

THE HISTORY, PRESENT STATUS, AND FUTURE DEVELOPMENT OF EDDY CURRENT TESTS

Robert C. McMaster

Departments of Electrical Engineering and Welding Engineering
The Ohio State University
Columbus, OH

1. Historical Development of Eddy Current Theory and Test Methods

It is probable that no other form of nondestructive testing has a history of illustrious scientific creativity and practical development that compares with the past century and a half of development of the concepts and applications of electromagnetic induction and eddy current testing. James Clerk Maxwell, in his remarkable two-volume work A Treatise on Electricity and Magnetism, published in several editions from 1873 to 1891, summarized the first half century of this history [1]¹. In addition, he conceived and published the comprehensive group of relations known as Maxwell's equations for the electromagnetic field, which mathematically represent almost the entire present knowledge of this subject. For the past hundred years, physicists and researchers in electricity and magnetism have occupied themselves with numerous applications of Maxwell's theory. However, during this past century, no one has conceived any significant new law to be added to Maxwell's principles (with the possible exception of Einstein's theory of relativity, which extends the theory of the electromagnetic field to a four-dimensional framework of three spatial dimensions and a fourth dimension of time). NOTE: In the following segments abstracted from Maxwell's treatise, the symbol indicates omissions. Parentheses are used to indicate explanatory words or comments inserted by the author of this paper. Superscript numbers following headings identify the specific articles of Maxwell's treatise used as sources.

2. Oersted's 1820 Discovery of the Magnetic Field of an Electric Current (475-478)

As described by Maxwell, "...Conjectures of various kinds had been made as to the relation between electricity and magnetism, but the laws of these phenomena, and the form of these relations, remained entirely unknown till Hans Christian Oersted, at a private lecture to a few advanced students at Copenhagen, observed that a wire connecting the ends of a voltaic battery affected a magnet in its vicinity. This discovery he published in a tract...dated July 21, 1820 [2].Oersted discovered that the current itself was the cause of the action, and that the 'electric conflict acts in a revolving manner', that is, that a magnet placed near a wire transmitting an electric current tends to set itself perpendicular to the wire, and with the same end always pointing forwards as the magnet is moved around the wire.... The space in which these forces act may therefore be considered as a magnetic field.... In the case of an indefinitely long straight wire carrying an electric current....the lines of magnetic force are everywhere at right angles to planes drawn through the wire, and are therefore circles each in a plane perpendicular to the wire, which passes through the wire." (Had Oersted been provided with a much larger current, it is possible that even a piece of nonmagnetic conducting metal lying adjacent to the current-carrying loop would have reacted to sudden application of the current, by eddy current reaction. Had this accident occurred, it is possible that the discovery of the effects of eddy currents might possibly have occurred more than 150 years ago.)

¹Figures in brackets indicate literature references at the end of this paper.

3. Ampere's 1820 Discovery of the Mutual Interaction of Two Currents (502-504)

Maxwell continues "...The action of one circuit upon another was originally investigated in a direct manner by Ampere almost immediately (in 1820) after the publication of Oersted's discovery.... Ampere's fundamental experiments are all of them examples of....the null method of comparing forces.... In the null method, two forces, due to the same source, are made to act simultaneously on a body already in equilibrium....No effect is produced, which shows that these forces are themselves in equilibrium. This method is peculiarly valuable for comparing the effects of the electric current when it passes through circuits of different forms. By connecting all the conductors in one continuous series, we ensure that the strength of the current is the same at every point of its course.... Since the current begins everywhere throughout its course almost at the same instant, we may prove that the forces due to its action on a suspended body are in equilibrium by observing that the body is not at all affected by the starting or the stopping of the current.

"Ampere's balance consists of a light frame capable of revolving about a vertical axis, and carrying a wire which forms two (rectangular loop) circuits of equal area, in the same plane or in parallel planes, in which (loops) current flows in opposite directions. The object of this arrangement is to get rid of the effects of terrestrial magnetism on the conducting wire....By rigidly connecting two circuits of equal area in parallel planes, in which equal currents run in opposite directions, a combination is formed which is unaffected by terrestrial magnetism....(This balance) is therefore called an Astatic Combination (see fig. 1). It is acted upon, however, by forces arising from currents or magnets which are so near to it that they act differently on the two circuits.Ampere's theory of the mutual action of electric currents is founded on four experimental facts and one assumption."

Ampere's 1820 experiments provided several useful techniques employed in present-day eddy current test systems, including:

1. The methods of shielding lead-wire connections to test coils.

2. The use of comparison-coil arrangements to reduce or eliminate test signal components related to common properties of two test objects.

3. The use of differential-coil arrangements to compare local differences in properties of adjacent areas of a single test object.

4. The methods of coupling magnetizing-coil fields with test material surfaces.

5. The use of dual-coil systems to balance out external magnetic and electric field effects (including terrestrial magnetism).

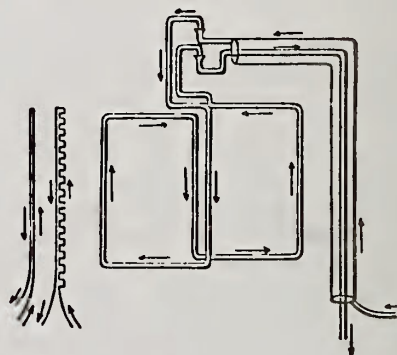


Figure 1. Maxwell's sketch illustrating Faraday's basic test arrangement with astatic balance coil arrangement [1].

(It would be difficult to estimate how many hundreds of 20th century patents are based upon these simple discoveries by Ampere a hundred years earlier. It would also be difficult to estimate the man-years of effort and dollar costs lost during recent developments of eddy current test systems by workers who were not aware of the full significance of Ampere's 1820 work.)

3.1 Ampere's first experiment (Shielding of lead wires) (505)

In Maxwell's words, "Ampere's first experiment is on the effect of two equal currents close together (flowing) in opposite directions. A wire covered with insulation is doubled upon itself and placed near one of the circuits of the astatic balance (See fig. 1). When a current is made to pass through the (looped-back) wire and (the compensated loops of) the balance, the equilibrium of the balance remains undisturbed, showing that two equal currents close together in opposite directions neutralize each other.

If, instead of two wires side by side, a wire be insulated in the middle of a metal tube, and if the current pass through the wire and back by the tube, the action outside the tube is not only approximately but accurately null. This principle is of great importance in the construction of electric apparatus, as it affords the means of conveying the current to and from any galvanometer or other instrument in such a way that no electromagnetic effect is produced by the current on its passage to and from the instrument. In practice, it is generally sufficient to bind the wires together, care being taken that they are kept perfectly insulated from each other, but where they must pass near any sensitive part of the apparatus it is better to make one of the conductors a tube and the other a wire inside it." (These techniques, including also twisted lead pairs, are commonly used to connect instruments to sensing coils or semiconductor detectors used today to detect eddy current magnetic field test signals. At higher frequencies, shielding by concentric conductors (usually grounded at one end) aids in avoidance of interfering signals from ambient electromagnetic fields or moving ferromagnetic machine parts or test objects.)

3.2 Ampere's second experiment (Effect of crooked current paths)⁽⁵⁰⁶⁾

Maxwell reports: "In Ampere's second experiment one of the wires is bent and crooked with a number of small sinuosities, but so that in every part of its course it remains very near the straight wire. (See fig. 1) A current flowing through the crooked wire and back again through the straight wire, is found to be without influence upon the astatic balance. This proves that the effect of the current running through any crooked part of the wire is equivalent to the same current running in the straight line joining its extremities, provided the crooked line is in no part of its course far from the straight one. Hence any small element of a circuit is equivalent to two or more component elements, the relation between the component elements and the resultant element being the same as that between component and resultant displacements or velocities." (This basic principle has been generally ignored with respect to its significance in detection of small discontinuities that locally distort eddy current flow paths. A circular test coil, for example, produces a mirror-image

circular flow path of eddy currents in the adjacent test material. Small diversions and excursions of eddy currents from a truly circular path will have very small effects upon signal pickup coils coincident with the magnetizing coils. Local detectors of distortions of the eddy current magnetic field can have far greater sensitivity to small discontinuities than large-area pickup coils.)

3.3 Ampere's third and fourth experiments^(507-509, 520-521)

Ampere's third experiment demonstrated that external currents or magnets had no tendency to move a straight current-carrying conductor in the direction of its length (see fig. 2). The fourth experiment showed that the force

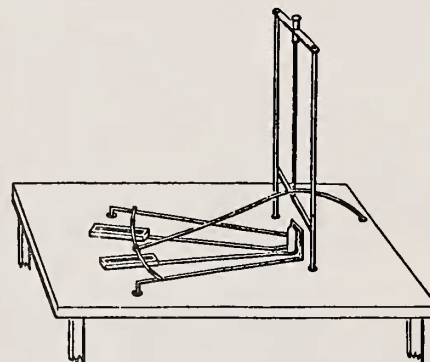


Figure 2. Maxwell's sketch illustrating Faraday's third experiment showing no force acting along the length of a current carrying conductor.

acting between two adjacent current-carrying loops varies as the square of the distance between the two loops. Analyses of these results indicates that the mutual potential M of two closed circuits carrying unit current expresses the work done by electromagnetic forces on either conducting circuit when it moves parallel to itself from an infinite distance to its actual position. Any alteration of its position, by which M is increased, will be assisted by the magnetic forces. Even when the motion of the circuit is not parallel to itself, the forces acting on it are still determined by the variation of M , the potential of one circuit on the other. The force between the circuits is dM/dx , and thus M , is related to the energy of the electromagnetic field of the current-carrying circuits.

4. Faraday's 1831 Discovery of the Law of Electromagnetic Induction (528-541)

Maxwell notes that: "The discovery by Oersted of the magnetic action of an electric current led by a direct process of reasoning to that of magnetization by electric currents, and of the mechanical action between currents. It was not, however, till 1831 that Faraday, who had been for some time endeavouring to produce electric currents by magnetic or electric action, discovered the conditions of magneto-electric induction. The method which Faraday employed in his researches consisted of a constant appeal to experiment as a means of testing the truth of his ideas, and a constant cultivation of ideas under the direct influence of experiment. Faraday...shows us his unsuccessful as well as his successful experiments, and his crude ideas as well as his developed ones. The reader, however inferior to him in inductive power, feels sympathy even more than admiration, and is tempted to believe that, if he had the opportunity, he too would be a discoverer. Every student should therefore read Ampere's research as a splendid example of scientific style in the statement of a discovery, but he should also study Faraday for the cultivation of a scientific spirit, by means of the action and reaction which will take place between the newly-discovered facts as introduced to him by Faraday and the nascent ideas of his own mind.

"The method of Faraday seems to be intimately related to the method of partial differential equations and integrations throughout all space...He never considers bodies as existing with nothing between them but their distance, and acting upon one another according to some function of that distance. He conceives all space as a field of force, the lines of force being in general curved, and those due to any body extending from it on all sides, their directions being modified by the presence of other bodies. He even speaks of the lines of force belonging to a body as in some sense part of itself, so that in its action on distant bodies it cannot be said to act where it is not. This, however, is not a dominant idea with Faraday. I think he would rather have said that the field of space is full of lines of force, whose arrangement depends on that of the bodies in the field, and that the mechanical and electrical action on each body is determined by the lines which abut on it."

4.1 Faraday's law for induction by variation of primary current (530)

Maxwell advises the reader to read Faraday's "Experimental Researches, Series i and ii," and then summarizes four forms of Faraday's law of induction. His description of the first form of Faraday's law follows:

"Let there be two conducting circuits, the Primary and the Secondary circuit. The primary circuit is connected with a voltaic battery by which the primary current may be produced, maintained, stopped, or reversed. The secondary circuit includes a galvanometer to indicate any currents which may be formed in it. This galvanometer is placed at such a distance from all parts of the primary circuit that the primary current has no sensible direct influence upon its indications.

