of the equipment can solve these problems without modifications. Several instruments are recommended for further study in connection with their use with aluminum tubing. None will be considered for use with stainless steel at this time.

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EDDY-CURRENT INSPECTION METHODS: TRIP REPORT - THE DR. FÖRSTER INSTITUTE, REUTLINGEN, GERMANY

I. SUMMARY

A. PURPOSE OF VISIT

The writer visited the Dr. Förster Institute at Reutlingen, Germany, in July 1952 to investigate the applicability of the eddy-current inspection methods developed by Dr. Förster to the stainless-steel and aluminum tube inspection problems at the Savannah River project.

R. Hochschild of the New York Operations Office, A.E.C. accompanied the writer on this visit. His interest included a number of inspection problems involved in the Commission's nondestructive test program.

B. RESULTS AND CONCLUSIONS

Sessions were held daily with Dr. Fritz Förster at his Institute from July 14 to July 28, 1952. General data was gathered on most of his nondestructive test methods. Performance, operating and application information was obtained on the equipment most applicable to A.E.C. inspection problems. Tests using Förster's equipment were conducted on samples brought along for this purpose.

The Dr. Förster Institute has developed over fifty different test instruments, most of which are for the nondestructive inspection of nonferrous (nonmagnetic) and ferrous (magnetic) metals for flaws, chemical composition, and structure. Eddy-current techniques are used for nonferrous metal inspection and magnetic measurements for ferrous metals. A brief description of the metal inspectors, their performance and field of application is given in Exhibit A. None of the instruments shown in Exhibit A or seen during the visit will solve, without modification, the inspection problems at S.R.P.

Dr. Förster's eddy-current inspection equipment separately measures both the resistive and the reactive impedance of the test coil in contrast to the conventional method of measuring only the vector sum of these two impedances. By this method, the presence of flaws in a test specimen which affect the resistive impedance of the coil can be detected in the presence of diameter changes which affect the reactive impedance of the coil. This unique feature provides a basis for instrument development superior to other known instruments or methods.

The Multitest inspector is designed to inspect cylindrical bars and tubes and is the most versatile of the eddy-current instruments developed by Dr. Förster. This electronic instrument compares the electrical properties of a test specimen inserted into a test coil to that of an acceptable or "standard" specimen placed in a similar coil. Changes in either or both the resistive or reactive impedances of the test coil caused by the test specimen can be seen as a two-dimensional display on a cathode-ray tube and can be indicated or recorded by auxiliary instruments.

The Crack Detector, Multiflux and Sigmaflux instruments, shown in Exhibit A, use the basic principle of the Multitest and differ only in the test coil arrangement or the indicator (meter or cathode-ray tube). The test coil of the Crack Detector consists of two closely-spaced, series-opposing secondary coils having a common primary. This coil arrangement, which compares one section of the test specimen to an adjacent specimen, provides the greatest sensitivity for the detection of short-length flaws. The Multitest, however, when equipped with equivalent coils, is more versatile and will outperform the above-mentioned instruments.

The Defectometer, and the Sigmatest, use probe coils and measure the resistivity of nonferrous bars, tubes, and plates without responding to minor variations in the probe-to-surface spacing. Flaws in the vicinity of the probe are indicated as a change in resistivity. The Defectometer is a null-balanced system and, thus, is more sensitive to resistivity changes in the specimen than the Sigmatest, which is mainly useful in measuring the absolute values of resistivity. The Defectometer's lack of response to probe-to-surface variations makes it attractive for the location of flaws in aluminum tubing. However, again the Multitest can be equipped with a special probe coil to achieve the same results.

Most of Förster's inspection methods for magnetic materials are built around the Förster-Sonde -- a novel pickup device for measuring very small magnetic fields. Flaw detection is achieved by electronically detecting the magnetic flux leakage associated with a defect in a premagnetized specimen. This method is more sensitive and somewhat similar in principle to the conventional iron-particle inspection method. The first five inspectors shown in Exhibit A-2 utilize this principle. No applications of these instruments to S.R.P. inspection problems are evident, but these methods look more promising than others for the detection of flaws on both the inside and the outside surfaces of ferrous metal tubing.

Seven stainless steel welded tubes containing small pin holes extending through the wall of the tube at the weld were tested on a Multitest inspector. The defects had been previously located by a hydrostatic test which undoubtedly enlarged the pin holes slightly. The tests were conducted using the regular comparison coils of the Multitest and special null-balance coils constructed for this test. The results were encouraging but not entirely satisfactory. Although some improvement can be expected with further development of the test coils, the test results indicate that the desired 100 percent detection of defects in these tubes cannot be achieved in production inspection.

Two ferrous metal 3/4-in. diameter samples -- a bar and a tube -- containing surface seams of varying depths were tested on the Förster-Sonde Crack Detector. The tests showed that seams as shallow as 0.01 in. in these samples could be reliably detected. Furthermore, a good defect indication for a 0.01-in. seam on the outside surface of the tube could be obtained when the probe coil was inserted into the bore (wall thickness 0.1 in.). This test indicates that bore defects as well as surface defects can be detected in ferrous metal tubes by inspecting only the outside of the tube.

Conclusions regarding the applicability of Förster's inspection equipment to S.R.P. inspection probes are summarized as follows:

1. None of Förster's equipment can solve known S.R.P. inspection problems without modification or development.

2. The Multitest and the Defectometer offer a better basis for equipment development to meet the inspection requirements on aluminum tubing than other known inspection equipment or methods. The critical portion of this work would center around the development of specialized test coil arrangements. Methods for handling the output signals and adapting Förster's equipment to production inspection would be more straightforward.

3. Although the Multitest inspector appears more promising than other eddy-current test methods for the inspection of stainless steel welded tubing, considerable equipment development would be required to approach the detection of 100 percent of the defects in production inspection.

C. RECOMMENDATIONS

1. Dr. Förster's eddy-current inspection equipment should not be considered at this time for replacing or augmenting the present routine inspection methods being used on the stainless steel welded tubing.

2. The nondestructive test program on S.R.P. aluminum tube inspection should include a comprehensive experimental investigation on the applicability of Förster's inspection methods, particularly the Multitest. It is anticipated that considerable development will be required to achieve optimum results.

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II. DISCUSSION

The discussion portion of this report is written for those interested in developing or modifying eddy-current instruments for specific inspection problems. Ths basic theory of eddy-current inspection is given to provide a background for a general description of Förster's instruments and applies to all methods of eddy-current inspection. Various pickup coil arrangements are qualitatively described and details of the tests conducted with Förster's equipment are given.

A. EDDY-CURRENT INSPECTION THEORY

All forms of eddy-current testing depend upon the production of eddy currents in an electrically conducting material when it is placed near a coil carrying alternating current. The magnitude and distribution of the eddy currents depend upon the magnitude and frequency of the alternating current, the inductance of the coil, the geometry and conductivity of the specimens of material, and its position relative to the coil. The eddy currents in turn produce a magnetic field and dissipate energy, so that the impedance of the coil is modified. The modification of the impedance is observed and is used to provide information concerning the state of the material.

Dr. Förster and his collaborators have carried out systematic theoretical and experimental investigations of the distribution of eddy currents for different geometrical systems of coil and specimen, different specimen conductivities, and the resultant effects upon the impedance of the coil. The main results of these investigations are summarized in the following paragraphs.

The distribution of magnetic field and eddy currents in a solid cylindrical bar inside a hollow cylindrical coil is expressed in a law of similarity.

The parameter f_g is defined as $\frac{5060}{\mu\sigma d^2}$ (for a solid bar)

where σ = the conductivity in meters/ohm mm.^{2}

d = the diameter of the bar in cm.

μ = the susceptibility of the material.

The constant (5060) is dependent upon the geometry of the sample -- solid bar, tube, or sphere.

If alternating current of frequency f is supplied to the coil, the distribution of magnetic field and eddy currents, both in phase and magnitude, are completely determined by the ratio f/f_g and the inductance of the coil

The law of similarity effectively means that if Hr is the magnetic field at a radius r from the axis of the specimen, Ho the field at the surface, ro the radius of the specimen, then for a given value of f/f_g the ratio Hr/Ho is a function only of r/ro and is independent of the conductivity and the absolute size of the specimen. Similarly, the eddy-current density ratio lr/lo, and the phases of both magetic field and eddy current are functions only of r/ro for a fixed value of f/fg. It follows from this relationship that once a family of curves for various values of f/f_g are drawn, the distributions are known for all cylindrical specimens.

Calculation and experiment show that the inductance and effective resistance of a hollow coil carrying a cylindrical specimen of the same diameter as that of the coil can be determined by a curve such as 1 in Figure 1 as the ratio of f/f_g is varied.

The point A corresponds to $f/f_g = 0$, i.e., nonconducting specimen or direct current, and the point E to $f/f_g = \infty$, i.e. infinite conductivity or infinite applied frequency. The point B corresponds to the maximum resistance of the test coil and is in all cases obtained for a value of $f/f_g = 6.25$.

Curve 1 is the curve for the theoretical case where the specimen completely fills the coil. In that case, the inductance approaches zero as the value of f/f_g approaches infinity.

The efficiency of the coil system decreases with a decreasing ratio (n) of specimen diameter to coil diameter. Curves 2 and 3 are drawn for specimens of smaller diameters.

If the applied frequency f is fixed, the curves represent the variation of the coil impedance. Curve 1 indicates the manner in which the impedance of the coil changes when specimens of fixed diameter, but increasing conductivity, are placed in the coil. Similarly, curves 2 and 3 indicate such changes for specimens of smaller diameter.

The dashed curves indicate the manner in which the impedance changes when specimens of the same conductivity but different diameters are placed within the coil.

Practically all eddy-current inspection methods can be discussed in terms of the test coil impedance plane of Figure 1. The test coil is electrically characterized by its two impedance values -- inductance L and ohmic resistance R. To eliminate dependence upon the particular construction of the coil, the curve of Figure 1 is normalized by using the ratio of the inductance with sample ωL to inductance without sample L_0 and the ratio of ohmic resistance R with sample to the inductance without sample ωL_0 as coordinates. Hence, the values $\omega L/\omega L_0$ and $R/\omega L_0$.

Given a test sample of certain electrical properties and diameter, an operating frequency can be chosen to give an f/f_g ratio of 16. This choice provides an operating point at "O" on Curve 1 (Curve 1, where sample completely fills the coil is chosen for discussion purposes -- Curve 2, with a fill ratio of 0.63, represents a practical case). Using an electrical bridge arrangement the complex voltage represented "O" can be balanced and considered zero indication for the test sample. Changes in conductivity of the sample will cause an output voltage shift along the heavy-line curve, while changes in diameter will result in a voltage shift in the "diameter" direction or along the dashed-line curve. For example, a decrease in conductivity such as caused by a crack will result in a vector voltage corresponding to line OC, while a decrease in diameter will cause a voltage change represented by line OD. It will be noted that the vectorial addition of these two voltage changes would result in an indication larger than the conductivity change caused by the defect. Also, that if the diameter had increased as shown by line OD_1, the vector sum for the diameter change and the defect would be smaller. Of course, diameter changes themselves could also be as large or larger than a defect indication. However, if a method can be used to show the direction as well as magnitude of any indication, the effect of diameter changes can be greatly reduced or eliminated.

Although the impedance sensitivity of the test coil to conductivity changes is greatest at an operating frequency where the f/f_g ratio is 6.25, higher operating frequencies are preferred. At higher operating frequencies, the angle between the conductivity and the diameter change lines increases (Figure 1). Thus, electronic phase-sensitive detectors can be used to discriminate against indications for diameter changes. For example, if by means of phase-sensitive detectors, the "line of response" of the detector can be rotated from an artibrary setting in the $R/\omega L_0$ direction to a direction perpendicular to the diameter direction as indicated by the dotted line, "X-Axis Response Line." Then the vector component in the line-of response direction OC' for the conductivity change OC will be large, while the indication for diameter changes, line OD, will be zero.

Even though the test coil impedance of all eddy-current inspection methods responds in a like manner, only the Multitest inspector described below with its two-dimensional display on a cathode-ray oscilloscope provides full information on the impedance changes occurring in the test coil. By such an arrangement, small changes in conductivity can be detected in the presence of diameter changes. Even small dimensional variations within normal tolerances have a pronounced effect on the impedance of the test coil. Dr. Förster points out that a 1 percent diameter change causes an impedance change as large as a surface crack of 5 percent diameter depth. In the case of subsurface defects, the comparative effect of diameter changes will be still greater.

B. MULTITEST INSPECTOR

The electronics of the Multitest inspector are designed to produce the two-dimensional display discussed above. This permits rotation of the direction of detector response to discriminate against test sample diameter changes.

This inspector is a universal tester. It is used for testing ferrous and nonferrous materials and is capable of detecting physical defects, diameter changes, and variations in alloy or hardness. It is primarily useful on nonferrous materials, as other methods are more suitable for ferrous metal inspection. The Multitest is a fairly recent development of Dr. Förster -- only 11 units have been sold.

The Multitest is basically a comparator in which two test coils are used. In one a "standard" sample is inserted and the sample under test is inserted in the other. As a result of this approach, the design of the test coils is not optimum for the detection of defects. For defect detection, the coils should be reduced in width and, in some applications, null coils, consisting of one primary and two secondary coils spaced close together, should be considered. By connecting the secondary coils in series opposition, a bridge-balanced arrangement is maintained without use of the "standard" coil. The use of null coils reduces the effect of differences in test samples (diameter, structure, etc.) and permits the use of more electrical amplification. In general, null coils provide maximum sensitivity to short-length defects.

1. OPERATING PRINCIPLE. Null coils are available with the Multitest or at least a set of null coils were constructed to test the stainless steel tubes during the writer's visit. It is not known whether null coils have been supplied with any of the eleven Multitest inspectors sold to date.

The operating principle of the Multitest can be described by reference to the block diagram of Figure 2. A.C. excitation energy is supplied by a fixed-frequency oscillator through a coupling transformer to the primaries of the two inspection coils. The frequency of the excitation voltage is determined by the f/f_g ratio chosen for the inspection of a given narrow range (conductivity and diameter) of test samples. The secondaries of the two inspection coils are connected in series opposition and the small residual output voltage present, when two similar test samples are inserted in the coil, is fed to an amplifier. The amplifier is connected to two separate phase-control detectors. The two detected or rectified signals are individually amplified and fed to the "X" and "Y" plates of the cathode-ray tube.

Voltage from the test coil primary system is also supplied to a phase shifter that is continuously variable in phase from 0° to 360°. Dual output from the variable phase shifter passes through a fixed phase-shift network that provides 0° and 90° voltage components which separately control the phase-sensitive detectors. This fixed phase-shift network permits the detectors to be responsive to the two 90°-apart components of the bridge output signal. Thus, the movement of the luminous spot in the cathode-ray traces out an impedance plane curve similar to that shown in Figure 1. The variable phase shifter permits rotation of the "X" axis of the cathode-ray tube (usually the inspection axis) to an angle or direction perpendicular to the voltage shift caused by diameter changes.

In operation, a test sample of acceptable quality is inserted in the "standard" coil and samples to be tested are passed through the "test" coil. With a sample in each coil, the spot on the cathode-ray tube will usually be off the face of the tube. Two centering controls not shown in Figure 2 are adjusted to center the spot. The face of the cathode-ray tube can then be considered to be a display of a small area around the operating point "O" in Figure 1. The spot will then move in the manner described in the above section for changes in diameter or conductivity of the sample. When the direction of diameter changes are known or established, the phase shifter can be adjusted to rotate the response of the "X" axis perpendicular to the diameter direction. Meter type indicators or recorders connected to the "X" or "Y" (or both) amplifiers (Figure 2) will then respond to conductivity changes and to diameter changes, respectively. A voltage regulated power supply not shown in Figure 2 is used to power the electronic circuits and the cathode-ray tube.

A complete schematic wiring diagram was supplied with the Multitest inspectors purchased by the N.Y.O.O. and the Argonne National Laboratory, but is not included with this report.

2. ALUMINUM TUBE INSPECTION. Unquestionably, the Multitest is capable of supplying more test information, provides more inspection selectivity, and is more flexible than the Cyclograph inspector (an American product) now being investigated at A.N.L. It remains to be seen whether or not these advantages can be utilized in routine inspection. Although test results to date using the Cyclograph have been encouraging, sufficient data are not available to determine the reliability of detecting subsurface defects in a large number of different samples. Small changes in diameter will increase the defect indications in some cases and reduce them in others.

Some of the advantages of the Multitest over other methods for the inspection of aluminum tube at S.R.P. are:

1. The influence of small diameter changes on the defect indication can be eliminated.

2. By the optimum choice of operating frequency, emphasis can be placed on defects just below the surface.

3. The bridge-balanced arrangement makes the inspector inherently stable over long periods.

4. The speed of response is, for all practical purposes, instantaneous; therefore, the speed of production inspection need be limited only by the material handling mechanism.

5. Null coils, which inherently have the highest sensitivity to short-length defects, can be used.

6. A "standard" method and a null coil method can be used simutaneously by using two detection systems. The former would give information on long continuous defects and the latter on short-length defects.

C. DEFECTOMETER

The Sigmatest and the Defectometer are designed to measure the conductivity of metals by eddy-current measurements. Both instruments use a probe that is placed on the metal surface and are unique in that compensation is provided for small probe-to-surface variations. The Sigmatest measures conductivity in absolute terms, while the Defectometer is sensitive to changes in conductivity. The latter is much more sensitive to small conductivity changes and more tolerant of gap spacing. Since the Defectometer uses a small probe, it should be of definite interest to detect localized subsurface defects in tubes. (When circumferential coils are used, the average effect of the subsurface detects around a ring of the tube is measured.) This device should also be useful on the inspection of sleeved flat plates.

The Sigmatest and Defectometer operate on the principle that the impedance of a test coil is affected by the conductivity of any metal (See Section A above, "Eddy-Current Inspection Theory") to which it is coupled. However, the impedance of the coil is also affected by small changes in coupling, such as spacing between the probe and metal surface.

The test coil arrangement of the Sigmatest is shown in Figure 3A. A.C. energy from a fixed-frequency oscillator is transformer-coupled to a series-resonant coil and capacitor system. The output voltage E_o from the system is developed across the capacitor, C, and is proportional to the current flowing in the series-connected LC system. This current is determined directly by the resistive impedance of the coil and indirectly by the effect of the inductive impedance influencing the off-resonance response of the tuned circuit. For example, Figure 3C shows the impedance plane of the test coil with relative values of conductivity indicated on the solid line curve for copper, aluminum, and zinc. Assuming the test coil is coupled to a copper sample, the operating point would be at "O". Variations in the coil-to-sample spacing are indicated by the dashed line. Figure 3D shows the current response curve of the resonant test coil system, with the resonant point readjusted to a frequency lower than the oscillator frequency f. If the conductivity decreases and the operating point moves from O to 2 on the solid line curve in Figure 3C, the resistive component of the coil, line O-1, increases, reducing the current, and the inductive component, line 1-2, increases, causing the test coil system to resonate at a lower frequency, which also reduces the system current. Hence, for decreases in conductivity, the current through the capacitor decreases and the voltage output drops. The reverse action takes place for increases in conductivity.

If an increase in spacing between the probe and the metal surface occurs, the operating point moves from 0 to 4. In this case, the resistive component, line 0-3, decreases, increasing the current and the inductive component, line 3-4, increases, reducing the current due to a shift in the system resonance. By properly proportioning the values of L and C in relation to the oscillator's frequency, these last two current changes can be made to cancel exactly over fairly large (50 to 100 mil) changes in gap spacing.

The Defectometer, Figure 3B, also makes use of a bucking voltage which is supplied from an oscillator and is variable in amplitude and phase. This bridge arrangement permits detection of changes in conductivity and decreases further the effect of spacing variations on the indication. In routine inspection, the Sigmatest is useful as a comparator, while the Defectometer is more useful to detect defects or changes in conductivity of a sample.

The obvious advantage of the Defectometer and Sigmatest over other probe-type inspectors is that it is free from probe-to-surface spacing variations. This feature is valuable when evaluating an inspector for a specific inspection application and greatly simplifies the problem of adapting a probe system to production inspection.

In a subsequent contact with Dr. Förster, he advised that the Multitest when equipped with probe coils of suitable design will also be insensitive to probe-to-surface variations. The effect on the test coil impedance of changing the coupling of either a probe or a circumferential coil is similar. Therefore, the Multitest can be adjusted to be insensitive to probe-to-surface variations. The Multitest equipment is more sensitive and flexible than the Defectometer and therefore is more useful for general eddy-current inspection.

D. INSPECTION COIL ARRANGEMENTS

The following section describes various arrangements of inspection coils and discusses their relative merits. This information should be useful in determining the optimum coil arrangement for specific inspection applications. Many of the statements are applicable to both seamless tubing and aluminum tube inspection.

1. CIRCUMFERENTIAL COILS. Circumferential coils are more convenient to use in production inspection than probe types, as methods need not be provided to rotate the probe around a sample as the sample is moved nor are probe-to-sample gap variations a problem. However, circumferential coils tend to average the changes in

conductivity that take place in a narrow ring around the circumference of the sample. The width of this ring is determined by the width of the secondary coil field and the depth by the operating frequency or thickness of the sample in the case of a tube. The width of the primary coil field generally should be wider than that of the secondary. The primary coil is usually limited in width to minimize end effects and thus permit inspection close to the end of a sample.

Wide primary coils are used to obtain a better coupling to the sample, i.e., to increase the magnitude of the eddy current in the sample. However, the magnitude of the eddy current affects only the sensitivity of the inspection system in the case of nonferrous materials. Therefore, when using methods involving weak eddy currents (low-powered oscillators or coils with poor coupling), the sensitivity of the inspector can be increased by electronic amplification of the signal.

The coil fill (the ratio of sample o.d. to coil i.d.) should be as large as possible, since small fills will not only reduce the eddy-current strength, but also reduce the sensitivity of the secondary coils to changes in conductivity caused by short-length defects.

The use of null type circumferential coils (two secondary coils connected in series opposition) permits use of greater signal amplification for a given amount of inspection "noise" than a single test coil (standard). The null coils, by comparing one section of a sample to another, approximately 1/4 to 1 in. apart, minimizes the effects of changes in diameter, stress, and structure that take place from sample to sample, placing a smaller selectivity burden on any electronic arrangement used to discriminate against these variables.

Examples of the two types of circumferential coils discussed are shown in Figure 4A.

For the detection of short-length defects in a tube, the null coils should be made as narrow as possible and spaced close together. In general, wider coils and spacings must be used when the diameter of the coils is large in order to obtain reasonable coupling. In the case of 1/2-in. diameter tubing, Dr. Förster thought that coils as narrow as 1 mm. in width spaced 2 mm. apart were practical. When using the narrowest possible coils, the coil fill must be large.

The most effective way to reduce the field width of a coil is to make the coils as narrow as possible and use copper shields. Förster saw no advantage in using ferrite or other special metal shields. For frequencies 10 kc. and higher, copper shields are quite effective. Below 10 kc., the use of copper shields plus soft iron is recommended. Figure 4B shows the suggested construction.

2. PROBE COIL: Probe coil arrangements have maximum sensitivity to surface defects adjacent to the coil. They are useful in the inspection of localized areas of a large sample. Probe coils can be arranged in a "standard" coil system or a null coil system. The characteristics of null coils as compared to a standard coil are the same for probe as for circumferential coil arrangements. Null coils minimize the effects of coil-to-sample gap variations and changes from sample to sample in average structure, stress, and conductivity. In the case of the Defectometer and the Sigmatest, the effect of changes in gap spacing are eliminated in the instrument regardless of the coil arrangement.

In considering coil arrangements that will be responsive to different type defects, a fundamental rule of eddy-current testing is that the defect must interfere with the flow of the eddy current. Circumferential coils will be responsive to defects having some length perpendicular to the coils but not to defects of short length or width parallel to the coil. Figure 4C illustrates this point.

As indicated in Figure 4C, circumferential coils are not responsive to transverse type defects unless the defect has significant width. Probe type coils are responsive to defects of any orientation. Laminar type defects are not theoretically detectable with circumferential coils unless they have significant "height."

Probe coils are of interest when inspecting welded tubing as the inspection can be confined to the zone of interest. The inspection of tubing immediately after the cooler on a welding machine is practical, since the weld zone is accurately oriented. After tubing, especially in long lengths, has been drawn or straightened, the weld line tends to twist, which complicates "zone" inspection.

3. INSIDE COIL. Maximum sensitivity to defects on the inside surface of tubes or pipes can be obtained with inside probe coils and inside circumferential coils. Inside probe and circumferential coil arrangements are illustrated in Figure 5A. With all inside coil arrangements, production

inspection is difficult in long tubes due to the awkwardness of tube handling and of any probe-pushing mechanism. Usually the coil arrangements are spring-loaded to accurately position the coil against the inside of the wall.

4. SPECIAL COILS. In discussing with Dr. Förster the detection of laminar type defects below the surface of a tube, Bundy tubing made from copper strip was cited as a sample of interest. The cross section of a Bundy tube is a spiral several layers thick, usually of copper and iron sheets. The tube described as an example of interest was a two-layer spiral of sheet copper with the inner surfaces of the spiral sweated together. Voids between the two surfaces were to be detected by outside surface inspection.

Because defects must interrupt eddy-current flow to be detected, the use of circumferential coils is not indicated. A probe arrangement as shown in Figure 5B has the desirable orientation in relation to the defect but its field strength normal to the axis of the coil is low. This limits its effective flux penetration.

With the yoke arrangement of Figure 5C, the eddy-current intensity in the region of the laminar-type defect should be effective. The secondary pick-up coil must be balanced with respect to the field of the primary. An output signal will result only when an irregularity in the field system is present. However, with such a coil arrangement, yoke spacing variations would present a serious problem in production inspection.

Yoke spacing problems can be minimized by the arrangement shown in Figure 5D. Here the primaries are large enough in relation to the sample to provide a fairly uniform field. Again the pick-up coil is balanced in the primary field with the sample in position.