"Let part of the primary circuit consist of a straight wire, and part of the secondary circuit of a straight wire near and parallel to the first, the other parts of the circuits being at a greater distance from each other.

"It is found that at the instant of sending a current through the straight wire of the primary circuit the galvanometer of the secondary circuit indicates a current in the secondary straight wire in the opposite direction. This is called the induced current. If the primary current is maintained constant, the induced current soon disappears, and the primary current appears to produce no effect on the secondary circuit. If now the primary current is stopped, a secondary current is observed, which is in the same direction as the primary current. Every variation of the primary current produces electromotive force in the secondary circuit. When the primary current increases, the electromotive force is in the opposite direction to the current. When it diminishes, the electromotive force is in the same direction as the current.

"These effects of induction are increased by bringing the two wires nearer together. They are also increased by forming them into two circular or spiral coils placed close together, and still more by placing an iron rod or a bundle of iron wires inside the coils."

(This experiment demonstrates the fundamental principles of the use of magnetizing coils in eddy current testing. The need for a time-varying primary current is clearly indicated. The advantage of close coupling or spacing between the magnetizing coil and test metal surface is also shown. This translates into control of lift-off of probe coils, and preference for high coil-fill factors with encircling-coil eddy current tests. The need for pulsating or alternating primary current is also now evident. Finally, the advantages of using ferrite or iron cores in eddy current probe coils are suggested. Present-day eddy current test systems make full use of each of these principles, enunciated clearly by Faraday in 1831.)

4.2 Faraday's law for induction by motion of the primary circuit⁽⁵³⁰⁾

"We have seen that when the primary current is maintained constant and at rest the secondary current rapidly disappears. Now, let the primary current be maintained constant, but let the primary straight wire be made to approach the secondary straight wire. During the approach, there will be a secondary current in the opposite direction to the primary. If the primary circuit be moved away from the secondary, there will be a secondary current in the same direction as the primary."

(Two principles are implied by the concept of induction by motion of the primary circuit. The first is that polarized and directional secondary currents can be induced by moving a straight-line primary current over a conducting test surface. Secondly, alternating current could be induced in a conducting secondary circuit or test material when a constant-current primary coil is moved cyclically up and down or side to side over a secondary coil or conducting test surface. Where scanning eddy current tests are required, it is possible that a permanent magnet or a direct-current magnetizing coil could be used to induce eddy currents, without the need for an electronic oscillator or ac power supply. An additional concept implied by this technique of induction would be that of using dc magnetic field detectors to measure the magnitude of secondary current or eddy currents in a conducting

material, under or lagging behind the moving primary coil. The decay rate of dc current measured at a fixed distance behind the moving primary coil. The decay rate of dc current measured at a fixed distance behind the moving primary coil would contain information similar to phase and amplitude data obtained by phase-plane analysis of ac eddy current test systems in common use today. Of course, this type of system would perhaps best be used with very rapid scanning over test surfaces.)

4.3 Faraday's law for induction by motion of the secondary circuit⁽⁵³⁰⁾

Maxwell states also: "If the secondary circuit be moved, the secondary current is opposite to the primary when the secondary wire is approaching the primary wire, and in the same direction when it is receding from it. In all cases, the direction of the secondary current is such that the mechanical action between the two conductors is opposite to the direction of motion, being a repulsion when the wires are approaching, and an attraction when they are receding. This very important fact was established by Lenz."

(This example suggests that a rapidly-moving conducting test material such as sheet metal in a rolling mill could pass by a stationary test coil carrying direct current which induces flow of current in material both approaching and leaving the area of this local magnetization. Detectors of the eddy current field in either location could respond to local discontinuities or variations in material properties which influence the amplitude and distribution of the eddy currents.)

4.4 Faraday's law for induction by the relative motion of a magnet and the secondary circuit⁽⁵³⁰⁾

Maxwell continues with: "If we substitute for the primary circuit a magnetic shell, whose edge coincides with the circuit, whose strength is numerically equal to that of the current in the circuit, and whose austral face corresponds to the positive face of the circuit, then the phenomena produced by the relative motion of this shell and the secondary circuit are the same as those observed in the case of the primary circuit." (The coil of the preceding

examples could be replaced by a permanent magnet when relative motion exists between the magnet and test material in eddy current tests, providing adequate secondary current magnitude and speed of motion can be attained.)

4.5 Summary expressions for Faraday's law of induction^(531,534,536)

Maxwell summarizes the various statements of Faraday's law with the following statements: "When the number of lines of magnetic induction which pass through the secondary circuit in the positive direction is altered, an electromotive force acts round the circuit, which is measured by the rate of decrease of the magnetic induction through the circuit....The intensity of the electromotive force of magneto-electric induction is entirely independent of the nature of the substance of the conductor in which it acts, and also of the nature of the conductor which carries the inducing current....The electromotive force of the induction of one circuit on another is independent of the area of the section of the conductors....The electromotive force produced in a coil of n windings by a current in a coil of m windings is proportional to the product mn"

Maxwell finally states the "true law of magneto-induction" in the following terms: "The total electromotive force acting around a circuit at any instant is measured by the rate of decrease of the number of lines of magnetic force which pass through it. When integrated with respect to time, this statement becomes: The time integral of the total electromotive force acting round any circuit, together with the number of lines of magnetic force which pass through the circuit, is a constant quantity....This quantity....may even be called the fundamental quantity in the theory of electromagnetism. Faraday...recognized in the secondary circuit, when in the electromagnetic field, a 'peculiar electrical condition of matter' to which he gave the name of the Electrotonic State."

(This quantity being defined as of most fundamental nature appears to be similar to the concept of 'flux linkages', measured by the product of the number of winding turns and the total magnetic flux enclosed in the winding, $N\Phi$. This quantity is also expressed by the term MI ,

where M is the potential of the coupled circuits, and I is the current in any coil winding.)

5. Lenz's 1834 Law Showing Effects Opposing Causes in Electromagnetic Induction⁽⁵⁴²⁾

Maxwell's narrative of the development of basic electromagnetic theory continues its description of the early years of development as follows: "In 1834, Lenz enunciated the following remarkable relation between the phenomena of mechanical action of electric currents, as defined by Ampere's formula, and the induction of electric currents by the relative motion of conductors.... Lenz's law is as follows:

"If a constant current flows in the primary circuit A, and if, by the motion of A, or of the secondary circuit B, a current is induced in B, the direction of this induced current will be such that, by its electromagnetic action on A, it tends to oppose the relative motion of the circuits."

(Stated more generally, Lenz's law states that the electromagnetic field will act so as to oppose or resist any effort made to change its intensity or configuration. Where mechanical motion causes the change, mechanical force developed within the system will oppose the change. If mechanical motion is absent, electromotive forces will be induced which tend to maintain the status quo, namely to maintain the total flux linkages in the system.)

6. Neumann's 1845 Development of Mathematical Theory of Induction⁽⁵⁴²⁾

Maxwell's history of developments continues with: "On (Lenz's) law, F. E. Neumann founded his mathematical theory of induction in which he established the mathematical laws of the induced currents due to motion of the primary or secondary conductor. He showed that the quantity M is the same as the electromagnetic potential of one circuit on the other.... We may regard F. E. Neumann, therefore, as having completed for the induction of currents the mathematical treatment which Ampere had applied to their mechanical action."

7. Helmholtz 1847 Derivation of Laws of Induction From Conservation of Energy⁽⁵⁴³⁾

In Maxwell's opinion: "A step of still greater scientific importance was soon after made by Helmholtz in his 'Essay on the Conservation of Force,' and by Sir William Thompson, working somewhat later, but independently of Helmholtz. They showed that the induction of electric currents discovered by Faraday could be mathematically deduced from the electromagnetic actions discovered by Oersted and Ampere by the application of the principle of Conservation of Energy.

8. Faraday's Recognition of Electromagnetic Kinetic Energy and Momentum⁽⁵⁴⁶⁻⁵⁵²⁾

Maxwell reports that: "Faraday showed that (the phenomenon of self-induction) and other phenomena which he describes are due to the same inductive action which he had already observed the current to exert on neighboring conductors. In this case, however, the inductive action is exerted on the same conductor which carries the current, and it is so much the more powerful as the wire itself is nearer to the different elements of the current than any other wire can be. He observes, however, that 'the first thought that arises in the mind is that the electricity circulates with something like momentum or inertia in the wire.' Indeed, when we consider one particular wire only, the phenomena are exactly analogous to those of a pipe full of water flowing in a continued stream. If while the stream is flowing we suddenly close the end of the pipe, the momentum of the water produces a sudden pressure, which is much greater than that due to the head of water and may be sufficient to burst the pipe...

"These results show clearly that, if the phenomena are due to momentum, the momentum is certainly not that of the electricity in the wire, because the same wire, conveying the same current, exhibits effects which differ according to its form; and even when its form remains the same, the presence of other bodies such as a piece of iron or a closed metallic circuit, affects the result." (This latter effect is that involved in eddy current testing.)

"It appears, therefore, that a system containing an electric current is a seat of energy of some kind; and since we can form no conception of an electric current except as a kinetic phenomenon, its energy must be kinetic energy, that is to say, the energy which a moving body has by virtue of its motion.

"We have already shown that the electricity in the wire cannot be considered as the moving body in which we are to find this energy, for the energy of a moving body does not depend upon anything external to itself, whereas the presence of other bodies near the current alters its energy.

9. Influence of Faraday's Research Upon 19th Century Inventors

Michael Faraday's two-volume work "Experimental Researches in Electricity" influenced numerous investigators and inventors in Europe and the United States from the 1830's to the end of the nineteenth century. This led many others to experiment with electromagnetic effects and to develop many basic inventions such as Morse's telegraph, Bell's telephone, and Edison's many improvements on telegraphic, telephonic, fire alarm, and stock ticker communication systems. Faraday in 1831 also showed before the Royal Society a homopolar generator (a disc rotating between the poles of a large horseshoe magnet) for converting mechanical energy into electric energy. His influence upon inventors with little or no scientific training was very great, for Faraday's accounts of his experiments did not use any complicated mathematical formulas. A biographer of Thomas Edison notes that Faraday appeared to be the Master Experimenter whose laboratory notes communicated the highest intellectual excitement--and hope as well. Faraday's explanations were simple, steeped in the spirit of truthfulness and humility before nature. For Faraday, the natural laws were revealed through experiment. To American inventors, Faraday, poor and self-educated, indifferent to money or titles, exemplified the ethics of a true man of science, whom they could emulate. Thus, during the period from 1831 to about 1875, the inventions made on the basis of Faraday's research were often developed by trial and error, empirically, and step-by-step.

10. Maxwell's Proposal for Development of Theory of the Electromagnetic Field⁽⁵⁵²⁾

Based upon the facts previously summarized in this introduction, James Clerk Maxwell outlines his plan for developing a unified theory of the electromagnetic field, as follows:

"We are therefore led to inquire whether there may not be some motion going on in the space outside the wire, which is not occupied by the electric current, but in which the electromagnetic effects of current are manifested.

"I shall not at present enter on the reasons for looking in one place rather than another for such motions, or for regarding these motions as of one kind than another.

"What I propose now to do is to examine the consequences of the assumption that the phenomena of the electric current are those of a moving system, the motion being communicated from one part of the system to another by forces, that nature and laws of which we do not even attempt to define, because we can eliminate these forces from the equations of motion by the method given by Lagrange for any connected system.

"....I propose to deduce the main structure of the theory of electricity from a dynamical hypothesis of this kind, instead of following the path which has led Weber and other investigators to many remarkable discoveries and experiments, and to conceptions, some of which are as beautiful as they are bold. I have chosen this method because I wish to show that there are other ways of viewing the phenomena which appear to me more satisfactory, and at the same time are more consistent with the methods followed in the preceding parts of this book than those which proceed on the hypothesis of direct action at a distance."