The Defectometer can be used with a yoke arrangement as shown in Figure 5E. By proper design and instrument compensation (See Section C, "Defectometer"), the effects of spacing variations can be eliminated or greatly reduced.

It will be noted in the last three arrangements described that the eddy currents will intercept the laminar type defect shown in Figure 5. Using such arrangements, the probe can be rotated while the sample is moved through the inspection zone or the sample rotated while the probe scans. Since either the laminar or the bore-type defects of interest are small in area, electronic differentiation can be used to emphasize the defects in relation to the "slower" signals caused by slight eccentricity of the sample (spacing variation) or gradual changes in the average penetration.

In the detection of defects in a plate, the Defectometer with its regular probe should detect defects perpendicular to the surface. In the case of a cylindrical sample, the Defectometer is also responsive to defects parallel to the surface when used with the probe shown in Figure 5E. Although the detection of defects parallel to the surface is considered quite difficult, a yoke arrangement as shown in Figure 6A has been used with some success. Such an arrangement has been quite successful in detecting voids between the bearing material and the iron backing of a sleeve-type, lined bearing. The bearing material was nonmagnetic and the probe was used to scan the assembly from the bearing surface side (Figure 6B).

E. MISCELLANEOUS INSPECTION METHODS

1. SELECTIVE DETECTION OF SUBSURFACE DEFECTS. The problem of detecting slightly subsurface defects in the presence of surface variations was discussed with Dr. Förster. The use of two inspection frequencies as suggested by others investigating this problem was not encouraging in the opinion of Dr. Förster. However, the following approach is of interest.

The phase angle of the eddy currents generated by a magnetic field increases with depth of penetration and with operating frequency. Emphasis can be given to subsurface defects if the inspection indications can be made phase-sensitive by this effect.

Figure 6C shows in detail the changes in coil impedance caused by different depth surface defects and subsurface defects of different depths below the surface. The effects illustrated have been calculated by Dr. Förster and proven experimentally. Figure 6C shows that there is a measurable phase angle difference between signal changes for surface defects and for subsurface defects of different depths.

Dr. Förster believes that an operating frequency can be chosen for a specific sample that yields a 90° angle between the direction for diameter changes, line 1-0-2, and the direction for the depth of subsurface defect of interest, say the defect represented by line 0-5 (Figure 6C). Under these conditions the direction-of-detector-response line will be rotated exactly perpendicular to the direction for diameter changes. The instrument's response to defects in the subsurface zone of interest will then be maximum and the effect of diameter changes will be eliminated. The effect of defects above and below the zone of interest will be minimized, as only the vector component of the changes in the coil will be indicated by the inspector. A certain size defect below the zone will have a smaller effect on the coil than the same size defect in the zone. The same size defect above the zone (nearer the surface) will have a larger effect on the coil but one signal for this change will be reduced by an amount proportional to the angle between the line-of-response direction and the direction of the defect.

This approach is interesting but the writer feels that samples would have to be supplied to Dr. Förster for direct experimentation in choosing the optimum operating frequency or, considerable research would have to be conducted here to achieve satisfactory results. However, a careful choice in operating frequency, calculated from available data and experience, would certainly be in the right direction when using the Multitest.

2. WELD INSPECTION. No method for the inspection of welds in plates appears promising. Only one method discussed is worthy of mention. Figure 7A indicates a probe arrangement that might be adapted to the inspection of welds. It meets the requirement of causing the eddy current to pass through the weld area in the proper direction.

3. COMMENTS ON THE CYCLOGRAPH. The Cyclograph is responsive only to resistive changes in the Test coil, which is not the same as being responsive only to resistive changes in the test sample. In choosing the operating frequency, only depth of eddy-current penetration is, with one exception, of prime concern. At an operating frequency of $f/f_g = 6.25$, it can be seen from Figure 1 that resistive changes in the sample are in a direction perpendicular to the resistive component of the coil. Hence, at this frequency, resistive changes in the sample will not be detected. It is interesting to note that at lower operating frequencies, an increase in sample resistivity will result in an increase in indication, while at higher operating frequencies, an increase in sample resistivity will give a decrease in indication. At a frequency higher than $f/f_g = 6.25$, an increase in diameter will have a vector component in the resistance of the coil in the same direction as an increase in resistivity of the sample (Figure 1).

4. ELIMINATION OF PERMEABILITY VARIATIONS IN "NON-MAGNETIC" MATERIAL. Occasionally, a ferritic structure is developed in the welding of stainless steel tubing. Since such a formation is magnetic, a large change in the test coil impedance results. Both American firms

and Dr. Förster have used a strong d.c. magnetic field to saturate any magnetic structures present. When saturation is reached, the permeability is zero or near zero. A yoke arrangement used to "saturate" test samples during inspection is shown in Figure 7B. Approximately 3000 amper-turns are used for tubing. Higher values are used for solid bars and large, thick-wall tubing.

5. FÖRSTER INSPECTION EQUIPMENT. Inspection equipment of Förster's design other than that discussed herein is of general interest. Exhibit A shows advertising material on Förster's equipment which provides information on the appearance, performance, and application of the equipment. Exhibit A-1 is on nonferrous material testing equipment, A-2 on ferrous material testing equipment and A-3 is a more complete listing of both types of equipment. The first two exhibits are in English while the latter is in German.

The Magnaflux Corp., Chicago, Illinois, has the sales rights in North America for certain nonferrous metal inspection equipment. Magnetic Analysis Corp., New York City, has the sales rights for certain ferrous metal inspection equipment. There is a definite price advantage in purchasing any equipment not handled by these two American firms directly from Förster.

F. FÖRSTER-SONDE EQUIPMENT

A number of instruments have been developed and are available from Förster based on the Förster-Sonde method of measuring magnetic fields and magnetic field components. The Sonde is a magnetic field detector of the "second harmonic" type.

The principle of operation is not new for it is believed to be used in certain types of magnetic compasses, but the sensitivity of this equipment is believed to be higher and the probes much smaller than similar U.S. devices.

The detector unit consists of two small probes having a straight, μ-metal core with a primary and secondary winding. For field gradient measurements, the primaries are connected series aiding and the secondaries in series opposition. For absolute field strength measurements, the primaries are connected in series opposition and the secondaries series aiding. The primaries are energized by an a.c. source, typically, a 100-kc. oscillator. The combined output voltage from the secondaries is amplified by a selective amplifier tuned to the second harmonic (200 kc.) and indicated by a rectifier and meter (detector) as shown in Figure 8.

The probes are matched so that in the absence of a flux field the fundamental output voltages are equal and, in equal flux fields, the second harmonic-voltage outputs are equal.

If the probes are placed in a magnetic field having a flux component parallel to the cores, a d.c. flux is induced in the cores that is superimposed on the a.c. flux induced by the current in the primaries. This d.c. flux biases or moves the zero of the B-H characteristic curve of the µ-metal core causing asymmetrical flat-topped output waveforms having a second harmonic component. When the secondaries are connected series aiding, for absolute field measurements, the second harmonic voltages add. When connected in series opposition, for field gradient measurements, the output voltages cancel. In the latter case only, unequal flux fields, that is field gradients, result in an output voltage.

By the above two arrangements of the probes, absolute magnetic field intensities can be measured in various directions or the presence of ambient flux fields -- earth's field and/or local fields of uniform nature -- can be ignored and the flux gradient produced by some local source measured.

Since a selective amplifier can be used at a frequency removed from the supply oscillator, high useful sensitivities are obtained. The sensitivity of the equipment demonstrated was 10^{-5} oersteds per 1 scale division (1 millimeter). Sensitivities of 10^{-6} oersteds per scale division can be supplied.

The Förster-Sonde principle is used in research studies to measure magnetic field direction and intensity, to detect the presence of magnetic parts in nonmagnetic assemblies and to detect buried magnetic mines and torpedoes. The first three inspectors (crack detectors) and the fifth instrument, "Magnetic Sorting Apparatus," listed in Exhibit A-2 utilize the operating principle of the Förster-Sonde.

As used for the detection of cracks in ferrous bars, the probe is moved over a plate or rotated mechanically around a bar to detect the magnetic leakage field associated with a crack or a sharp defect. The sample is magnetized before inspection, usually by passing a d.c. current through the sample for an instant. The current flow should be parallel to the direction of the cracks to be detected so as to produce poles of opposite polarity on each side of the crack. For example, if longitudinal cracks in a bar are to be detected, passing current through the length of the bar will circularly magnetize the bar, thus creating magnetic poles on each side of the defect. For transverse cracks, the bar should be longitudinally magnetized by means of a solenoid type coil.

Wide-type defects such as surface pits and scale will have a weak leakage field as compared to a fine-line defect such as a crack. The use of electronic differentiation which is associated with the scanning speed of the rotating probe also helps in emphasizing a fine-line defect as compared to a broad surface pit or the presence of localized stress in the bar.

Dr. Förster has found that a subsurface crack will have a measurable magnetic gradient at the surface of a bar. This is of interest in the inspection of seamless steel (magnetic) tubing for bore cracks. Tests made on a tube sample containing a surface seam indicated that defects as shallow as 0.01 in. can be detected in the bore of the tube with about 70 percent of the indication obtained by surface inspection.

G. TESTS ON SAMPLES

Two groups of samples were taken to the Dr. Förster Institute to obtain first-hand data on equipment performance.

1. STAINLESS STEEL TUBE TESTS. The first group consisted of nine stainless steel welded tubes 1/2-in. diameter, 0.049-in. wall, and approximately 30 in. long. Seven of the tubes contained small pinholes in the weld area previously detected by a 5000 lb. hydrostatic test. Some of the seven defects were of the "seeper" class where water pressure must be maintained for a period before a noticeable amount of water seeps through the hole. Two tubes, containing no known defects, one welded and one seamless, had not been subjected to a pressure test. These tubes were included to determine if the noise background of these tubes would be different than those previously subjected to pressure.

A Multitest inspector was used for the tests. The first tests were made with "standard" coils, i.e., a primary and a secondary coil through which the samples were moved and compared electrically with another set of primary and secondary coils in which a similar tube was inserted but not moved. The defect in 6 of the 7 defective tubes could be detected with reasonable signal-to-noise ratio. However, the defect in the seventh tube gave an indication that was mainly in the "diameter direction" and therefore could not be detected unless its presence in the tube was known.

It was suggested that null-type coils, one primary with two closed-spaced secondaries, would provide more sensitivity to these short-length defects. A null-type coil assembly was constructed and tried just before the end of the visit.

Although the signal-to-noise ratio using the null-type coils was definitely better, the major portion of the indication in the seventh tube was still in the diameter direction. A recording of the indications taken in the "defect direction" of the Multitest for each of the nine tubes is shown in Figure 9.

No evidence of the presence of ferritic structures in the tubes was noted. However, tests were also made using a saturating d.c. field. No resulting change in any of the test records could be observed.

Referring to Figure 9, the tubes numbered from 1 to 4 inclusive are from one mill while tubes from 5 to 7 inclusive are from another. No significant difference could be noted in the signal characteristics from these two groups nor from the tubes numbered 101D and 124C that had not been subjected to high pressure.

With the exception of the one tube, the Multitest inspector operated and responded to adjustment as expected. The phase rotation knob could be adjusted so that the amplifier to which the recorder was attached would respond to changes other than the defect, presumably diameter and stress changes. When properly adjusted, indications were noted on the cathode-ray tube throughout the length of the tube that represented changes in the test sample other than in the resistivity direction, but these indications were small compared to the defect indication. Without the phase-sensitive circuits of the Multitest, some of the smaller indications for defects would have been overshadowed by the acceptable variations.

The null coils constructed for the tests were about 5 mm. wide, spaced 45 mm. apart. After the last test was made, Dr. Förster stated that coils as narrow as 1 mm. wide spaced 2 mm. apart would be better and might detect the one defect missed. Dr. Förster offered to construct new coils and review the choice of operating frequency to determine if the Multitest could be altered to detect this defect. The operating frequency used was 200 kc. which provided an eddy current intensity at the bore surface about 25 percent of that on the outside surface.

Conclusions and recommendations concerning the use of the Multitest to replace the hydrostatic test now being used on this type tubing are given in the Summary.

2. FERROUS METAL SAMPLE TESTS. A steel tube 3/4-in. diameter, 0.1 in. wall and a 3/4-in. steel bar both containing defects were tested with the Förster-Sonde equipment. The steel tube contained a tapering seam varying in depth from about 0.005 to 0.04 in. for a length of about 6 in. The equipment detected the seam with good signal-to-noise ratio as indicated by scanning around the circumference of the tube. However, a meaningless indication as large as that for a 0.01 in. deep portion of the defect was noted. The characteristics of this indication were similar to that expected for a localized stress area. It is believed that electronic differentiation would minimize this meaningless indication.