11. Maxwell's Equations for Electric Circuits and for Electromagnetic Fields⁽⁵⁷⁸⁻⁶¹⁹⁾

Maxwell's remarkable achievement of integrating the available knowledge concerning electromagnetic circuits and fields provides the basis for analysis of all basic eddy current and electromagnetic induction problems--and for most of modern electromagnetic theory. These

simple equations in both integral and differential form were derived by the methods of Lagrange, using relationships from the calculus of variations. Solutions for alternating fields are also available for many configurations of the fields.

It is of interest that simpler techniques, using an 'operational map' have been devised by the author for presenting these types of equations and their derivations in simple form for use by second-year engineering students. Since the equations are available in nearly all basic textbooks on the electromagnetic field, they will not be repeated here. Lord Kelvin devised the solutions of Bessel's equation for the cases of probe coils, for example, and provided the so-called Kelvin functions from which simple cases can be readily calculated by hand or by digital computers.

11.1 Development of practical electromagnetic induction test methods

It has been reported that Hughes demonstrated the basic features of eddy current nondestructive testing in the 1860's showing that it was possible to differentiate between metallic conducting coins by a simple arrangement of magnetizing coil and induction of eddy currents in the coins.

12. Early Tests for Eddy Current and Hysteresis Losses in Electrical Steel Sheets

Active practical interest in use of electromagnetic means for sorting of metals and detection of discontinuities did not result in many useful test devices prior to the beginning of the twentieth century. However, the numerous developments including that of alternating current electric power systems, and the use of transformers and other induction machines, provided a base of practical design and a need to investigate the losses occurring in magnetic core materials used in these devices. Much effort was devoted to reduction of eddy current and magnetic hysteresis losses in laminated steel sheets, particularly by addition of silicon and other alloying elements which lowered their electrical conductivity and use of purer iron alloys with, in some cases, directional rolling to attain maximum permeability and minimum hysteresis losses.

To a first approximation, in cores formed of thin magnetic laminations, it was shown that eddy current losses tended to increase in proportion with the square of the frequency, and hysteresis losses in accordance with the 1.6th power of the frequency of alternation of the magnetic field intensity. Numerous laboratories, including those of electrical equipment manufacturers such as Westinghouse and The General Electric Company, and of manufacturers of electrical steel sheets such as Allegheny-Ludlum and Armco Steel Company, established measurement laboratories to monitor properties of production steel sheets and assure specified electromagnetic loss factors for electrical steel sheets. The well-known Epstein test, and many others, were used for these material tests.

Many improvements resulted, including use of thinner sheets, use of oriented steel sheets, and use of insulating coatings between sheets to limit eddy current flow paths. Also discovered during these magnetic core improvements were the undesirable effects of mechanical clamping stresses and stresses resulting from punching and shearing of laminations, which tended to increase core losses under ac excitation. Hydrogen annealing and other techniques, such as those developed by Dr. Trivie Yensen of Westinghouse Research Laboratories, led to improved materials such as Hyper-sil, Hypermik, and other magnetic sheet alloys with superior properties. Control of other alloying elements, additions of up to 50% nickel, and orientation of grain structures and magnetic domains were used to develop special steels with rectangular hysteresis loops which are used in magnetic switching of electrical currents, saturable reactors and magnetic amplifiers, and many novel electromagnetic devices. These developments illustrated the variations in electrical conductivity, magnetic permeability, grain orientation and anisotropy, mechanical stresses, alloy contents, and impurity contents, which influenced the electromagnetic response of ferromagnetic materials and changed the apparent inductance and resistive losses measured by their magnetizing coils. The use of direct-current bias to adjust the apparent inductance in saturable reactors and transducers for power control purposes also illustrated a means for reducing magnetic permeability and incremental inductance or inductive reactance. It was also observed that many magnetic

core materials introduced odd harmonics into the magnetizing currents or voltages across inductances of their magnetizing coils (or into unloaded secondary windings on the cores), and the high sensitivity of the harmonic signals to material conditions and mechanical stressing were known and purposely avoided where possible.

These various effects, well-known to electrical designers at the turn of the century, have since become possible methods for control or read-out of eddy current nondestructive test signals. (However, in general, the highly-permeable electrical steel sheets now commercially-available are not ideal for eddy current tests since their eddy current losses are so very low. For their evaluation, electromagnetic induction tests responsive primarily to hysteresis effects, including higher harmonic effects, may prove more useful.)

13. Development of Techniques for Analysis of Inductive ac Electrical Circuits

The sinusoidal oscillations of alternating-current electric power system voltages and currents introduced new complexities in analysis of circuit performance, as compared with analyses for Edison's earlier direct-current electric power systems. As early as 1893, Professors Crehore and Beddell of Cornell University prepared a textbook of analysis of ac electric circuits, including effects of resistive, capacitive, and inductive circuit elements. This book was based upon detailed solution of the differential equations developed by Maxwell, and involved use of calculus in each solution. Soon thereafter, Steinmetz came to the United States with the Thomson-Houston Company (later General Electric Company) and he developed much simplified methods of analysis using rotating line segments which he called "vectors" (now called sinors) to represent sinusoidal quantities. As such line segments rotated about one end (at the origin of coordinates), their vertical projections mapped out the ordinates of the sinusoidal waves, when these vertical projections were plotted as functions of time. Together with the technique of representing impedances on a complex plane (with resistance R as a horizontal coordinate, and inductive reactance, X , as a vertical coordinate), the use of these phasor quantities reduced the

solutions for steady state alternating currents to simple algebra and trigonometry, rather than integral calculus. These methods of signal analysis on the complex plane are widely used today in analysis of eddy current tests, following their clear enunciation by Dr. Friedrich Förster of West Germany, following World War II.

14. Early Industrial Development of Electromagnetic Induction Comparators

Numerous electromagnetic induction or eddy current comparators were patented in the United States in the period from 1925 until the end of World War II in 1945. Many of these were referenced in 1950 by McMaster and Wenk in an ASTM publication, updating a prior (1948) summary of basic nondestructive test methods. (See Tables I, II and Appendix I.) Innumerable examples of comparator tests were reported in the literature and in patents. Many provided simple comparator coils into which round bars or other test objects were placed, producing simple changes in amplitudes of test signals, or unbalancing simple bridge circuits. In nearly all cases, and particularly where ferromagnetic test materials were involved, no quantitative analyses of test-object dimensions, properties, or discontinuities were possible with such instruments. Often, difficulties were encountered in reproducing test results, since some test circuits were adjusted or "balanced" to optimize signal differences between a "known good test object" and a "known defective test object," for each group of objects to be tested. Little or no correlation could then be obtained between various types of specimens, each type having been compared to an arbitrarily-selected specimen of the same specific type.

Many simple comparators operated on 60 Hz alternating current from 110 volt ac circuits, using conventional instruments such as voltmeters, ammeters, wattmeters and, occasionally phase meters. Such meters typically absorbed energy from the test circuits, and had typical accuracies and reproducibilities often of only 1% or 2% of full-scale readings. In other cases, well-known Wheatstone bridge circuits were employed to balance out comparison test arrangements, and to provide greater sensitivity to signal differences. For the most

part, many of these early comparator systems were short-lived, and received little acceptance in industry. By comparison, a few such developments, sponsored by major industries or persistent creative inventors who sought support and set up their own companies, survived and are used in their modernized form in American industry today.

14.1 1925-1945 American developments of electromagnetic tests for steel products

Examples of continuing development of electromagnetic induction tests for use in inspection of round bars, tubes, billets, and products of the steel industry of the United States were those of Magnetic Analysis Corporation and Republic Steel Corporation. Both are based upon the continuing efforts of a few dedicated individuals who passed their skills and enthusiasms along to their successors in the same development organizations. Charles W. Burroughs, Carl Kinsley, and Theodore W. Zuschlag were among the pioneers of the Magnetic Analysis Corporation, whose test products are still commercially available in 1978. Archibald H. Davis, Horace G. Knerr, and Alfred R. Sharples received basic patents for Steel and Tubes, Inc. (now Republic Steel Corporation). Their developments were extended and continued in the Electromechanical Research Laboratory of Republic Steel in Cleveland by Cecil Farrow, Archibald W. Black, William C. Harmon, and Joseph Mandula to the large-scale, automated, production-line eddy current test machines for tubes, bars, and billets in use today. (Other steel companies had early inventors and developers of electromagnetic tests but, in many cases, their managements did not support their continuing developments over a period long enough to achieve practical applications.) Within the General Electric Company, an early sequence of inventive development was pioneered by men like James A. Sams, Charles D. Moriarity, and H. D. Roop. Ross Gunn of the U. S. Naval Research Laboratory pioneered a new form of probe-coil magnetizing system with two small-diameter pickup coils displaced symmetrically along a diameter of the magnetizing coil. This was an early example of use of one size of coil for magnetization, and of pickup coils of much different size, in non-concentric positions. (See Tables I and II for details of operation of these test systems, and for other examples from this period.)

14.2 Post World War II developments in electromagnetic induction tests

Rapid technological developments prior to and during World War II (1941-1945) in many fields contributed both to the demand for nondestructive tests and to the development of advanced test methods. Radar and sonar systems made acceptable the viewing of test data as images on the screens of cathode-ray tubes or oscilloscopes. Developments in electronic instrumentation, and in magnetic sensors used both for degaussing ships and for actuating magnetic mines, brought a resurgence of activity. After the war ended, developments such as Professor Floyd Firestone's "supersonic reflectoscope" for ultrasonic testing, and Dr. Friedrich Förster's advanced eddy current and magnetometer systems, became available as industrial nondestructive testing systems. These systems offered new dimensions for nondestructive measurement both of material properties and of discontinuity locations and relative sizes. The ten-year lag (from 1945 to about 1955) in industrial management's acceptance of novel developments was uniquely short, in the case of these instruments. Electronic instrumentation based upon vacuum and gas-filled electron tubes was approaching the peak of its development. These developments permitted easy construction of variable-frequency oscillators and power supplies for the magnetizing coils of eddy current test systems. They also permitted minute voltage or current signals to be amplified linearly to levels adequate for display systems, graphic and permanent recording systems, and for operation of sorting gates, automation of scanning, and mechanization of materials handling during tests. Aerospace and nuclear power industries were developing rapidly, and made unique demands for sensitivity and reliability of instruments for materials evaluation and reliability assurance during service. These industries (and government agencies related to these industries) were the primary sponsors of research to advance the art of all forms of nondestructive testing. However, in the case of eddy current instrumentation, governmental support was significantly less than in other fields of nondestructive testing, for two reasons which are discussed next.

15. Development of Quantitative Eddy Current Test Systems By Institut Dr. Förster

By far the most important factor contributing to the rapid development and industrial acceptance of electromagnetic induction and eddy current tests during the 1950-1965 period in the United States was the introduction of sophisticated, stable, quantitative test equipment, and of practical methods for analysis of quantitative test signals on the complex plane, by Dr. Friedrich Förster. Dr. Förster is rightly identified as the 'father of modern eddy current testing.' His experience prior to World War II included advanced university education in physics and a significant introduction to electromagnetic measurements related to the metallurgy and structure of steels and non-ferrous metals in German research institutes. During World War II, this advanced knowledge was used in naval warfare, particularly with respect to magnetic mines. At the conclusion of the war, after a period of imprisonment by the French, Dr. Förster retrieved his technical reports and, "with the aid of a screwdriver and a technician," began his further development of electromagnetic test instruments in the upper story of an old inn just a few miles from Reutlingen, where he later established his Institut Dr. Förster. By 1950, he had developed precise theory for many basic types of eddy current tests, including both absolute and differential or comparator test systems, and probe or fork coil systems used with thin sheets and extended surfaces. Painstaking calibration tests were made with these coil systems and with mercury models (in which defects could be simulated by insertion of small pieces of insulators). Each test was confirmed also by precise solution of Maxwell's differential equations for the various boundary conditions involved with coils and test objects, at least for symmetrical cases such as round bars, tubes, and flat sheets where such mathematical integrations were feasible. Further studies were made of the nonlinear response characteristics of ferromagnetic test objects, and methods utilizing very low test frequencies (5 Hz), harmonic signal analysis, comparators at various levels of magnetization, and precise bridge circuits were developed. In most instances, Dr. Förster replaced measurements of the inductance or

impedance of test magnetizing coils with the more precise technique of measuring response with unloaded 'secondary coils' coupled to the test materials almost identically with the magnetizing coils. The extent and depth of these scientific studies were not matched by any laboratory in the United States, whether under government sponsorship or operating independently. By extensive publications (not initially in the form of U. S. Patents, but in the open literature), Dr. Förster made the end results of this research available to the world of technical personnel. His monumental contribution of almost the entire theory and technology of electromagnetic induction and eddy current test techniques to the ASNT Nondestructive Testing Handbook in the 1955-1959 period provided the means for educating thousands of other nondestructive test personnel in the theory, methods, equipment, and interpretation of eddy current tests. This integrated presentation was then used throughout the world to update eddy current test technology.

16. Importation of Dr. Förster's Eddy Current Technology to the United States

The unique developments in Dr. Förster's new laboratory in Reutlingen, West Germany, were made known in the United States, not only by those capable of reading his publications (in German) prior to 1950, but also by missions in which American personnel were sent to Dr. Förster's laboratory for education and experience with these new forms of test instrumentation. Richard Hochschild, for example, made a visit of perhaps six months in Reutlingen. Upon his return, he prepared summary reports which were distributed by the AEC sponsors of his visit. Other personnel from private industry and from other laboratories made visits to learn of these new techniques. In the United States, numerous facilities began research to test these new concepts and instrumentation, including significant efforts at Oak Ridge National Laboratories, at the Hanford Works, and in other facilities. The splendid creative work of Mr. Hugo L. Libby at Hanford during the past quarter century, and that of Robert Oliver, Robert McClung, Caius V. Dodd, J. A. Deeds, and others at Oak Ridge, which have continued into the 1970's, may well have initially been inspired (and sponsored in response to) the new work done by Dr. Förster.

However, even more significant has been the complete transfer of Dr. Förster's advanced technology to enterprising American firms manufacturing and distributing nondestructive testing equipment, since 1952. As many of you may remember, Dr. Förster made his first presentation before an ASNT audience early in the 1950's, after learning aboard ship about five words of English, namely: "Sonny boy" and "I love you." This first personal presentation in the United States was followed by meetings with management of the Magnaflux Corporation, in which the author served as a technical advisor to explain Dr. Förster's designs and discussion. Agreements for licensing under Förster patents were later concluded, and the basic Förster instruments were "Americanized" by use of U.S. components and electron tubes, for Magnaflux, by the NDT staff at Battelle Memorial Institute in Columbus, Ohio. (Here, again, the author had an opportunity to become aware of the remarkable character of these new instruments.) During the next few years, increasing amounts of technology were transferred to Magnaflux, whose staff (under Dr. Glenn L. McClurg) became qualified in the design and production of Dr. Förster's various instruments, and then marketed these electromagnetic induction test systems throughout the United States.

17. Proliferation of Sources of Eddy Current Equipment Derived from Dr. Förster

The collaboration between Dr. Förster and the Magnaflux Corporation lasted perhaps ten years, during which rapid progress was made in both the German laboratory and in the United States in advancing the art of eddy current testing. Upon completion of the arrangement with Magnaflux, Dr. Förster marketed his instruments through the Förster-Hoover organization in Ann Arbor, Michigan. Rudy Hentschel, who was trained in Reutlingen at Institut Dr. Förster, provided information transfer to this new organization. (More recently, he has developed similar advanced instruments at his own facility in Ann Arbor.) After a few years, the licensing of Förster instruments to Automation Industries, Inc. resulted in further transfer to advanced technology, and marketing of equipment throughout a new organization. The most recent arrangement with Krautkramer-Branson has repeated this

unique educational process. At present, the large organizations manufacturing many types of nondestructive testing equipment and marketing their services widely in the United States are presenting updated versions of Dr. Förster's basic test instruments and modifications developed by their own staffs. Also in the market are the instruments developed by Magnetic Analysis Corporation, those based upon Hugo Libby's research at Hanford (by Nortec), those based upon the Oak Ridge Laboratory research and developments by Richard Hochschild and Donald Erdman (which have migrated from the originators through the Budd Company, Automation Industries, and Tech-Tran in recent years). Basically, in 1977, these various brands of conventional eddy current instruments are redundant and similar in nature, having been updated to semiconductor circuit elements and more recently to integrated circuits in some cases. With the typical instruments used to cover various needs and applications, the presently-available instruments operate with absolute or differential probe coils, encircling coils, internal bobbin coils, and various special coil and circuit arrangements, many of which were described in the 1959 ASNT Nondestructive Testing Handbook by Dr. Förster. Self-balancing or adjusting instruments, which establish reference points simply by the placing of probes upon reference test materials or specimens, are available in several cases, utilizing developments by Hugo Libby and other innovators. Designs of probes based upon digital computer analyses of eddy current distributions in single- or multiple-layer sheet materials have been made feasible through the pioneering work at the Oak Ridge National Laboratory. Special probes with split coils, internal magnetic shields, and other complexities have also been developed for crack detection and other special applications. Digital displays of test signals are also being introduced.

18. Introduction of Microwave Nondestructive Test and Measuring Systems

At very high frequencies, electromagnetic fields can be concentrated into beams and propagated through space. When such a beam pulse strikes a conducting metallic surface, for example, it is reflected and may return as an echo to the site of the original pulse transmitter, or to other detectors, as in radar detection. In dielectric materials, microwaves can

be subject to rotations and phase shifts, as well as to attenuation due to dielectric hysteresis losses. In many ways, microwave nondestructive test systems are analogous in performance applications to immersion ultrasonic test systems. By Maxwell's theory of the electromagnetic field, microwaves are reflected like light waves by eddy currents induced in the surface layers of highly-conducting metallic materials. Thus, microwaves appear to have the capacity to apply high-frequency eddy current tests to a metallic surface from a distance, and perhaps to scan such surfaces to detect discontinuities which change the pulse-reflection patterns.

When the Radac eddy current systems were sold to the Budd Company, Richard Hochschild turned his attention to formation and development of Microwave Instruments Company in Corona del Mar, California. Soon a series of instrument systems had been developed, and the long task of educating industrial and scientific users in the capabilities and applications of electromagnetic tests had to be done all over again for these new higher frequencies. Of course, the theory and design of microwave generators, horns, antennas, detectors, and display systems had been previously developed for long-distance ranging in radar. Many textbooks presented the electromagnetic theory of microwaves in terms readily used by electrical engineers. Microwave system components and electron tubes were commercially available. However, these electrical engineers rarely were aware of the needs of nondestructive test engineers, and NDT engineers had little familiarity with microwaves. In fact, many NDT personnel were still struggling to catch up with the art of eddy current testing at the lower frequencies, as explained by Dr. Förster. After several years of diligent development and continued application research and marketing efforts with the assistance of Ron Botsco, Microwave Instruments Company was sold and its proprietor moved to greener pastures in the area of medical services. A few other organizations built simple microwave test systems, but the development of industrial microwave nondestructive testing has been languishing during the 1970's. Limited research sponsored by ARPA and other government agencies has resulted in indications of possibilities of crack detection from a distance, since slots and wires simulating discontinuities in metallic test object surfaces can be detected under proper conditions of microwave

pulse-reflection testing. (The theory of microwave antennas and of time-domain reflectometry of microwaves in tubes, passing along wires, and reflecting and refracting in dielectric layers, offer many indications of potentially-valuable nondestructive test applications.) Since microwaves can be focused, microwave systems could also potentially be designed analogous to optical instruments and test systems, as well as ultrasonic test systems. However, in 1978, there appears to be no significant commercial development or application of microwave nondestructive tests in progress.

On the other hand, a large-scale example of microwave exploration of objects at great distances is occurring in radio astronomy laboratories throughout the world. For example, Professor John D. Kraus of The Ohio State University has constructed a large radio telescope in Delaware, Ohio, and is using it continuously to map the universe of radio stars and objects which emit microwave signals. The mapping has progressed to where many radio sources found have been confirmed by films from optical telescopes, and others have been predicted in location. Possibilities of emissions from galaxies, 'black holes', and other astronomical features still exist. Professor Kraus has recognized this as a form of "nondestructive testing of outer space" and has written a delightful biographical book "The Big Ear," which summarizes a lifetime of study and applications of Maxwell's theory of electromagnetic fields in clear and simple words.

19. Advantages of Eddy Current Test Systems Commercially Available in 1977-78

The eddy current test systems available commercially in 1978 have many advantages which justify their present wide usage. One great advantage is the reproducibility of measurements possible with many well-built instruments and test systems. Absolute conductivity meters and instruments designed for thickness measurements of specific metals and alloys are often quantitative and can have accuracies of 1% or better. Comparison instruments permit unique sensitivities for detection of discontinuities and of variations in material geometries or properties. With stable reference specimens, tests can also be repeated with a high degree of confidence. Instruments with phase and amplitude signal capabilities

which duplicate phase-plane data consistently permit a wide range of interpretations to be made, depending upon the strategic test conditions selected. Phase separation of signals to suppress unwanted signals and provide desired signals without interfering effects are especially valuable where consistency of geometry and physical properties of test materials permit their use. The general use of reference standards with drilled holes, milled or EDM slots, stepped wall thicknesses, and certain natural defects provides a quick means of assuring proper operation during testing, or of calibration and adjustment of control settings at the beginning of test sequences on objects of a particular type or material. These advantages generally accrue with nonferromagnetic test materials and symmetrical simple shapes of test objects. They cannot always be attained with magnetizable test materials or with parts of complex geometry where reproducible positioning may not be feasible.

By use of magnetic bias (or 'saturation magnetization'), depths of penetration of eddy currents and a.c. magnetic fields into ferromagnetic materials can be greatly increased. Many simple detectors of surface discontinuities operate quite effectively during automatic scanning despite difficulties due to surface roughness or variations in hardness or magnetic permeabilities in test objects. Large-scale through-coil test systems for smaller-diameter rounds and tubes, and orbiting probe coil systems used with rods, welded tubes, and even rectangular billets have been developed to a high degree of ruggedness, serviceability, and reliability for use in steel mills and on large-volume inspection applications. Automatic marking of defect locations permits salvage by grinding out and welding repair (if the latter is needed) on production line operations. Detection of defects in surface layers of steels is well-developed, but measurement of physical or metallurgical properties of steels is generally not feasible by eddy current tests in the United States. One basic source of difficulty is the sequential use of sheets, tubes, or rounds from different mills or different heats, in rapid succession on production lines. Although the chemical and physical properties of these steels from different sources may meet manufacturing requirements adequately, no effort is made to control the magnetic permeability properties of these steels to any type of calibrated standard. As a

consequence, random variations in magnetic permeability prohibit the development of reproducible correlations between absolute measurements of eddy current test signals and the actual physical or metallurgical structures of the test objects.