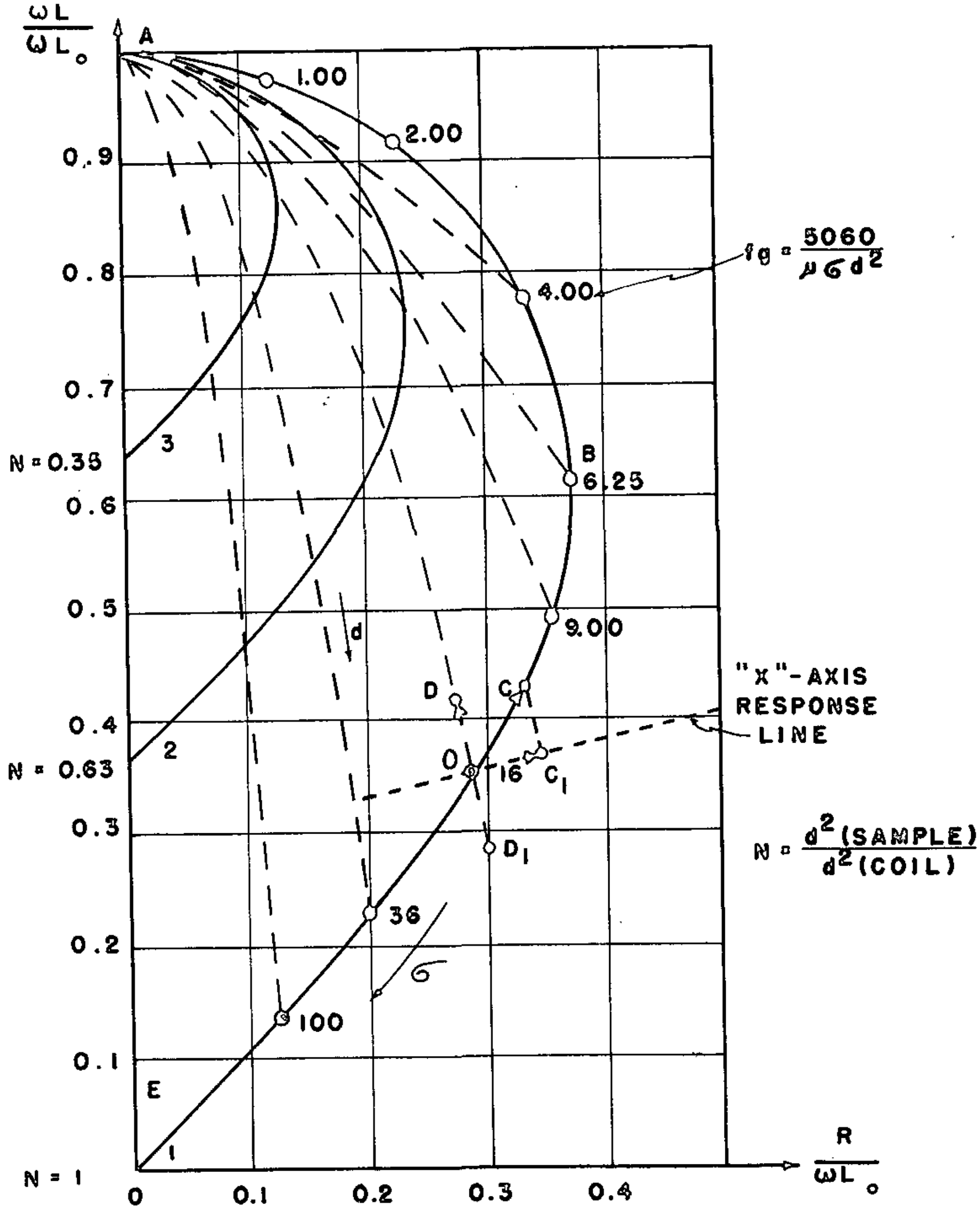
A new inspection method using only a very small pick-up coil and a sensitive amplifier was assembled for additional tests. This new method operates on the principle of voltage being induced in the probe coil when flux lines from the defect's leakage field cuts through the coil as the bar is rotated. This method has been used by Magnetic Analysis Corp. and is claimed by them to be superior to the Förster-Sonde Crack Detector. The amplifier is connected to an oscilloscope whose sweep is synchronized with the rotational speed of the bar or of the probe.

The type response from the two inspection methods when inspecting the tube sample is shown in Figure 10. The five oscilloscope traces for each method were taken at five different locations in the tube. The length of each scan represents one scan of the circumference of the tube. The indications for the pick-up coil method are superior to those for the Förster-Sonde equipment. Although it is not shown in these recordings, the pick-up coil method detected a shallower defect than the first method and did not respond to the meaningless indication observed with the first method.

Encouraging results were obtained in detecting the surface defect when inspecting the bore of the tube with the probe of the Förster-Sonde equipment. The magnitude of the indications were about 70 percent of those obtained with surface inspection. The signal-to-noise ratio was good. The meaningless indication noted with surface inspection was not observed with bore inspection. Apparently, the meaningless indication was caused by a shallow stress condition on the surface whose magnetic gradient lost its identity by the time it passed through the wall thickness.

The 3/4-in. bar contained two continuous seams about 0.01 in. in depth. Using either inspection method, definite indications were obtained for the two defects throughout their length, however, the signal-to-noise ratio was marginal in several areas of the bar. This is indicative that the detection of 0.01 in. defects in a 3/4-in. bar is about the limit of these inspection methods. The steel in the bar was soft. It is probable that defects of this size could be detected in a bar of harder steel.