High sensitivity to material electrical conductivity (in nonferromagnetic materials) has been attained with small probe coil test instruments typically operating in the range of 64 kHz test frequencies. Such small coil probes tend to be sensitive to lift-off, and 'lift-off compensation systems' such as those developed by Dr. Förster are often used to correct lift-off effects over a small range. Similarly, small differential coil or field detector systems provide high sensitivity to surface cracks in both non-magnetic and in ferromagnetic materials. However, in general, for such crack detection, manual positioning and scanning with these fine probes is usually required on nonsymmetrical part surfaces or materials in service structures and machines. There is no low-cost means for total inspection for cracks on parts with complex surfaces, such as those for which liquid penetrant tests (or magnetic particle tests on iron or steel parts) provide overall surface inspection at high speed and low costs.

20. Limitations and Disadvantages of Presently-Available Eddy Current Test Systems

The primary disadvantage of eddy current test systems available in 1977-78 is the fact that their test indications are psychologically-unacceptable. They are far less effective in stimulating management and worker comprehension and corrective action than the graphic images provided by other processes such as liquid-penetrant, magnetic-particle, or x-ray inspection, for example. These eddy current tests fail to produce a clear, visible, interpretable image of defects or discontinuities from which an almost-instant recognition of their nature, shape, size, or location is obvious to all observers. Thus, where the purpose of nondestructive testing is to motivate personnel to best efforts or to permit immediate correction or repair of defects, eddy current tests which produce fugitive traces on cathode-ray tube screens or 'meaningless' movements of the needle of a panel instrument, are quite ineffective. Secondly, even when these tests are used

to measure material properties or dimensions, the fact that the quantitative displays of signal amplitudes, component values, or phase angles have no direct meaning to the untrained observer acts to create doubt. When numbers have to be 'looked up in a book or chart' to find the real meaning of test indications, the opportunity exists for human errors. In addition, since the same book or chart would not be valid for materials other than a specific material for which the chart is designed, untrained observers will question the results. If modern eddy current tests provided clear, informative images or direct read-outs in numbers of a specific dimension, property, or service characteristic (which could be immediately checked on reference samples if needed), their use could be multiplied indefinitely. For example, where today x-ray or ultrasonic tests are specified for control of weldments, no one dares to trust eddy current measurements of these same welds for control of welding operators or for acceptance of the welds for specific service conditions.

The second disadvantage of present eddy current test systems is that they are greatly limited by artificial constraints inherent in the thinking of present designers, manufacturers, and users of these tests. No one has made any fundamental change from the basic designs which Dr. Förster provided in 1955, nor in the methods for interpreting test signals. Because of these unnecessary constraints adopted by tradition, eddy current tests are far less informative or sensitive than they should be. Examples of such mental straight-jackets are cited in a succeeding paragraph. True advancement to the next era of eddy current testing cannot occur until the responsible and active engineers, management, and test personnel develop systems to utilize the full capabilities of the method and use these systems for effective control of people, processes, products, and in-service materials and systems.

The third disadvantage of present eddy current test systems is that they are limited in penetration depths (often to less than 5 or 10 mm) and in magnetizing coil and detector adaptability to rough or contoured test material surfaces. Few probes or test coils are designed to fit into a sharp inside corner or intimately to the outer edge of a sheet material, for example. In general, many probe coils are on rigid forms, and cannot conform to

irregular contours on test objects. It is also often assumed that small-diameter probe coils must be used to measure fine defects or the properties of small areas of test objects. Yet, small coils assure lack of deep penetration of the magnetic field into metals or alloys (since the coil field in air is proportionately small).

The fourth disadvantage of present eddy current test systems is their insensitivity to local conditions or discontinuities which produce only small distortions in eddy current flow paths. (In this sense, "small" is related to the diameter of the test coil.) In general, present test systems do not detect discontinuities or defects which lie outside the perimeter of the test coils. They are also typically insensitive to small defects which lie on the centerline of the test coils. In fact, existing test coils integrate all magnetic flux lines which their winding turns enclose. With discontinuities small in dimensions compared to the coil diameter, the defect signals are submerged in a large average coil signal so that highly-sensitive detector circuits are needed to detect the minute changes in amplitude or phase. Even worse, present coil-type detectors are insensitive to the tilt or angle of magnetic flux lines encircled by the coils. They simply measure the time rate of change of the total magnetic flux enclosed by the test coil. This often loses signal magnitude by ratios as great as 100 to 1. Finally, the use of coils for detection of signals limits the most minute area detectable to that roughly corresponding to the pick-up coil diameter (or the diameter of a ferromagnetic core within the pick-up coil.) Modern microelectronics can far exceed these limitations on reducing the size of test area whose electromagnetic test signal is detected and displayed.

The fifth disadvantage of present eddy current test systems is their limitation to higher test frequencies and to tests at larger phase angles on the complex plane. The voltage signal amplitude provided by a pickup coil is proportional to the test frequency. If an effort is made to operate at very low test frequencies to attain deeper penetration and response to 'rear-surface' conditions, the signal can become too low to detect in the presence of normal noise signals. Even if amplification can permit signal display, the low-frequency test condition leads to signal points on the upper left portion of

the locus curves of response on the complex plane. Here, the signal closely approaches the 'empty-coil signal' in both amplitude and phase. The small contribution of the eddy current losses to this test signal also imply lack of test sensitivity.

The sixth disadvantage of some present eddy current test systems is the variation of magnetizing current amplitude with test frequency. Higher test frequencies require higher power supply voltages to provide a given magnitude of current in the test coils. If variations in test frequency result in inverse changes in magnetizing current, tests may be made on ferromagnetic test parts at widely-different levels of maximum magnetization, at different test frequencies. This can create difficulties with harmonic signal generation and non-linear response characteristics in eddy current test measurements. Alternatively, if true constant-current magnetization levels cannot be provided as frequency varies over a wide range, the designer may limit the test instrument to one or a few discrete test frequencies for which constant current levels can be assured. Even when multi-frequency tests are made at these few frequencies, a loss of information at other intermediate frequencies results.

A final limitation of some present eddy current test systems is their use of sinusoidal continuous ac current excitations. A useful signal thus lost is that of magnetic retentivity, and its relation to eddy current pulse decay characteristics. Square wave or spike excitation can provide both retentivity signals and decay curves for eddy currents within the test materials. The use of coil-type pickups prevents detection of the dc components of test signals which could be generated with pulse or rectangular waveshapes, since response is zero to steady-state magnetic flux conditions.

21. Artificial Constraints in Design and Use of Eddy Current Test Systems

Possible present stagnation in development of new or unique forms of eddy current test systems could result from constraints in thinking about novel approaches, perhaps because these new concepts are not fully documented in the past history of eddy current inspection. For example, circular test coils were selected for initial investigations because they

were easy to build and many test objects had circular symmetry. Theory also has been directed to circular test coils since the solutions of Maxwell's equations for the electromagnetic field could be attained more easily with symmetric circular boundary conditions (such as can be solved with Bessel's equation and its modifications). Actually, however, test coils can be wound around square, triangular, or spherical forms. They could be made highly flexible so that they can be made to conform to surfaces of any shape. In all cases, advantages accrue in eddy current testing if the magnetizing coil lift-off can be minimized. Flexible magnetizing coils with stranded conductors imbedded in rubber-like sheets or tubes might offer considerable advantages. Applied under pneumatic or other pressure, such flexible sheet magnetizing coils could be fitted to gently curved test parts with essentially zero lift-off. If the detector coil could also be in intimate contact with the curved surface of the test object, maximum test sensitivity and elimination of non-uniform lift-off conditions could be attained.

A further typical constraint lies in the assumption that the magnetizing coil and the pick-up coil should be either (a) one and the same coil, or (2) of identical diameter and coincident in position. True, the literature describes such simple arrangements redundantly. However, the pickup coil could be of any diameter (preferably smaller than the magnetizing coil), and be placed at any angle and in any desired position with respect to the magnetizing coil. For example, the pick-up coil could be located at any point, and in any orientation, within or completely outside the annulus of the magnetizing coil, or even at a point directly under only one point of the magnetizing coil winding. In fact, if the pickup coil is replaced by a semiconductor magnetic field detector, total freedom exists with respect to the number, positions, and angulations selected for the individual semiconductor detector elements. For example, an array of semiconductor detectors could be placed anywhere within, under, or external to the magnetizing coil windings to provide a multiplicity of input signals with only one magnetizing coil. Ideally, such an array should cover the entire area enclosed within the magnetizing coil or be extended over an area much larger than the magnetizing coil to provide total test information concerning the entire eddy current test field created

by the magnetizing coil. If this detector array could be interrogated in sequence by rapid techniques such as used to read computer memories or to digitalize images, for example, the resultant multi-channel data could be analyzed by digital techniques, and displayed in any desired image format (including two- or three-dimensional images on a television screen).

A particularly desirable change from prior art would be to utilize very large diameter magnetizing coils closely fitting test-object contours, to assure deep geometrical penetration of the magnetizing field. For example, a 10 in diameter test coil could easily project strong magnetic fields 2 or 3 inches in front of the coil face. Used with lower test frequencies, such a coil might provide penetration through 1 or 2 inches of nonmagnetic test material (particularly in the case of materials with electrical conductivities less than about 10% IACS). With arrays of semiconductor type magnetic field detectors, detail sensitivity to near-surface discontinuities might become sufficient to provide good recognizable images of typical discontinuities and defects. Alternatively, a linear array of magnetic field detectors might scan linearly across the field, or be rotated to provide a circular scan of the field within or adjacent to the magnetizing coil. The instantaneous appearance of a recognizable eddy current image of defects would convert this test into a psychologically-acceptable test and greatly increase demand and use for eddy current tests. The repeatability of such images, as coil and probes are moved over test surfaces, or tests are repeated after a time period, would do much to establish confidence in the reliability of such images. In general, the instantaneous character of eddy current images and the ease with which depth sensitivity could be changed or polarized eddy current flow established, might compare favorably with x-ray or ultrasonic test images of welds or with fluorescent penetrant or magnetic particle tests of surface cracks or seams and laps.

Another potentially attractive technique is that of using differential probe signal pick-ups (preferably by detecting unbalance in a four-detector array analogous to a Wheatstone bridge) which would be a direct map of the flow of eddy currents below test surfaces. The reality of eddy current flow paths and their deviations caused by discontinuities could then

be visualized readily. Since local detectors in the vicinity of crack ends, for example, can have surprisingly large test signals (as compared to those of large-area pick-up coils), unique opportunities exist for precise measurements of crack lengths and of crack extension rates. These topics are of special interest where fracture mechanics analyses are to be made of cracks to determine their capability to propagate under service stresses.

22. The Pending Revolution in Microprocessor Control of Eddy Current Tests

Already upon us in the 1977-78 time period is the explosion of use of microprocessors and digital computer techniques as integral components of nondestructive test systems and controls. The costs of these components have become so low that they are now toys for amateurs like the older "ham" radio operators. Home computers are available in the corner computer store which rival large-scale digital computers of just a few years ago. Microprocessors have already invaded control of ignition and carburetors in automobiles or domestic appliances in the house-wives' kitchens. They are urgently needed in eddy current instruments, where EPROMs (erasable read-only program memories) can be dedicated to specific purposes, such as providing direct correlations of eddy current test signals with material dimensions or properties. Since small test instruments could now be made direct reading for any valid measurements by eddy currents, the old business of table look-up or intelligent interpretation has become obsolete. The advantages are obvious in that each purpose could involve a separate low-cost test instrument, or plug-in PROM's could be used to change the correlation data from one test material to another or from one test frequency to another.

The additional advantages to be attained by integration of microprocessors and computers into eddy current test instrumentation are the possibilities for much more sophisticated real-time analysis of test signals. Positions of signal points could be determined on the complex planes, the directions of signal change established in response to each test material variable, and undesired signal components could be eliminated, without the

use of the analogue circuits used previously for such purposes. In addition, incoming test data could be continuously compared with prior data (from the same or other test objects) to detect and define differences resulting from discontinuities or changes in material properties. A further operation of data-smoothing as point-by-point data are entered into memory could add an additional degree of precision. Simple extrapolation or interpolation estimates could be derived from test data so that changes in trends could be detected rapidly as tests progress. Of course, differential measurements, or comparison measurements, could be made also from absolute input signals, thus eliminating the need for several test arrangements (absolute, differential, or comparison coils) to attain full information from eddy current tests.

A further natural consequence of use of digital techniques in data collection and analysis would be the possibilities for real-time control systems based upon eddy current test inputs. Recognition of material damage in service, high stress levels, or high temperature effects could be used to shut down or control systems to prevent premature failures. In addition, in processes such as fusion welding, a multiplicity of eddy current detectors could be used to monitor and control the welding process. Input signals might be derived from changing conditions such as material thickness, edge or weld groove distance, conductivity of metal, temperature of metal, depth of penetration of fusion, and final weld inspection for root defects, undercutting, cracking, lack of penetration at the root, and other undesired conditions. Other similar production control applications could be cited.

Still another advantage could be attained in telemetering and storage of eddy current test data. Digital data could be stored in computer memory, transferred to magnetic tapes, floppy discs, or other large-scale memories, and used as permanent inspection records (much as data on nuclear pressure vessels obtained by ultrasonic tests are digitized and stored today). In addition, digital data storage may in the future permit direct correlation of conditions detected by one type of test (such as ultrasonics) with another type of test (such as eddy currents).

23. Future Development of Direct-Imaging Eddy Current Test Systems

As noted earlier, the greatest limitation of eddy current tests, as compared with more popular tests like x-ray, penetrant, magnetic particle, and C-scan ultrasonic tests, is the lack of interpretable images derived from eddy current tests. Of course, there is no reason why eddy current test probes could not be scanned over test-object surfaces, just as is now done in immersion ultrasonics to establish C-scan (or plan view) images showing defect locations on the test surfaces. However, such scanning is slow and costly which inhibits its use even with ultrasonic testing. If eddy current tests could provide instant images (somewhat like x-ray fluoroscopy) or permit recording of test information so that it could be displayed on the face of a cathode-ray tube like a television picture, the data could become psychologically attractive and understandable to many more observers. In addition, if eddy current test images could be informative of conditions through much greater metal thicknesses so as to compete effectively with x-rays and ultrasonics, their usefulness could be increased.

With semiconductor detectors, such as indium-arsenide Hall devices, the detector size can be made quite small (as compared to the diameters of large magnetizing coils). If the semiconductor detectors were formed into arrays (like checkerboards) of perhaps 100 by 100 elements or more, within a magnetizing coil of large diameter, the individual picture elements could then be read-out one-by-one in sequence, just as microprocessor or digital computer images are recorded and reproduced on the X,Y coordinates of a television picture tube screen. (The hobby computers are now often equipped with facilities and programs (in software or PROM's) for such data display as images in color.) Such data could be collected from the detector array, subjected to interpretation criteria, and the results displayed on a full-screen image in short times, such as one or two seconds. They could then be interpreted from the screen, particularly if the microprocessor also presents needed digital data correlations for test conditions and test-object dimensions and properties. Such tasks as determining if discontinuities were located in critical areas of test parts could also be carried out by the microprocessor if critical areas had been identified and

mapped similarly for the specific test objects in advance.

A further potential advantage of television screen imaging of eddy current test signals could be the low-cost, high-speed production of permanent video tape records of all test conditions and results. Such video tapes can be made today on recorders so low in cost that they too are becoming toys in the home. Such video tapes are easily transported and can be played back later and at other locations for review of test results. Video-taped images of standard reference specimens and defects might also be used during visual evaluation of the eddy current test images. Also feasible, in these cases, is digital enhancement of image contrast, and display of enhanced images in various colors or with various brightness levels which could be adjusted for best discrimination of significant discontinuities or defects.

24. Future Development of Deep-Penetration Eddy Current Test Systems

The future should see a huge improvement in the depth capabilities of eddy current test systems. At present, most eddy current tests are used for surface and near-surface inspection where they provide high test sensitivities. Uniquely-good performance can be attained with thin-wall test objects, namely those whose metal wall thickness is a small fraction of the eddy current penetration depth. (Eddy current penetration depth is the metal depth at which the eddy current density, J , is reduced to about 37% of its value at the test material surface closest to the magnetizing coil.) At a depth of three times this penetration depth, the eddy current density is only about 5% of the surface current density. At five times the penetration depth, the eddy current density is negligible at less than 0.5% of its surface intensity. The standard penetration depth is an inverse function of the square root of the product of test frequency, material conductivity, and/or material magnetic permeability. In highly-ferromagnetic test materials, the penetration depths are typically reduced by a factor of 10 to 100, as compared with a nonmagnetic test material.

Improvements in penetration depth are obviously attainable by lowering the test frequency or saturating ferromagnetic materials to lower their relative magnetic

permeability. The first technique, of lowering test frequency, was limited in the past by the difficulty of detecting low test frequencies with pickup signal coils. With semiconductor detector systems, or by adding integrating operational amplifiers to pickup coils so as to integrate the test signals, it should be possible to work at much lower test frequencies. If, as an example, it were feasible to lower a conventional 10 kHz eddy current test frequency to 1 Hz, the standard penetration depth should increase by 100 times. However, at such a low test frequency, it would take one second to complete one cycle of alternation. With modern electronic integration systems, such frequencies are not out of the range of feasible measurements. In fact, low frequency oscillators and analysis systems should be able to handle frequencies as low as 0.01 Hz.

However, increasing the penetration depth by lowering of test frequency is of no value if the magnetizing coil diameter is such that the magnetizing field in air is reduced geometrically so that very few or no flux lines can reach the new penetration depth limits. The answer here is to employ large-diameter magnetizing coils (although the eddy current detectors can be as small as desired). An example of a large-diameter magnetizing coil in present use is the metal detector used to inspect air passengers prior to boarding aircraft in the United States. Such large-size test coils should also conform to surface contours of test objects, where feasible, and provide adequate levels of low-enough test frequencies to meet inspection requirements. Ideally, where feasible, the eddy current test should also result in interpretable images with good psychological impact, so that they can influence both management and workers to their best efforts.

25. Future Development of Time-Domain Reflectometry Eddy Current Tests

Time-domain reflectometry is a well-known technique for detection of discontinuities in high-frequency electromagnetic field transmission lines, telephone and telegraph lines, and by radar. Similar time-domain reflectometry techniques are used in ultrasonic nondestructive testing, and particularly in immersion testing. Short pulses of high-frequency wave trains, or a single step or square wave pulse, can be used. It is also pos-

sible to utilize short electromagnetic pulses in through-transmission electromagnetic testing. For example, Paul Gant of Shell Development Laboratories in Emoryville, California, used such a system many years ago to transmit electromagnetic pulses along oil well drill pipe and steel tubes. Encircling coils used as transmitters and receivers permitted detection of larger discontinuities and of zones of reduced wall thickness. Richard Hochschild also used radar-type echo ranging with his microwave test equipment to establish distances to metallic sheet and other reflectors.

Time domain reflectometry and standing-wave analyses are widely used in high-frequency electronic engineering analyses. Microwave parts and 'plumbing' fixtures are available from electronic equipment manufacturers, for construction of such systems. TDR plug-in hardware is available for high-quality cathode-ray oscilloscopes, which can be used directly for time-domain reflection eddy current tests. In such tests, microwave pulses are transmitted along metallic or dielectric rods, tubes, or sheets. Where impedance mismatch conditions are encountered, reflections occur. These systems are entirely analogous to ultrasonic pulse-reflection tests. Where the electromagnetic waves travel in dielectrics or in air around a metallic conductor, reflection can result from liquid or solid dielectrics (such as ceramics), or from metal surfaces (which typically act as total reflectors). Such techniques might apply for rapid inspection of metallic material moving at high speeds in a rolling mill, or perhaps for inspection of dielectric coatings being applied to wires, tubes, or sheets under fast transport conditions. (The travel speed of waves encountered in typical electromagnetic time domain reflectometry on metallic structures is perhaps two-thirds the speed of light (or about 2×10^8 meters per second.) Thus, echoes would return from a reflector one meter from the source in a time period of 10^{-8} seconds or 10 nanoseconds. Precision, fast-response, high-resolution electronic signal detection and analysis equipment, such as a cathode-ray oscilloscope or digital systems, would be needed in most cases (except when standing wave resonance conditions are present).

Further development of the recent efforts to use microwave beams to interrogate metals surfaces at a distance, to detect conditions such as slots or cracks,

highly-conducting surface coatings, dielectric surface coatings, or projections and surface irregularities, is still needed to permit practical test systems to be developed. In a similar sense, use of microwave distance measuring devices to detect movements of structures such as large tanks or bridges during earthquakes or under service loading might also be feasible. The still higher frequency laser beams used to range distances in surveying are similar, since their electromagnetic waves are still shorter in wavelengths than microwaves. As optical waveguides and signal transmission systems improve, it may be possible that these will also be used for analysis of electrical and magnetic properties of materials, and so join the ranks of practical nondestructive test systems.

26. The Ultimate Goal: Intelligent Materials with Microwave Trouble Signals

The ultimate goal with all forms of nondestructive test system development should be that of discovering or developing 'intelligent engineering materials' which detect troubles by themselves and transmit suitable alarm signals in time to permit human control to prevent disastrous failures. The presently-available technique of acoustic emission nondestructive testing is an example of transmission of signals from materials under mechanical stresses or subject to damaging events such as stress corrosion or fatigue damage leading to cracking. Man has not tried very hard to hear the many signals emitted by natural and artificial materials. Recent interest has been directed to earthquake prediction and prediction of dangerous storms. Probably many nondestructive test engineers have not bothered to "listen" to the microwave signals emitted by metallic surfaces and structures under stress, vibration, or surface attack. Yet, engineers often have to work very hard to muffle or destroy these signals when they tend to interfere with intentional human microwave or radio transmissions. For example, it has long been known that railway axles rotating in journal bearings create radio "noise" which is considered objectionable. In fact, copper straps are applied to short-circuit these emissions to assure that they do not interfere with railway signal systems or other communications.

Every citizen who drives a car with a radio has also had an opportunity to ob-

serve the microwave signals from large trucks, bridges, and machinery. If the car radio is tuned between broadcasting stations, so as to receive only "static" noise signals, variations in these signals can be quickly found as his car passes large trucks with metallic bodies, or drives across older iron or steel bridges with loose bolts or connections. If long-distance static is screened out (as in a shielded room), the radio signals from contacts dragging across metal surfaces, or from rotating bearings, or from loosely-bolted joints undergoing vibration, can be heard distinctly. In fact, if while wearing gloves, one taps a knife and fork together while walking about in the vicinity of the radio receiver, he can send Morse code or any other sequence of signals which can be heard on the radio loudspeaker. When two metals rub together, enormous sounds and screeches can be heard as the metals complain of the damage their surfaces are undergoing. When ball or roller bearings rotate under heavy load or with inadequate lubrication, each metal-to-metal contact can be announced by clicks and distinct signals. Often the same sequence of signals is broadcast with each rotation of the shaft or of a ball or roller with a damaged surface. In all cases, the intensity of these signals can be greatly increased by connecting one of the metal surfaces to the antenna lead of the radio (preferably through a shielded cable). The other metal surface may be grounded or allowed to stand insulated from all other surfaces. On the other hand, short-circuiting the two pieces of metal together at the point of signal generation generally extinguishes the radio signals broadcast.