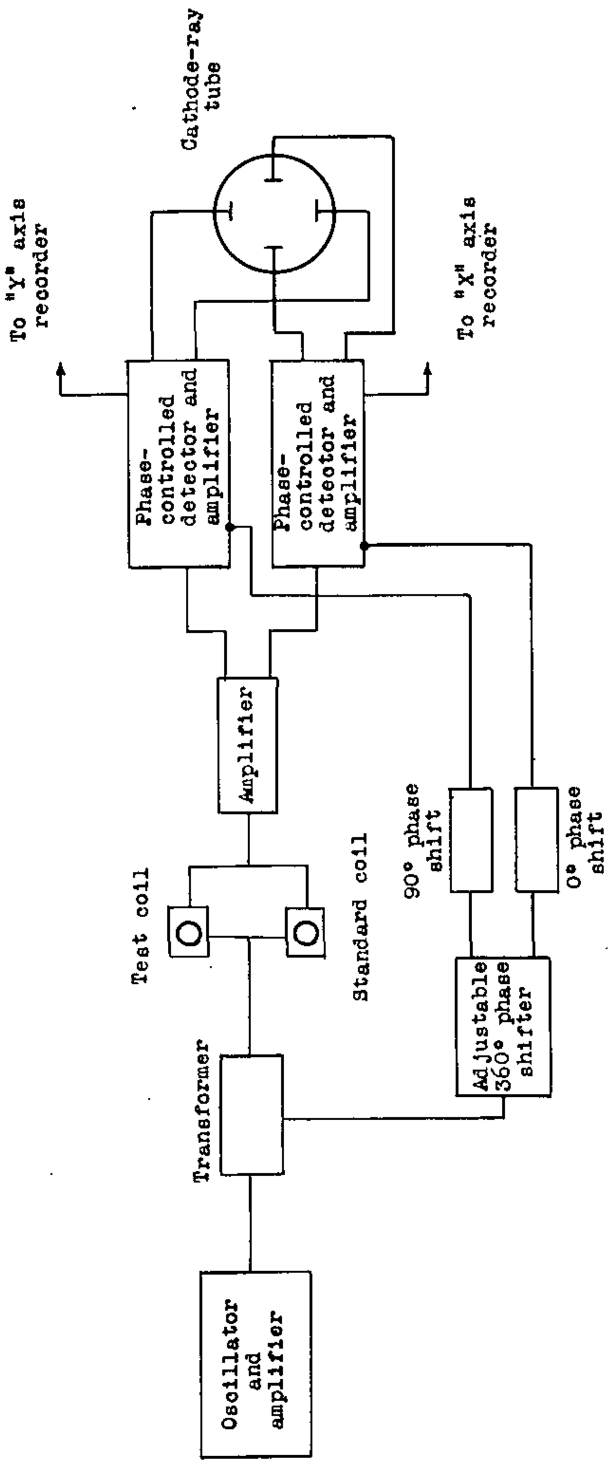
FIGURE 1



NORMALIZED IMPEDANCE PLANE CURVES

R. C. McMILLEN
C. S. ZUNSER 9-29-52

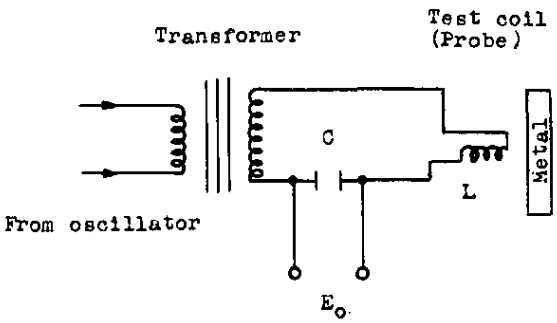
FIGURE 2



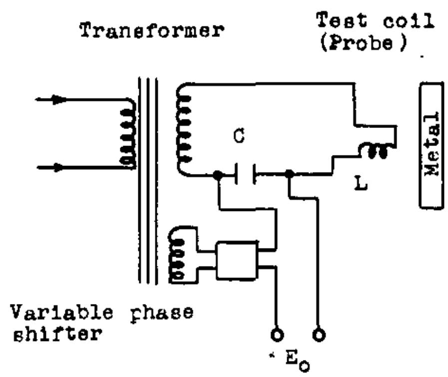
BLOCK DIAGRAM OF MULTITEST INSPECTOR

R. C. McMILLEN
C. S. RUNSER 6-11-52

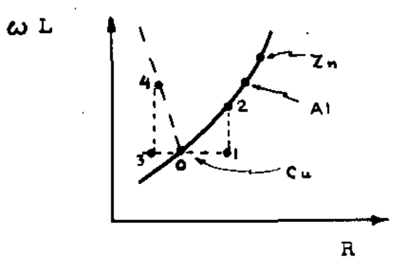
FIGURE 3



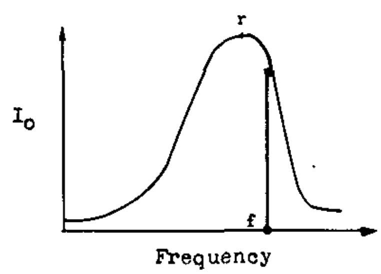
(A). SIGMATEST



(B). DEFECTOMETER



(C). IMPEDANCE PLANE OF TEST COIL



(D). TEST COIL CIRCUIT RESPONSE CURVE

INSTRUMENTS FOR CONDUCTIVITY MEASUREMENTS

R. C. McMillen
C. S. Zunser 5-25-53

FIGURE 4

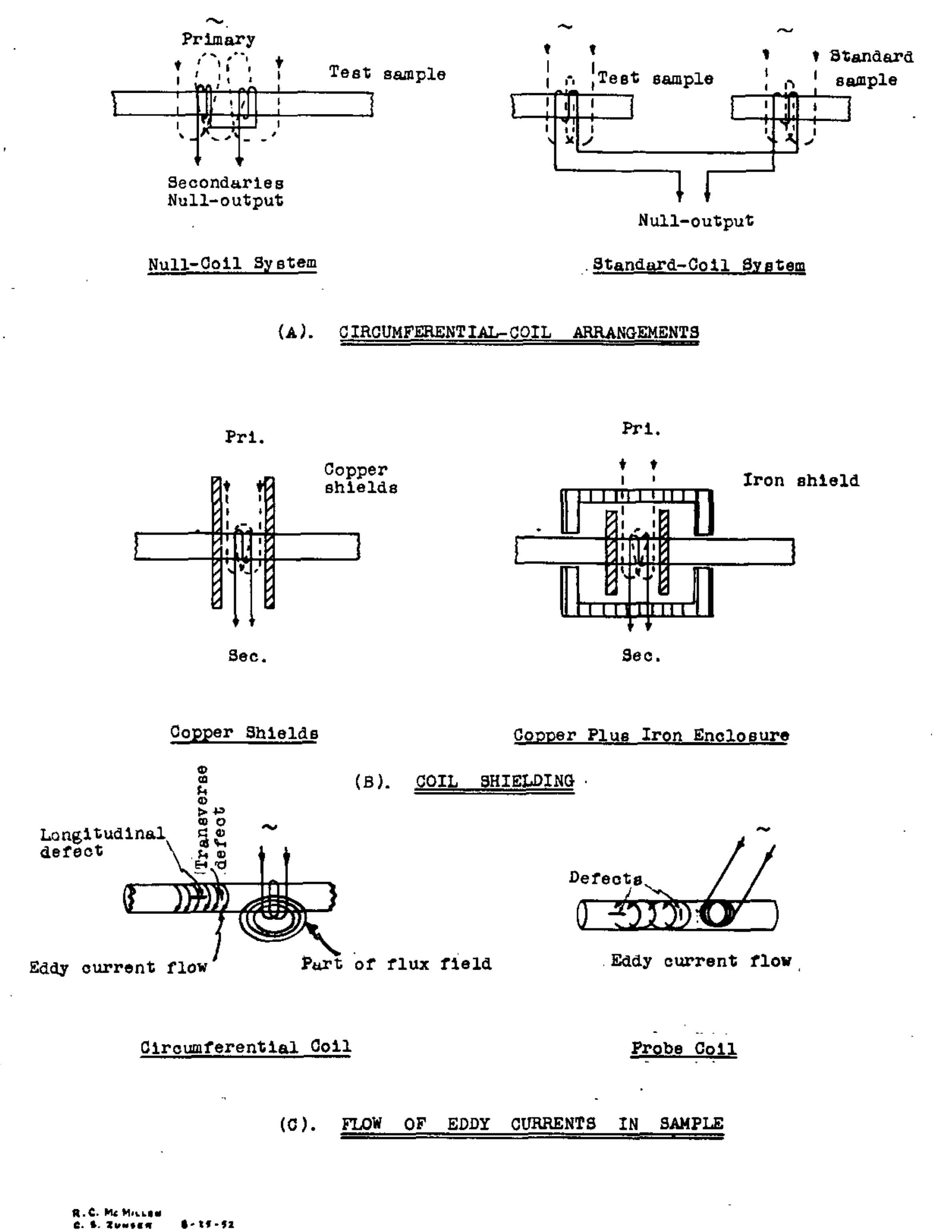
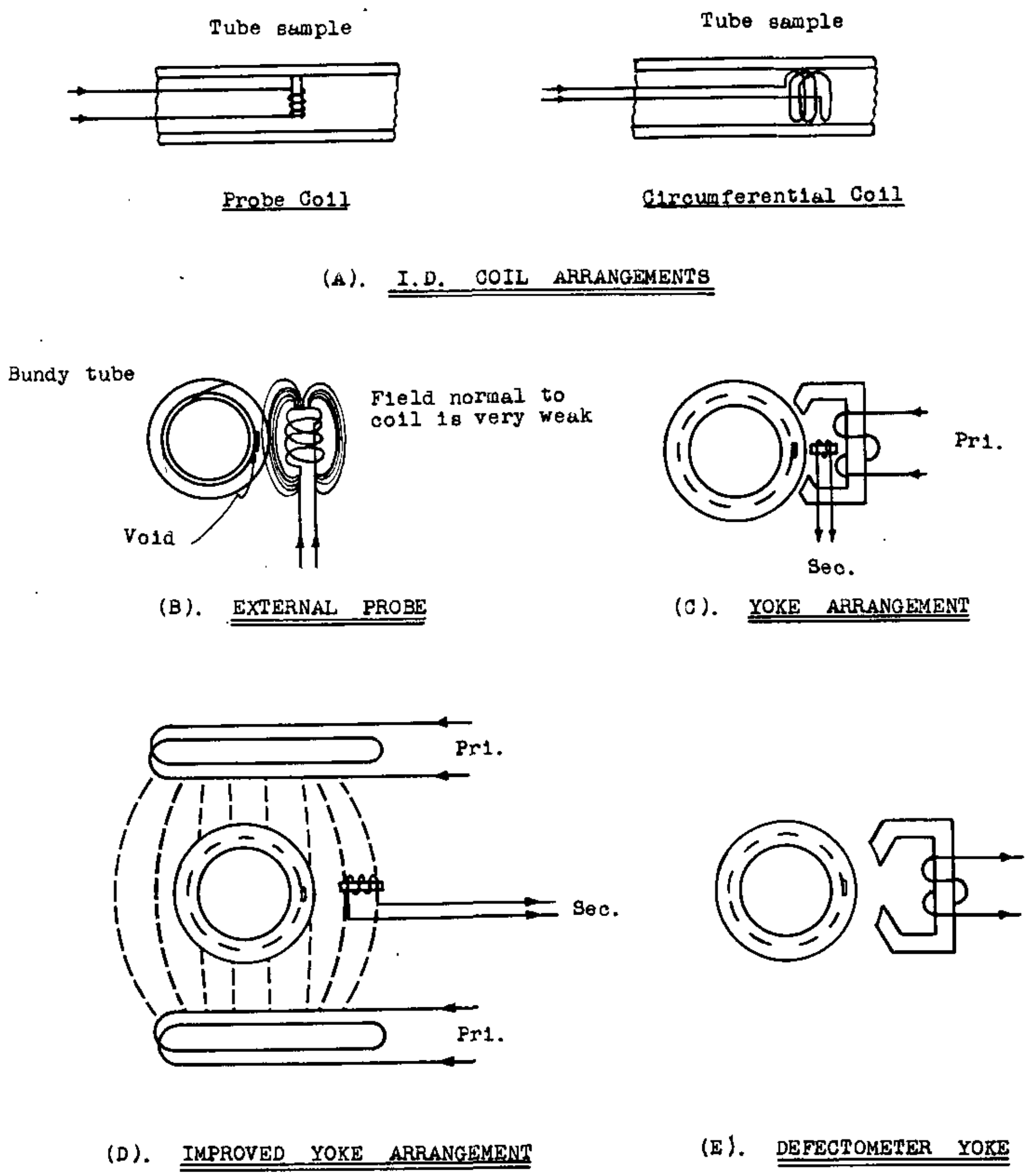

Primary
Test sample
Secondaries
Null-output
Null-Coil System
Test sample
Standard
sample
Null-output
Standard-Coil System
(A). CIRCUMFERENTIAL-COIL ARRANGEMENTS
Pri.
Copper
shields
Sec.
Copper Shields
Pri.
Iron shield
Sec.
Copper Plus Iron Enclosure
(B). COIL SHIELDING
Longitudinal
defect
Transverse
defect
Eddy current flow
Part of flux field
Circumferential Coil
Defects
Eddy current flow
Probe Coil
(C). FLOW OF EDDY CURRENTS IN SAMPLE

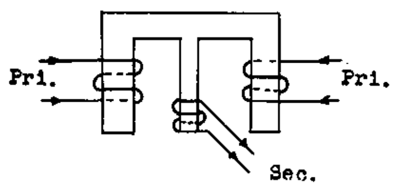
FIGURE 5



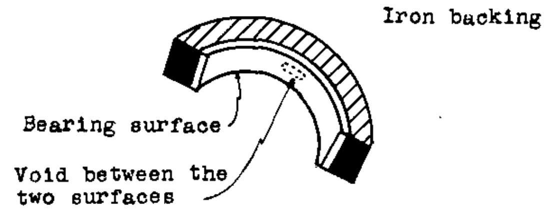
COIL ARRANGEMENTS

R. C. McMILLEN
C. S. ZUNSER 8-26-52 8

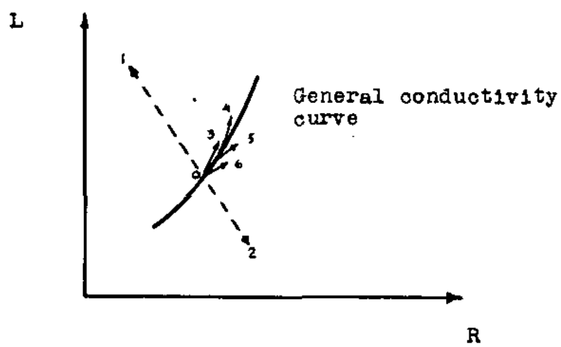
FIGURE 6



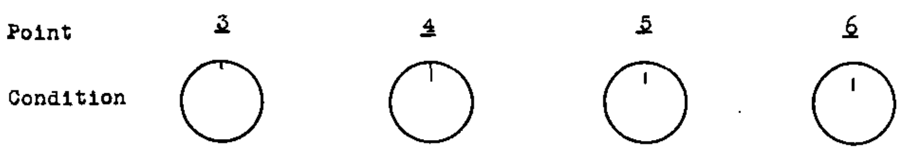
(A). YOKE ARRANGEMENT FOR PLATES



(B). BEARING WITH LACK-OF-BOND AREA



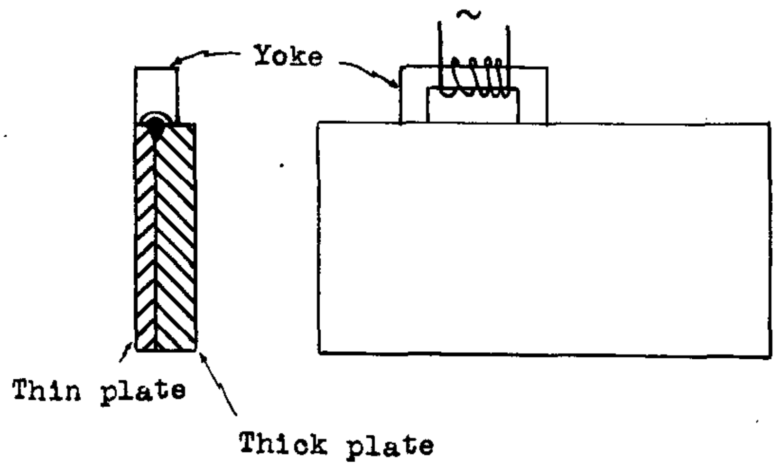
Indication	Sample change
0 - 1	Decrease diameter
0 - 2	Increase diameter
0 - 3	Shallow surface crack
0 - 4	Deeper surface crack
0 - 5	Subsurface crack
0 - 6	Deeper subsurface crack



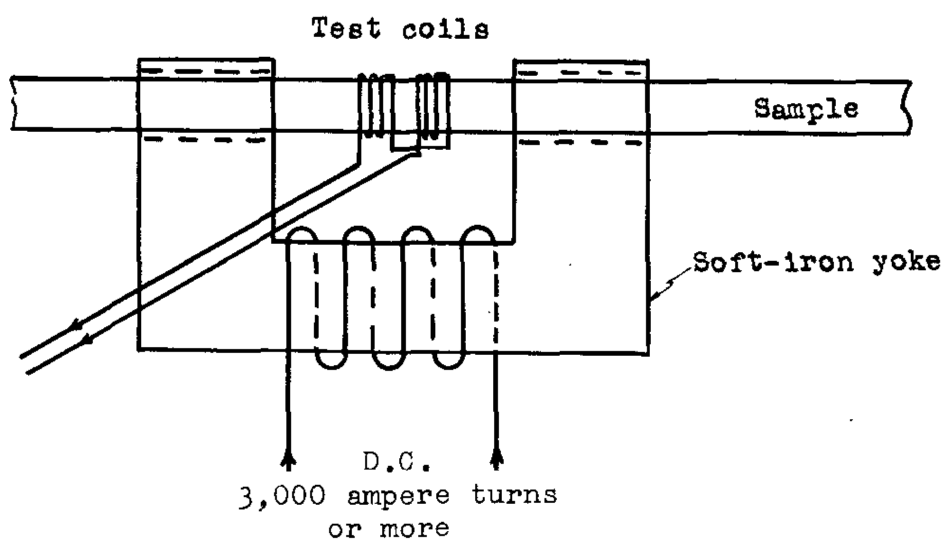
(C). COIL IMPEDANCE CHANGES FOR CRACKS OF DIFFERENT SIZES AND DEPTHS BELOW SURFACE

R.C. McMILLEN
C. S. ZUNSER 8-22-52

FIGURE 7



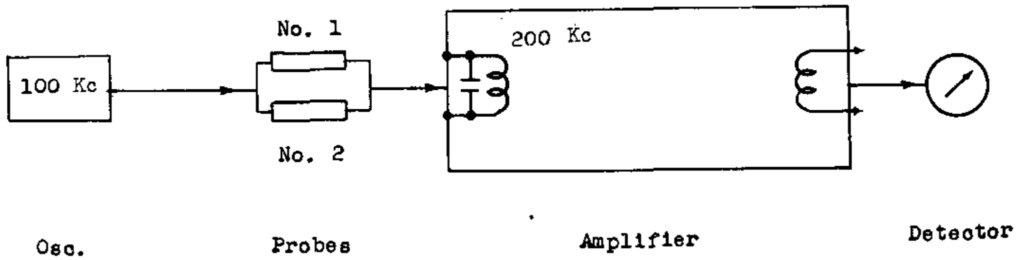
(A). YOKE ARRANGEMENT FOR TESTING WELDS



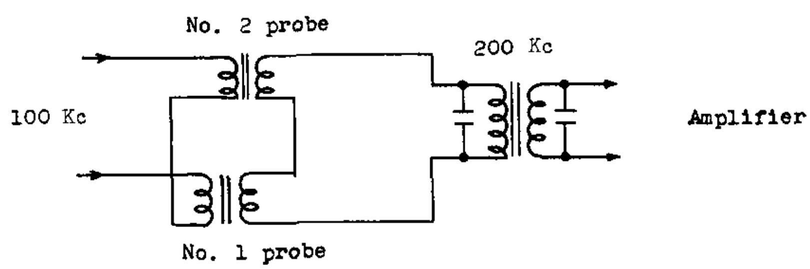
(B). D.C. SATURATION OF SAMPLE

R.C. McMILLEN
C. S. ZUNSER 8-22-52

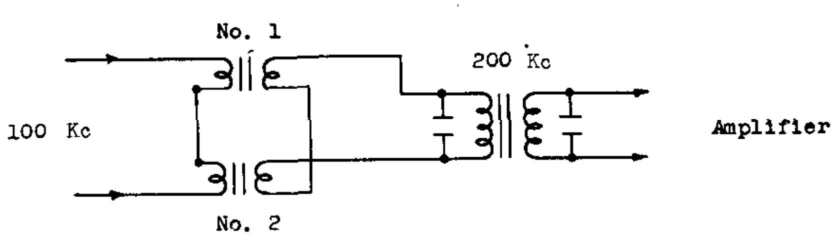
FIGURE 8



(A). Block diagram of Sonde-type instruments



Probe secondaries connected series aiding for magnetic field measurements.



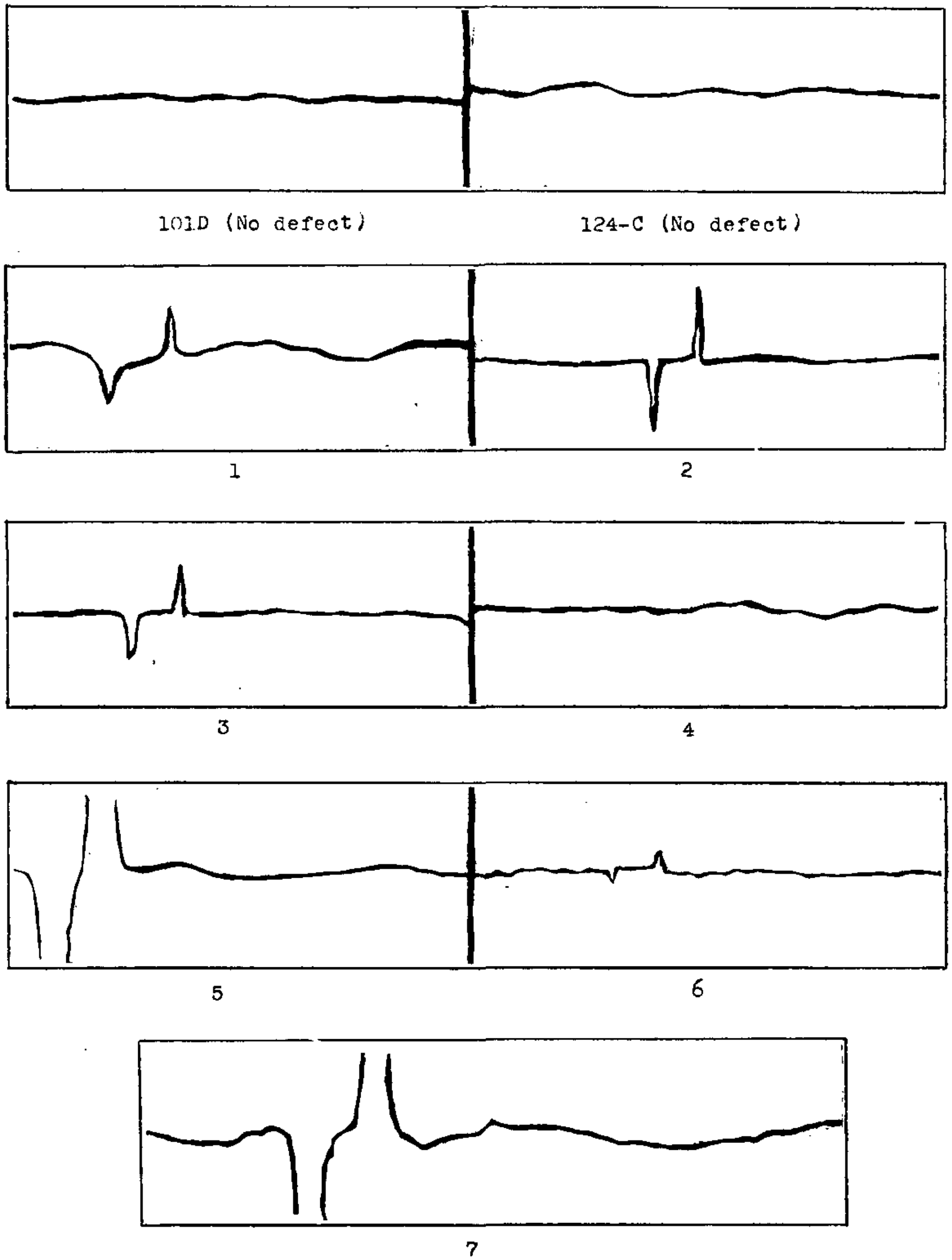
Probe secondaries connected series opposition for magnetic field gradient measurements.

(B). Probe connections for magnetic field and for field gradient measurements

FORSTER-SONDE OPERATING PRINCIPLE

R.C. McMILLEN
C.S. ZUNSER 8-22-52

FIGURE 9

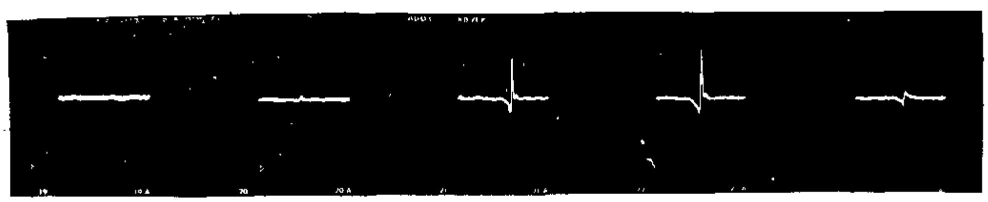


INSPECTION OF STAINLESS STEEL TUBES

R.C. McMillen
C.S. Zunser 8-18-52

FIGURE 10

Foerster-Sonde Method



Pick-Up Coil Method

OSCILLOGRAMS OF STEEL TUBE INSPECTION
BY TWO DIFFERENT METHODS

R.C. McMiller
C. S. Zunser 8-10-52

EXHIBIT A-1

INSTITUT Dr. Förster
REUTLINGEN

INSTITUT DR. FÖRSTER

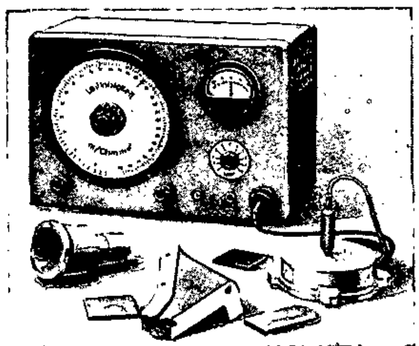
ELECTRONIC EQUIPMENT
FOR NON-DESTRUCTIVE TESTING

REUTLINGEN

GERMANY

TESTING OF NON-FERROUS METALS

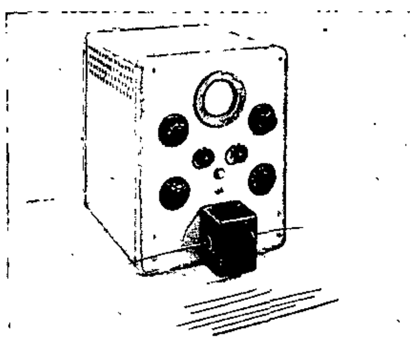
SIGMATEST — type 2.061



The apparatus will measure directly the conductivity of all non ferrous specimens, using a small wandering hand tester. The readings are independent of surface conditions, and after calibration on standards provided, direct readings of conductivity in international units may be made from the large scale. The minimum specimen diameter is 12 mm. Changes of conductivity of 5 to 60 m/ohm sqmm may be made with an accuracy of 0.5%.

Applications:
- Scrap separation
- Hardness testing of precipitation hardet light alloys.
- Determination of purity on cupper and aluminium.

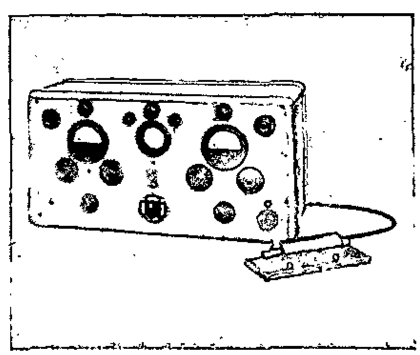
CRACK DETECTOR FOR NON FERROUS WIRES — type 2.020



The apparatus indicates qualitatively and quantitatively changes in impedence of the measuring coil due to cracks on a fluorescent screen. Cracks may be detected independently from diameter changes. The specimen wire is passed through a conveniently placed measuring coil, and after calibration, the screen indicates continuously changes of the above variables. The diameter range is from 0.2 mm to 13 mm.

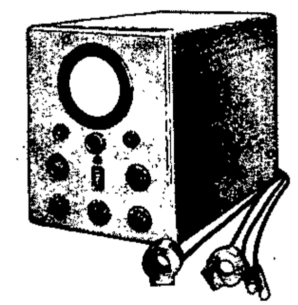
Applications:
- Crack detektion of tungsten and moly wire for valves.
- Determination of rolling defects on cupper and aluminium wire.

MULTIFLUX — type 2.050



The MULTIFLUX apparatus will indicate separately, and independently, variations in diameter and cracks; changes in conductivity may also be shown. These indications are shown quantitatively on two meters, whilst the overall change in impedence of the measuring coil is indicated on a fluorescent screen. It is suitable for the testing of non ferrous bars in continuous production processes. Range 5—60 mm ∅.

Applications:
- Testing of bars for cracks and uniformity.

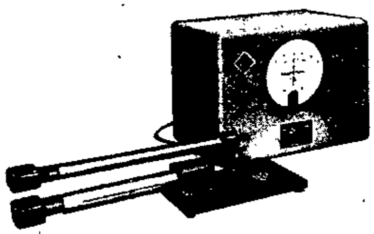


MULTITEST-SORTING APPARATUS — type 2.011

Inductive sorting apparatus for small parts of steel and non ferrous metals. A point on the screen indicates all differences in composition and heat treatment. Two dimensional signification. Test time less than 1 sec per piece.

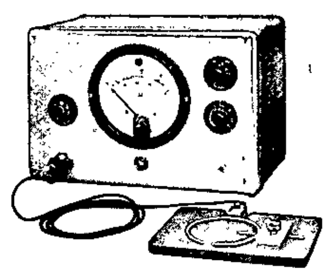
Applications:

Full automatic hardness sorting of drills, tops, bulls, screws etc.



NON MAGNETIC SHEET TESTER — type 2.121 CONTACTLESS METHOD

The apparatus may be used to measure moving bands sheets or foils from 0,006—2,0 mm thick. Direct positive and negative readings are indicated by the meter. Accuracy ± 0.1% with a minimum measurable thickness variation of 0,0005 mm. The apparatus may be made to operate a signal lamp reject mechanism with adjustable tolerances.



COATING THICKNESS TESTER — type 2.090

The apparatus measures thickness of non magnetic coatings on magnetic base (varnish, enamel, zinc, chrom, copper etc.). The coating thickness may be read absolutely on a calibrated meter. Ranges from 0—100 μ to 0—2 mm. Also curved surfaces may be measured. Accuracy 2% of coating thickness.

Special apparatus for piston rings — type 2.091.

ISOMETER — type 2.080

The apparatus will mesure directly the thickness of insulating coatings (Eloxal, varnish) on non ferrous metals, using a small wandering hand tester. The readings are independent of base conductivity. Direct readings of coating thickness may be made from a calibrated scale. Accuracy: 0.002 mm.

ARGENTOMETER — type 2.160

The tickness of silver coatings on knife and fork may be mesured with a small hand tester. The meter is calibrated in 1/1000 mm coating thickness. The apparatus will mesure the coating thickness from 0 to 0.2 mm with an accuracy of 5%.

SIGMAFLUX — type 2.070

The apparatus indicates the uniformity of composition and heat treatment of non ferrous wires or bars. The changes of conductivity may be indicated quantitatively on a meter, independently from diameter tolerances. Wires of 0.5 to 5 and bars of 5 to 50 mm diameter can be examined. The wires or bars to be tested may pass the test coil with a speed up to 10m/s.

EXHIBIT A-2

INSTITUT DR. FÖRSTER

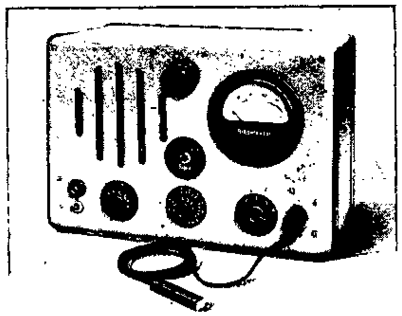
ELECTRONIC EQUIPMENT
FOR NON-DESTRUCTIVE TESTING

REUTLINGEN

GERMANY

TESTING OF FERROUS METALS

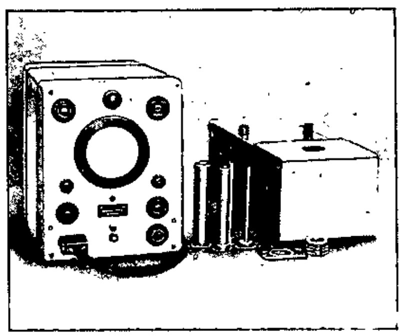
CRACK DETECTOR — type 3.031



An apparatus for the detection of cracks, cavities, and slag inclusions in steel and cast iron parts, by measuring the residual stray external fields with a hand tester. Aural and visual pre-set rejection mechanism incorporated. Operated by hand tester.

Applications:
- Localisation of cracks in forgings.
- Detection of porosities in cast iron.
- Determination of white solidifite zones in cast iron.