The well-known triboelectric effect (electrification by friction) known by the Greeks 2000 years ago, illustrates the basis of such microwave emissions. During rubbing, one material steals electrons from the other material, particularly when contact is broken. Since the electron cloud within conducting metals constitutes a plasma, the sudden removal or injection of charge locally may create plasma oscillations. If one of the metal pieces is insulated from the other, it is possible that such oscillations result in electromagnetic waves traveling through the metal. It then serves as an antenna to broadcast these waves into the space around it. These weak signals can be easily lost in static conditions. Tests in a shielded room permit their clear identification and their correlation with

material surface characteristics. The author has found these signals to approximate 'white noise', in that they can be detected at all frequencies from those of audio amplifiers, through those of a.m. and f.m. radio broadcasting, to frequencies of 100 MHz or higher. This could be expected from the short time duration involved in the robbery of electrons from a metal surface.

Thus, the ultimate in-service monitor system for metallic systems and machines may well be formed of microwave monitors of electron emissions. When the electron charges are removed from a metal, the eddy current reaction is one of high frequencies, capable of being transmitted through the metal antenna and from it to detectors at moderate distances. Increased stressing or rubbing of contacts across contaminated (oxidized) metal surfaces results in enhanced microwave distress signals. These same signals can be used to create television images of metal surfaces, including geometric features such as scratches, or chemical features such as corrosion, oxides, contaminants such as fingerprints, or even the effects of adsorbed gas layers or amorphous coatings. With a low-voltage electron beam scanning such surfaces (as in a vidicon television camera tube), the surface features are not damaged, and their images can be reproduced faithfully over long periods of time. In this special case, conditions reflected by eddy current reactions as electrons transit metal surfaces can be imaged with remarkable clarity. Typical images enlarged 30X show detail approaching a few micrometers in dimensions.

Appendix I

Electromagnetic Induction Non-Destructive Tests

Principle of Operation:

Electromagnetic induction non-destructive tests are characterized by the induction of varying electrical currents in the test object by means of repeated variations in an electromagnetic field. This method contrasts with the electric current conduction tests in which current flows into the test object through direct electrical contacts from an external source. No input contacts are required with induction-type tests. The induced current in the test object produces

differences in electrical potential, magnetic fields, and heat or temperature gradients. When alternating or varying currents are induced in ferromagnetic materials, heat is produced not only by ohmic losses proportional to the square of the current density, but also by hysteresis losses in the magnetic material. The total "iron" losses, composed of both eddy current losses and hysteresis losses, are sometimes employed to indicate material properties. The pick-up may detect variations in electrical potential distribution, in magnetic field strengths, in high-frequency electromagnetic wave properties, in temperature, in mechanical force or torque, or in losses in the material of the test object, or combinations of these factors. A large number of patents cover tests of these types (Tables III and IV).

Potential Pick-up Methods:

Electromagnetic induction tests with potential contact pick-ups were proposed for testing of lead-sheathed cables and other tubular conductors by Atkinson (U.S. Patent Reissue 21,853) and Edgar (U.S. Patent 2,186,826). The method has not been too popular, however, because it is difficult to screen the pick-up circuit from the exciting electromagnetic field variations. Both Atkinson and Edgar proposed methods of introducing suitable neutralizing or compensating voltages in the pick-up circuit, 180 deg. out of phase with the disturbing emfs. Braddon (U.S. Patent 2,074,739) provided a method of locating the flaws in cable sheaths with a suitable indicator. Knerr (U.S. Patent 2,124,577) also included the use of potential pick-ups in his method for testing tubes and cylindrical objects.

Magnetic Field Distortion Pick-up Methods:

The detection of flaws by measurement of distortion in electromagnetic fields (which would have uniform intensity in the absence of flaws) has found wide use. Chappuzeau and Emersleben (U.S. Patent 1,782,462) employed a series of coils whose turns were parallel to the surface of test objects, such as tubes, bars, and rails, to detect deviations from normal magnetic field distributions. They further employed tuned output and input circuits to obtain optimum response to harmonic signals. Stein (U.S. Patent 1,992,100) proposed tube- and bar-testing apparatus which consists of main exciting coils which set up a normally neutral zone in the fields between them, and a test

coil located in the neutral zone, whose output actuates an indicator such as a cathode-ray tube.

Several arrangements of exciting and pick-up coils, including those in which the exciting coil is placed within the tube and the pick-up coils are placed outside the tube, were patented by David (U.S. Patent 2,065,118). He also employed electronic amplification of pick-up signals, with provision for permanent records or for marking the test object. In U.S. Patent 2,065,119, he points out that voltages induced by distortion of the magnetic fields are exceedingly minute, often as low as one-millionth of a volt. Also, a variation of 0.0001 in. in the position of the detector element from its true electrical center in the exciting field can produce comparable signals. Furthermore, as the article being tested moves through the exciting field, its motion tends to deflect the electrical center of the system in the direction of its travel. Precision adjustments of coil locations are essential to correct these difficulties.

A simple means for testing interior surfaces of tubes was proposed by Greenslade (U.S. Patent 2,104,646), and consisted of search coils connected in a Wheatstone bridge circuit.

Hay (U.S. Patent 2,150,922) produced longitudinal a-c. magnetization in cylindrical test objects which were then rotated past a fixed pick-up coil to reveal flaws. The depth of flaw penetration was estimated by varying the exciting frequency or by providing d-c. saturation of ferromagnetic materials, so as to vary the depth of penetration of eddy currents. A cathode-ray tube was used as an indicator.

In U.S. Patent 2,162,710, Gunn showed a small probe containing exciting coils and pick-up coils located so as to be sensitive only to distortions in eddy current flow in the test object. The pick-up signal was synchronously rectified so that it might actuate a sensitive d-c. galvanometer. An automobile tire nail detector patented by Wages (U.S. Patent 2,502,626) employed a vacuum tube amplifier and place circuit meter to detect magnetic field distortion.

A third harmonic in the pick-up signal was found responsive to flaws in test objects excited uniformly with a 60-cycle magnetic field, by Sams and Moriarty (U.S. Patent 2,007,772).

Michel (U.S. Patent 2,489,920) used vacuum tube phase discriminator circuits to actuate neon indicators and relays in a metal detector for use in manufacturing linoleum. Bovey (U.S. Patent 2,495,627) used a rectifier bridge to convert unbalanced field signals to a d-c. meter deflection in his metal-object sorter.

Transformer Pick-up Methods:

Several tests have been proposed in which test objects form the cores of transformer arrangements. The primary coils are excited with sinusoidal alternating currents, and the secondary induced voltage magnitudes and wave shapes are examined to detect flaws or material properties. Kinsley (U.S. Patent 1,813,746) proposed the use of a magnetic oscillograph to examine such wave shapes, as well as the use of relays operating on the difference between secondary signals obtained from standard and unknown test objects such as tubes and bars. Billstein (U.S. Patent 1,958,079) proposed a rail tester in which the secondary signal is amplified and its magnitude suitably indicated. In U.S. Patent 2,084,274, he claimed improved sensitivity as a result of shunting the exciting and pick-up coils with suitable capacitors. Hallowell (U.S. Patent 2,010,189) employed a cathode-ray oscillograph with the exciting signal applied to one set of deflection plates, and the differential output signal (between standard and unknown test objects) applied to the second set of deflection plates. Ebel (U.S. Patent 2,111,210) used concentric exciting and pick-up coils of pancake form, located in a plane parallel to the surface of the cable sheaths under test. A similar arrangement was patented by Loewenstein (U.S. Patent 2,116,119), the inner pancake coil diameter being designed to intercept a component of flux greatly dependent upon the thickness of the sheet or tube being tested.

To detect small flaws by eddy current flow in magnetic tubes and bars, Knerr (U.S. Patent 2,124,577) rendered the material substantially nonmagnetic by subjecting it to a high degree of magnetic saturation with a saturating d-c. coil or strong permanent magnet. A transformer-type exciting and pick-up circuit arrangement was used to compare standard and unknown test objects. In U.S. Patent 2,124,579, he indicates that pick-up coils should have small dimensions comparable to those of flaws to be detected, for optimum sensitivity. A plurality of such small

coils, disposed over the surface of the test object, may be required for complete coverage.

Zuschlag arrives at similar conclusions in U.S. Patents 2,353,211 and 2,398,488, in which he proposes the use of small pick-up coils near the surface of a rotating specimen, and suggests several arrangements of circuit and detector. Canfield (U.S. Patent 2,245,568) also proposes to detect flaws by detecting variations in eddy current flow, but he uses the quadrature component of pick-up flux as a sensitive measure of changes in eddy current resistance. This component gives an indication which is relatively insensitive to changes in permeability of the article being examined.

Irwin (U.S. Patent 2,290,330) developed equipment for the simultaneous independent measurement and recording of a magnitude related to the phase angle between excitation and pick-up waves, and a second magnitude characteristic of the pick-up a-c. signal. Variation of leakage flux, as through a shunt transformer path, is employed by Thorne (U.S. Patent 2,311,715) to detect flaws which influence the permeability of rails.

DeLanty (U.S. Patent 2,315,943) proposed to concentrate the flux in tubular test objects by introducing low-resistance inserts within the tube at the point of testing. These high-conductivity inserts have induced in them large eddy currents which oppose the entry of magnetic flux into the insert, and presumably concentrate the flux in the tube wall under test.

High-Frequency Electromagnetic Wave Pick-up Methods:

Recent developments in ultra-high frequency sources, wave guides, oscillators, and detectors, particularly in wartime radar developments, have contributed new techniques to non-destructive testing. Because of the normal time lag before issuance of patents, only a limited number of such tests have been revealed. Two typical examples are given below:

Larrick (U.S. Patent 2,489,092) proposed the use of a high-frequency source and open-ended wave guide against which the surface of the test object is placed. Surface resistance and the thickness of nonconducting coatings are evaluated in terms of the resonant frequency of the wave-guide system.

Schlesman (U.S. Patent 2,491,418) proposed that the standard and unknown test objects be placed successively within or across the opening of a high-frequency cavity resonator. Changes in conditions of cavity resonance would detect test objects differing from the standard.

Magnetic Loss Pick-up Methods:

Burrows (U.S. Patents 1,676,632 and 1,686,679) proposed the use of pick-up coils adjacent to tubes and bars excited by an alternating electromagnetic field. The pick-up coils were connected to the moving coils of a dynamometer relay or meter whose fixed coils were connected in series with the exciting current, to obtain a measure of hysteresis losses in the test specimen. The signal was obtained from series-opposed pick-up coils, one coil being used with a standard specimen, and the second coil being used with the unknown specimen. The "duroscope," invented by Sams and Shaw (U.S. Patent 1,789,196-Reissue 18,889), provided magnetizing and pick-up coils in a single probe, and used a similar wattmeter arrangement to measure the iron losses in the area of cutting tools under the probe.

DeForest (U.S. Patents 1,897,634 and 1,906,551) provided means for measuring magnetic losses in sheets and tubes under different testing conditions such that the indication was influenced first by the combined electrical and magnetic properties of the material, and second, by a change in, and characteristic of, but one of the unobserved properties--; for example, the magnetic one. These measurements were correlated with stresses in the material, in U.S. Patent 1,906,551.

Electromagnetic induction tests in which plates and tubes were excited by a high-frequency field coil connected to a vacuum tube oscillator were employed by Kranz (U.S. Patent 1,815,717) and by Mudge and Bieber (U.S. Patent 1,934,619). The reaction of the test object (presumably the magnetic losses) was detected by changes in the amplitude of the exciting oscillations in the vacuum tube circuit.

Eddy current losses in the test object were employed to detune a high-frequency oscillator, one of whose harmonics was heterodyned with a different harmonic of a standard frequency signal to provide beat signals, in a rod tester described by Dana (U.S. Patent 1,984,465). Roop (U.S. Patent 2,055,672) placed stan-

dard and test bars in opposite sides of an inductance-type bridge circuit, whose unbalanced output signal was amplified and applied to a thyratron relay which operated suitable markers to indicate the location of defects on the test object.