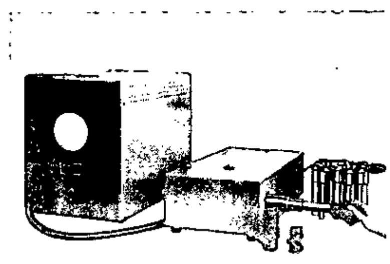
SEMI AUTOMATIC CRACK DETECTOR — type 3.021



The resultant residual stray fields from defects in symmetrical parts are measured by the rotation of the detecting coils around the specimen. These fields are indicated directly on a fluorescent screen, showing both depth and position of fault. The reject lamps may be pre-set to desired tolerances. Diameter range from 8 to 50 mm. Test time less than 1 sec. per piece.

Applications:
- Crack detection of pins and chafts.
- Semi automatic sorting of rings and nuts.

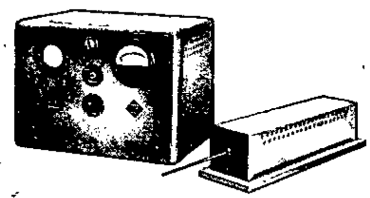
INTERNAL SURFACE CRACK DETECTOR — type 3.011



The stray residual field detecting coil rotates in cylinder of 15mm to 65 mm diameter. Cylindrical specimens may be investigated by the introduction of the specimen over the measuring cylinder. The resultant stray fields from defects being indicated directly on a fluorescent screen.

Applications:
- Testing of braking cylinders and fittings.

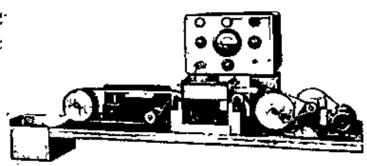
FOR THE TYPES 3.031, 3.021 and 3.011 SPECIMENS MUST BE MAGNETIZED BY DC — SHOCK.



MAGNATEST D — type 6.000
CRACK DETECTOR FOR FERROUS TUBE AND BARS

The apparatus indicates the various changes in hysteresis characterisics due to various faults and conditions of the specimen. The indication is made directly on a fluorescent screen. The desired variable may be separated and measured quantitatively on a meter. Diameter range from 2 to 60 mm.

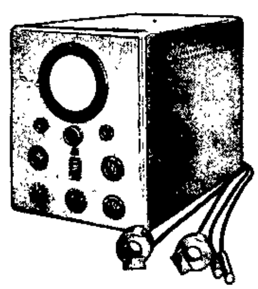
Applications:
- Testing of bundy weld tubes.
- Testing of gas, water and radiator pipes.
- Testing of bars of free cutting steels, ball bearing steels and tool steels.



MAGNETIC SORTING APPARATUS — type 3.051

This apparatus measures the residual magnetic field of various steel or iron parts. The composition and quality of these parts being indicated after such operations as heat treatment. An automatic signal lamp reject mechanism is incorporated offering three sorting possibilities. The tolerances for rejection are variable as desired. The apparatus is extremely sensitive and may be employed to operate mechanical devices.

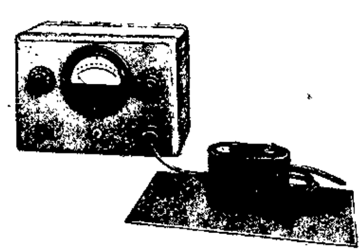
Applications:
- Sorting of piston pins (depht penetration of case hardening).
- Hardness sorting of needles.



MULTITEST — type 2.011
SORTING APPARATUS

Inductive sorting apparatus for small parts of steel and non ferrous metals. A point on the screen indicates all differences in composition and heat treatment. Two dimensional signification. Full automatic hardness sorting of drills, tops, bulls, screws etc. Test time less than 1 sec. per piece.

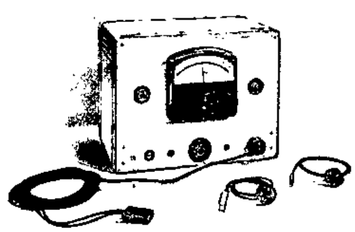
Applications:
- Full automatic hardness sorting of drills, tops, bulls, screws etc.



THICKNESS TESTER — type 2.200

The apparatus is designed to measure rapidly and continuously plate thicknesses of ferro-magnetic materials from 0—2.5 mm (thick), with an accuracy of 2%. The meter on the apparatus is for accurate absolute readings, whilst the smaller meter on the hand tester is for rapid comparative measurements.

Applications:
- Thickness measurement of transformer sheets.



PRECISION MAGNETIC FIELD MEASURING APPARATUS — type 1.100

The apparatus is the universal precision magnetic field measuring device. Providing absolute readings of field strength and direction. It will measure absolutely or relatively field strength gradients. The apparatus incorporates 10 sensitivity ranges, indicating on full scale deflection 1 to 1000 mOe. On the highest sensitivity range 1 scale division = 0.01 mOe or 10^{-5} Oe.

EXHIBIT A-3

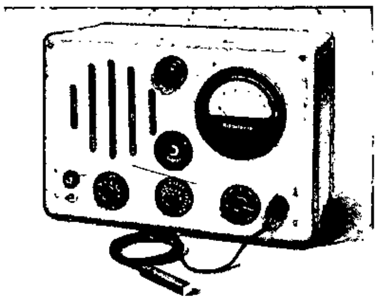
INSTITUT DR. FÖRSTER

Verfahren zur zerstörungsfreien Werkstoffprüfung
Elektronische Meß- und Prüfverfahren für Industrie und Forschung

REUTLINGEN

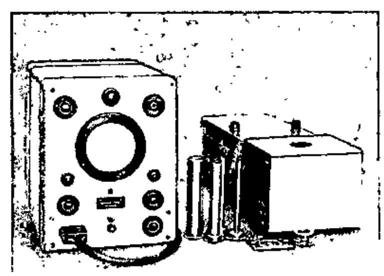
Riß-Detektor — Typ 3.031

Gerät zur örtlichen Feststellung und Ausmessung von Rissen, Schlackenzeilen, Lunkern usw. in Stahl- und Gußeisenteilen mit optischer und akustischer Anzeige. Die zu prüfenden Teile werden durch Stromstoß magnetisiert. Der durch den remanenten Magnetismus an den Rißstellen entstehende magnetische Streufluß wird mit einem Taststift gemessen. Die Anzeige ist proportional zum Streufluß. Das Gerät besitzt eine Signallampe, die bei Überschreiten einer einstellbaren Fehlertoleranz anspricht.



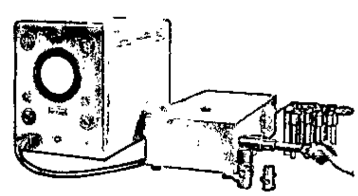
Riß-Sichtgerät für Kleinteile — Typ 3.021

mit umlaufendem Meßorgan zur Prüfung von rotationssymmetrischen Massenteilen aus Stahl und Eisen. Augenblickliche Anzeige der Größe und Lage des Streuflusses auf einem Leuchtschirm. Größter Prüfdurchmesser für lange Teile 40 mm, für flache Teile bis zu 50 mm ∅. Prüfdauer 1 bis 2 Sekunden je Prüfstück, bei Fließbandzuführung weniger als 1 Sekunde. Erreichte Leistung: 20 000 Stück pro Tag (8 Stunden). Gleichzeitige Fehleranzeige durch Signallampe, deren Ansprechpunkt entsprechend der zulässigen Fehlertoleranz eingestellt wird.



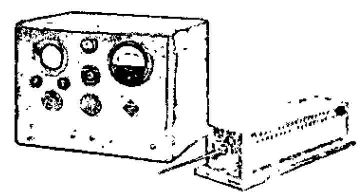
Riß-Sichtgerät für Innenprüfung — Typ 3.011

mit umlaufendem Meßorgan zur Prüfung von Innenflächen von Kleinteilen auf Risse (Bohrungen, Rohre, Zylinderbüchsen). Kleinster Prüfdurchmesser 8 mm. Fehleranzeige auf einem Leuchtschirm und mit optischem Signal. Zur Prüfung werden die Teile auf den Meßdorn aufgeschoben.

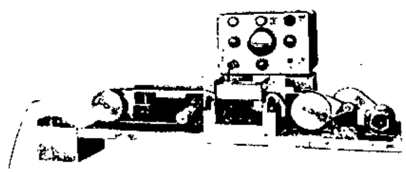


Magnatest D — Typ 6.000

Gerät zur Prüfung von Stahlstangen und Rohren auf Risse im Durchlaufverfahren. Durch Anwendung der sogenannten magnetischen Analyse ist die Fehleranzeige unabhängig von Durchmesserschwankungen, Gefügeunterschieden, Kaltverformungen und inneren Spannungen. Die Halbzeuge brauchen zur Prüfung nicht vorher magnetisiert werden. Optisches Signal bei Überschreitung der Fehlertoleranz. In Verbindung mit einer Rollbahn zum Transport der Stangen kann die Ausscheidung der fehlerhaften Halbzeuge automatisch durchgeführt werden.

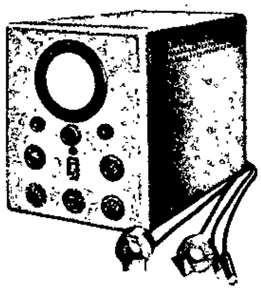


Für die erstgenannten 3 Gerätetypen ist ein Stromstoßgerät zur Magnetisierung der Prüfstücke erforderlich.



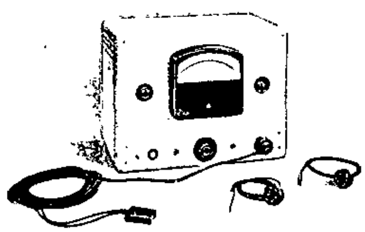
Sortiergerät — Typ 3.051

Magnetisches Prüfgerät zum Sortieren von Kleinteilen aus Stahl nach Legierungszusammensetzung, Härte, Einsatztiefe usw. Prüfung von Massenteilen aller Art, wie Schrauben, Muttern, Kolbenbolzen, Nadeln, Kugellagerteilen. Drei Signallampen, mit einstellbaren Ansprechpunkten zur Schnellsortierung in drei Qualitätsgruppen. Die Teile werden nach der Magnetisierung an der Meßstelle vorbeigeschoben. Die Anzeige der Signallampen erfolgt trägheitslos und ist völlig unabhängig von der Geschwindigkeit des Prüfstückes. Anschluß für die Steuerung einer vollautomatischen Sortiervorrichtung vorgesehen.



Multitest — Typ 2.011

Wirbelstromprüfgerät zum Sortieren von Teilen aus Stahl und NE-Metallen nach Legierungszusammensetzung und Härte. Unmittelbare zweidimensionale Kennzeichnung, d. h., jeder Werkstoff bzw. jeder Werkstoffzustand wird durch die Lage eines Leuchtpunktes auf dem Leuchtschirm des Prüfgerätes gekennzeichnet.
Dadurch vielfach erhöhte Trennungsmöglichkeit.
Spezialgeräte auch mit vollautomatischer Sortierung ausgeführt.



Präzisions-Magnetfeldmesser — Typ 1.100

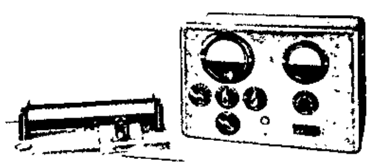
Gerät zur exakten Vermessung magnetischer Felder nach Größe und Richtung. Universalgerät für absolute Feldmessung und Feldgradientenmessung. 10 Empfindlichkeitsstufen von 1 bis 1000 mOe. Höchste Empfindlichkeit: 1 Skt. = 0,01 mOe. (10^{-5} Oe).

Restfeldprüfer — Typ 1.050

Gerät zur Prüfung des Entmagnetisierungszustandes von Werkstücken im Anschluß an die Magnetpulverprüfung. Direkte Anzeige des Restfeldes vom Prüfstück in mOe.

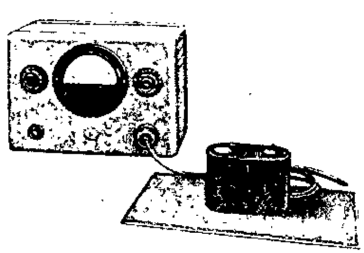
Polsucher — Tpy 1.060

Gerät zur Messung der Größe und Richtung von magnetischen Polen. Die Anzeige ist unabhängig von der Lage der Sonde im Erdfeld. Der Handgriff mit dem Meßinstrument besitzt etwa die Größe eines photoelektrischen Belichtungsmessers. Der Prüfstift hat einen Durchmesser von 8 mm, so daß auch verwickelte Teile geprüft werden können. Meßbereiche ± 50 mOe, ± 250 mOe und ± 500 mOe umschaltbar.



Präzisions-Koerzimeter — Typ 1.090

mit Erdfeldkompensation zur Messung der Koerzitivkraft von kleinen Teilen aus magnetisch weichen Werkstoffen. Unmittelbare Anzeige der Koerzitivkraft auf einem Präzisions-Meßinstrument.
Für Koerzitivkräfte bis herab zu 20 mOe.
Meßgenauigkeit 1%.

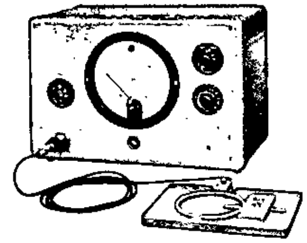


Blechdickentaster — Typ 2.200

zur schnellen Messung der Dicke von Eisenblechen von einer Seite aus. Bei Aufsetzen des Handtasters erscheint sofort ein bleibender Ausschlag am geeichten Meßinstrument und zeigt die Absolutdicke des Bleches an. Für schnelle Vergleichsmessungen befindet sich ein zusätzliches Nullinstrument im Handtaster.
Meßumfang: 0 bis 2,5 mm. Meßgenauigkeit: 2% der Bleckstärke.

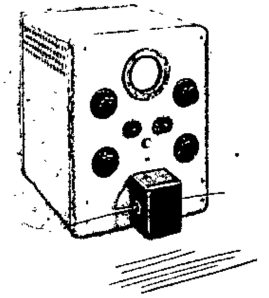
Schichtmesser — Typ 2090

Gerät mit Handtaster zur Messung von nicht ferromagnetischen Schichten auf ferromagnetischem Grundwerkstoff (Farb-, Emaille-, Zink-, Chrom- und Kupferschichten). Direkte Ablesung der Schichtdicke auf geeichtem Meßinstrument. Meßbereiche von 0—100 /u bis 0—2 mm. Der Mikrotaster erlaubt auch gekrümmte Flächen zu messen.
Meßgenauigkeit 2% der Schichtstärke.
Chromschichtmesser für Kolbenringe — Typ 2091.



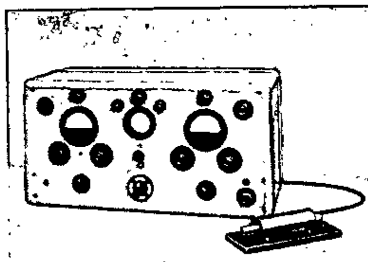
Draht-Rißprüfgerät — Typ 2.020

Gerät zur Anzeige von Fehlern in Drähten aus NE-Metallen, insbesondere Einschmelzdrähten. Getrennte Anzeige von Durchmesserschwankungen und Fehlstellen. Aus der Anzeige auf dem Leuchtschirm des Gerätes kann die Fehlergröße und Fehlerlage bestimmt werden. Das Gerät arbeitet ohne Vergleichsprobe. Es werden Geräte für 0,2 bis 13 mm Drahtdurchmesser hergestellt. Die Anzeige ist unabhängig von der Durchlaufgeschwindigkeit des Drahtes. Gleichzeitig lassen sich noch Durchmesseränderungen unabhängig von Fehlern quantitativ ablesen.



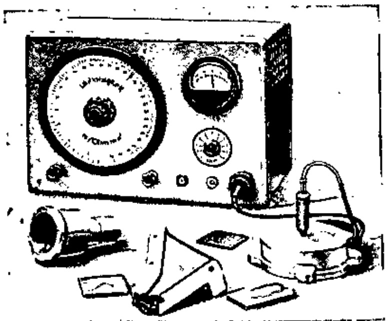
Multiflux — Typ 2.050

Kombiniertes Gerät zur Prüfung von Stangen und Rohren aus NE-Metallen auf Verwechslung, Härteunterschiede, ungleiche Wärmebehandlung und Risse. Das Multiflux-Gerät vereinigt die Rißprüfung und Qualitätsprüfung in einem einzigen Gerät und erspart somit eine doppelte Prüfung der Halbzeuge. In Verbindung mit einer von den Anzeigerelais des Gerätes gesteuerten automatischen Prüfbank, die die Zuführung, Prüfung, Kennzeichnung und Sortierung des Halbzeuges vornimmt, ergibt das Gerät eine 100%-ige Prüfung der Halbzeugproduktion sowohl auf Fehler als auch auf Gleichmäßigkeit der Qualität.



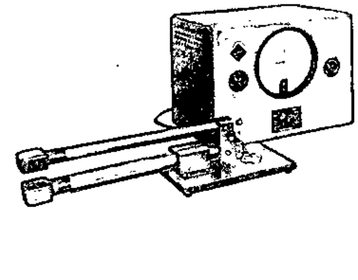
Sigmatest — Typ 2.061

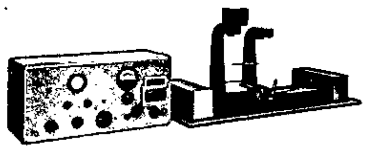
Tastspulgerät zur Messung der elektrischen Leitfähigkeit von NE-Metallen mit direkter Anzeige in m/Ohm mm². Das Gerät dient zur Prüfung von Blechen, Bändern, Profilen, Preß- und Gußteilen auf Verwechslungen, Gleichmäßigkeit und Härte (bei aushärtbaren Al-Legierungen). Die Anzeige ist in gewissen Grenzen unabhängig von Schmutz-, Oxyd- oder Lackschichten auf der zu messenden Metalloberfläche. Das Gerät besitzt eine besonders kleine Tastspule und benötigt nur eine Aufsatzfläche von 12 mm Ø. Der Meßumfang des Gerätes umfaßt den Leitfähigkeitsbereich von 5 bis 60 m/Ohm mm², wobei für Sonderzwecke kleinere Bereiche gewählt werden können. Meßgenauigkeit 0,5%.



Berührungsloser Blech- und Folienmesser für NE-Metalle Typ 2.121

zur laufenden Überwachung der Dicke während des Walzvorganges. Mit direkter Anzeige der Dickenabweichung in Tausendstel Millimeter oder in Prozent vom Sollwert.
Typ a für Folien von 0,005 bis 0,1 mm
Typ b für Bleche von 0,1 bis 2 mm.
Meßumfang des Anzeigeinstrumentes: ± 15% Dickenabweichung vom Sollwert.
Meßgenauigkeit: 0,0005 mm.
Das zu messende Blech läuft frei durch den gabelförmigen Meßkopf hindurch. Der Meßkopf kann während des Walzens seitlich verschoben werden, um am Rande oder in der Mitte zu messen. Unempfindliche Anzeige gegenüber Flattern des Bandes. Für Blechbreiten von 100 bis 2000 mm.





Elastometer — Typ 1.010

Gerät zur Messung des E-Moduls und der Dämpfung von Werkstoffen. (Messung auch bei höheren Temperaturen möglich). Messung der Resonanzfrequenz eines frei transversalschwingenden Prüfstabes, der in unmittelbarer Nähe seiner Schwingungsknoten aufgehängt ist. Belastungsfreie Ermittlung der Werkstoffkonstanten. Direkte Ablesung der mechanischen Dämpfung an geeichter Skala. Eichung des Frequenzgenerators während der Messung durch Anschluß an die Normalquarzfrequenz.

Schrifttum:

Zeitschrift Metallkunde 29, 1937, S. 109; 29, 1937, S. 116

Naturwissenschaft 25, 1937, S. 436

Zeitschrift Metallkunde 29, 1937, S. 287; 30, 1938, S. 345

The Journal of the Inst. of El. Eng. Vol. 84 May 1939

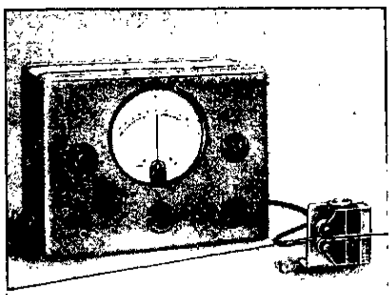
Arch. Eisenhüttenwesen 12, 1938, S. 103

Zeitschrift Metallkunde 32, 1940, S. 145; 32, 1940, S. 151; 32, 1940, S. 156; 32, 1940, S. 160; 32, 1940, S. 163; 32, 1940, S. 282

Arch. Eisenhüttenwesen 14, 1940, S. 271

Zeitschrift Elektrochem. 49, 1943, S. 233

Zeitschrift Metallkunde 35, 1943, S. 194; 35, 1943, S. 246; 36, 1944, S. 63; 39, 1948, S. 1; 39, 1948, S. 9; 39, 1948, S. 111; 39, 1948, S. 145; 39, 1948 S. 231



Banddickenmesser — Typ 2.111

Zur kontinuierlichen Messung und Überwachung der Dicke von Bändern aus nichtferromagnetischen Werkstoffen (Nichteisenmetalle und Kunststoffe). Für beliebige Banddicken und für Bandbreiten von 6 bis 2000 mm. Direkte Anzeige der Banddicke in Tausendstel Millimeter auf einem Schalttafelinstrument.

Meßumfang des Anzeigerinstrumentes $\pm$ 20 μ

Meßgenauigkeit: 0,0005 mm.

Mit Signallampen, die bei Überschreiten der eingestellten Dickentoleranzen (positiv und negativ) ansprechen. Anbau direkt an die Walze zur laufenden Überwachung und Nachregelung der Bandstärke.

Weitere Geräte aus unserem Fertigungsprogramm

Magnatest Q — Typ 3.200

Gerät zur Prüfung von Stahlstangen und Rohren auf Qualitätsunterschiede wie Legierungszusammensetzung, Wärmebehandlungszustand im Durchlaufverfahren. Eindeutige Anzeige der gewünschten Werkstoffunterschiede durch Anwendung der sog. magnetischen Analyse. Optisches Signal bei Überschreitung der Toleranz.

Magnatest DQ — Typ 6.200

Kombiniertes Gerät zur Prüfung von Stahlstangen und Rohren sowohl auf Risse als auch auf Qualitätsunterschiede in einem einzigen Durchgang des Prüfstückes. Getrennte Anzeige und Signale für die Fehler und für die Qualitätsprüfung.
Durchmesserbereich 8 bis 40 mm, in Sonderausführung bis 65 mm ⌀.

Ferrograph — Typ 1.030

Gerät zur schnellen Messung magnetischer Größen mit unmittelbarer Anzeige der Hysteresisschleife auf dem Leuchtschirm. Besonders für die Prüfung von Drähten und Bändern geeignet. Infolge der hohen Empfindlichkeit können noch Drähte von 0,1 mm ⌀ gemessen werden. Durch das Differenzverfahren können kleine Änderungen der magnetischen Eigenschaften des Werkstoffes durch äußere Einflüsse (Spannungen, Verformungen, Analysenunterschiede) mit bisher unerreichter Empfindlichkeit gemessen werden. Das Gerät findet Anwendung zur schnellen Prüfung von Ringkern-Werkstoffen, Transformatorenblechen, magnetisch weichen Legierungen.

Wandstärkenmesser — Typ 2.110

Gerät zur Messung der Wandstärke von großen Teilen aus nichtferromagnetischen Werkstoffen (Metallgußteile, Behälter, Blechtafeln in großer Entfernung vom Rand, Rohre usw.). Die Teile müssen von beiden Seiten zugänglich sein. Die Wandstärke ist direkt in Hundertstel- oder Zehntelmillimeter am Meßinstument ablesbar. Meßbereiche von 1 mm bis 100 Millimeter Endausschlag. Völlige Unabhängigkeit der Anzeige von der Leitfähigkeit des Werkstoffes (auch Isolierstoffe, Beton, Glas usw. meßbar).

Isometer — Typ 2.080

Gerät mit Handtaster zur Messung der Dicke von Farb-, Oxyd- oder Korrosionsschichten auf NE-Metallen. Das Gerät ist direkt in Tausendstel-Millimeter Schichtdicke geeicht. Die Anzeige ist unabhängig von der Leitfähigkeit des Grundmetalles.

Argentometer — Typ 2.160

Gerät mit Handtaster zur Messung der Dicke der Silberauflage auf Besteckteilen usw. Das Anzeigeinstrument ist direkt in tausendstel Millimeter Schichtdicke geeicht.
Meßbereich 0 bis 0,2 mm.
Meßgenauigkeit: 5% der Schichtdicke.

Sigmaflux — Typ 2.070

Gerät zur Prüfung der Gleichmäßigkeit (Legierung, Wärmebehandlung, Härte) von Drähten und Stangen aus NE-Metallen. Die Abweichung der Leitfähigkeit wird unabhängig von den Dickenschwankungen direkt in Prozent auf der Instrumentenskala während des Durchlaufs der Drähte abgelesen. Die maximale Empfindlichkeit beträgt 100 Skalenteile für 1% Abweichung. Die Durchlaufgeschwindigkeit kann bis zu 10 m/s betragen.

Drahtdickenmesser für NE-Metalle — Typ 2.073

zur laufenden Messung und Überwachung der Drahtdicke während des Ziehvorganges. Für Drähte von 0,04 bis 1 mm Stärke. Direkte Anzeige der Querschnittsänderung in %.
Meßgenauigkeit 1%.
Optisches Signal, das bei Überschreitung der Maßtoleranz anspricht.

Suchgerät — Typ 4.010 bis 4.040.

zum Nachweis von Eisenteilen (Blindgänger, Wasser- und Gasleitungen, Kabel usw.) im Erdboden und in Wasser. Tragbares Gerät mit Batterieanschluß. Am Kopf des Prüfrohres befindet sich das Anzeigeinstrument, das bei Vorhandensein von Eisenteilen im Erdboden anspricht. Die Suchtiefe beträgt mehrere Meter (Blindgänger wurden bis zu 5 m Tiefe nachgewiesen). Sondergeräte zum Nachweis von Wasseradern in Entwicklung.