Zuschlag (U.S. Patent 2,077,161) reveals the difficulties of compensating loss testers for variations (other than flaws) in test objects and standards, and for electromagnetic interference from extraneous sources, and proposes circuit improvements to reduce their undesirable effects. In U.S. Patent 2,098,991, he proposes an artificial standard circuit which introduces into the pick-up circuit signals corresponding to the indications of a standard test object, with which the indications of an unknown test object are automatically compared during testing. Further improvements in the detection circuit are shown in U.S. Patents 2,208,145, 2,329,810, and 2,329,811.

Kinsley (U.S. Patent 2,101,780) designed exciting coil assemblies which produced uniform flux densities over the test area in sheets, bars, and strips, so that eddy current and hysteresis losses (of importance in sheet materials for transformers, dynamos, and other electrical equipment) might be measured in a manner comparable to standard Epstein tests of specially cut samples.

Fermier (U.S. Patent 2,389,190) devised equipment whereby tubes and bars could be subjected to a series of exciting frequencies, each producing a different penetration of eddy currents. The voltage drop across the exciting coil (in the tank circuit of a vacuum tube oscillator) was registered, for each frequency, by a point on the screen image of a cathode-ray oscilloscope, so that the response to several test frequencies could be observed simultaneously. The indications have been correlated with properties, such as carbon content of material in the surface layers.

Thermal Pick-up Methods:

DeForest (U.S. Patent 1,869,336) described several arrangements of coils for induction heating of tubes and welds, whose temperature distribution was indicated by isothermals delineated by melting of stearin or other suitable temperature indicators. Some (U.S. Patent 2,340,150) proposed the use of high-frequency induction heating with heavy induced currents. As the induction-heated zone progressed

uniformly along the tube wall, the heavy currents, upon striking a high-resistance sand hole or pocket hidden from the surface by a layer of homogeneous metal, caused a burn-out resulting from fusion at the point, thus breaking down the wall of the tubular object and revealing the hidden defect.

Mechanical Pick-up Methods:

A novel method of detection was proposed by Burrows (U.S. Patent 1,599,645) in which a magnetizable test object was placed on a rotatable spindle in a three-phase rotating magnetic field. The torque developed in the object (which acted somewhat like the rotor of an induction motor) was measured by the displacement of the supporting spindle against a restraining spring, and was assumed to measure significant physical characteristics of the test object.

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SYMPOSIUM ON NON-DESTRUCTIVE TESTING

TABLE III.—PATENTS ON ELECTROMAGNETIC INDUCTION NON-DESTRUCTIVE TESTS.

Patent No.	Patent Date	Inventor	Assignee	Title	Number of Claims	Expired
1,599,645	1/26/24	Charles W. Burrows	Burrows Magnetic Equipment Co.	Method of Testing Magnetizable Objects	6	Yes
1,676,632	7/10/28	Charles W. Burrows	Magnetic Analysis Corp.	Method of and Apparatus for Testing Magnetizable Objects	36	Yes
1,686,679	10/ 9/28	Charles W. Burrows	Magnetic Analysis Corp.	Apparatus for Testing Magnetizable Objects	..	Yes
1,782,462	11/25/30	Helmut Chappuzeau and Otto Emersleben	Neufeldt und Kuhnke Betriebsgesellschaft	Arrangement for Testing Magnetizable Objects	8	Yes
1,813,746	6/ 7/31	Carl Kinsley	Magnetic Analysis Corp.	Method of and Apparatus for Magnetic Testing	8	No
1,815,717	7/21/31	Hermann E. Kranz	Western Electric Co.	Apparatus for Measuring Variations in Thickness of Metallic Bodies	3	No
1,869,336	7/26/32	Alfred V. de Forest		Thermal Method of Testing Metallic Bodies	23	No
1,897,634	2/14/33	Alfred V. de Forest	American Chain Co.	Method of and Apparatus for Electromagnetic Testing	30	No
1,906,551	5/ 2/33	Alfred V. de Forest		Magnetic Testing Method and Means	12	No
Re. 18,889	7/ 4/33	J. A. Sams and Virgil F. Shaw	General Electric Co.	Apparatus for Testing Metals	10	No
1,943,619	1/16/34	Wm. A. Mudge and Clarence G. Bieber		Method and Apparatus for Testing Materials	2	No
1,958,079	5/ 8/34	Arthur E. F. Bilstein	The Pennsylvania Railroad Co.	Method and Apparatus for Testing for Internal Flaws	21	No
1,984,465	12/18/34	David W. Dana	General Electric Vapor Lamp Co.	Method of and Apparatus for Detecting Structural Defects in Materials	15	No
1,992,100	2/19/35	Wilhelm Stein		Testing Flaws and the Like in Working Materials	8	No
2,007,772	7/ 9/35	J. A. Sams and Charles D. Moriarty	General Electric Co.	Magnetic Testing Apparatus	6	No
2,010,189	8/ 6/35	Howard T. Hollowell, Jr.	Standard Pressed Steel Co.	Means for Testing Metal	2	No
2,055,672	9/29/36	Harold D. Roop		Metal Testing Device	7	No
2,065,118	12/22/36	Archibald H. Davis, Jr.	Steel and Tubes, Inc.	Method and Apparatus for Testing Metals for Defects	9	No
2,065,119	12/22/36	Archibald H. Davis, Jr.	Steel and Tubes, Inc.	Flaw Detection	11	No
2,074,739	3/23/37	Fred D. Braddon	Sperry Products, Inc.	Indicating Device for Flaw Detector	5	No
2,077,161	4/13/37	Theo. Zuschlag	Magnetic Analysis Corp.	Magnetic Analysis Method	8	No
2,084,274	6/15/37	Arthur E. Billstein	The Pennsylvania Railroad Co.	Electrical Tester	64	No
2,098,991	11/16/37	Theo. Zuschlag	Magnetic Analysis Co.	Magnetic Analysis	8	No
2,101,780	12/ 7/37	Carl K. Westfield	U. S. Steel Corp.	Electromagnetic Testing of Materials	18	No
2,104,646	1/ 4/38	Grover R. Greenslade	Pittsburgh Dry Stencil Co.	Means for Testing	3	No
2,111,210	3/15/38	Lawrence C. Ebel	Anaconda Wire and Cable Co.	Apparatus for Determining Wall Thickness	7	No
2,116,119	5/ 3/38	Alfred Loewenstein		System for Electrically Measuring the Thickness of Metallic Walls, Sheets, and the Like	13	No
2,124,577	7/26/38	Horace C. Knerr and Alfred R. Sharples	Steel and Tubes, Inc.	Method and Apparatus for Testing Metal Articles	9	No
2,150,922	3/21/39	Donald L. Hay		Apparatus and Method for Detecting Defects in Electrically Conductive Objects	9	No
2,162,710	6/20/39	Ross Gunn		Apparatus and Method for Detecting Defects in Metallic Objects	23	No
2,186,826	1/ 9/40	Robert F. Edgar	General Electric Co.	Eccentricity Indicator	4	No
2,208,145	7/16/40	Theo. Zuschlag	Magnetic Analysis Co.	Magnetic Analysis	18	No
Re. 21,853	7/15/41	Ralph W. Atkinson	General Cable Co.	Method and Apparatus for Measuring Eccentricity	36	No
2,245,568	7/17/41	Robert H. Canfield		Method of and Apparatus for Examining Ferromagnetic Articles	12	No

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TABLE III.—PATENTS ON ELECTROMAGNETIC INDUCTION NON-DESTRUCTIVE TESTS (Continued).

Patent No.	Patent Date	Inventor	Assignee	Title	Number of Claims	Expired
2,290,330	7/21/42	Emmett M. Irwin	Magnetest Corp.	Method of and Apparatus for Testing Properties of Materials	..	No
2,311,715	2/23/43	Harold C. Ghorne		Apparatus for and Method of Detecting Flaws in Rails and Other Objects	26	No
2,315,943	4/ 6/43	Loren J. DeLanty	Sperry Products, Inc.	Means for Testing Tubes	2	No
2,329,810	9/21/43	Theo. Zuschlag	Magnetic Analysis Corp.	Electromagnetic Inspection	19	No
2,329,811	9/21/43	Theo. Zuschlag	Magnetic Analysis Corp.	Electromagnetic Inspection	19	No
2,334,393	11/16/43	Lyle Dillon	Union Oil Co.	Determination of Magnetic and Electrical Anisotropy of Formation Core Samples	10	No
2,340,150	1/25/44	Howard E. Somes	Budd Induction Heating, Inc.	Fault-Testing Articles of Electrically Conductive Material	3	No
2,353,211	7/11/44	Theo. Zuschlag	Magnetic Analysis Corp.	Electrical Analysis	3	No
2,389,190	11/20/45	George F. Fermier	Reed Roller Bit Co.	Testing Means	4	No
2,398,488	4/16/46	Theo. Zuschlag	Magnetic Analysis Corp.	Magnetic Analysis	4	No
2,489,092	11/22/49	C. V. Larrick	General Electric Co.	High-Frequency Surface Testing Instrument	6	No
2,489,920	11/29/49	F. C. Michel	General Electric Co.	Metal Detector	5	No
2,490,554	10/15/46	Harcourt C. Drake	Sperry Products, Inc.	Flaw Detector for Tubing	4	No
2,491,418	12/13/49	C. H. Schlesman	Socony-Vacuum Oil Co., Inc.	Automatic Inspection Device	2	No
2,495,627	1/24/50	D. E. Bovey	General Electric Co.	Method for Sorting Metallic Articles	1	No
2,502,626	4/ 4/50	Morris L. Mages	Magnaflux Corp.	Electronic Metal Detector	4	No

TABLE IV.—OPERATIONAL FEATURES OF PATENTED ELECTROMAGNETIC INDUCTION NON-DESTRUCTIVE TESTS.

Patent No.	Type of Energy Source	Form of Energy Input	Form of Energy Output	Type of Pick-up	Type of Detector	Type of Indicator	Quantity Measured	Required Accessibility	Typical Application
1,599,645	a-c. generator or transformer	Electromagnetic induction	Magnetic field	Torque	Torque indicator	Torque indicator	Torque	Outside only	Magnetizable objects
1,676,632	a-c. generator or transformer	Electromagnetic induction	Magnetic field	Induced emf. coils	Dynamometer-type instrument	Dynamometer-type instrument	Hysteresis losses	Outside or one side only	Bar and tube tester
1,686,679	a-c. generator or transformer	Electromagnetic induction	Magnetic field	Induced emf. coils	Dynamometer-type instrument	Dynamometer-type instrument	Magnetic losses	Outside or one side only	Tube and bar tester
1,782,462	a-c. generator or transformer	Electromagnetic induction	Magnetic field	Induced emf. coils	Tuned circuit and amplifiers	Galvanometer-type instrument	Eddy current distortion	Outside or one side only	Tube, bar, rail, and sheath tester
1,813,746	a-c. generator or transformer	Electromagnetic induction	Magnetic field	Induced emf. coils	Galvanometer-type instrument	Galvanometer-type instrument	Electrical signals	Outside only	Tube and bar tester
1,815,717	Vacuum tube oscillator	Electromagnetic induction	Magnetic field	Induced emf. coils	Grid circuit of vacuum tube oscillator	Plate current of vacuum tube oscillator	Magnetic losses	One side	Cable sheath or plate tester
1,869,336	a-c. generator or transformer	Electromagnetic induction	Thermal	Thermal	Stearin	Stearin	Temperature	One or two sides	Tube or weld tester
1,897,634	a-c. generator or transformer	Electromagnetic induction	Magnetic field	Induced emf. coils	Bridge circuit	Variable resistance	Magnetic losses	One side only	Wire, bar, plate, sheet, and tube tester
1,906,551	a-c. generator or transformer	Electromagnetic induction	Magnetic field	Induced emf. coils	Dynamometer-type instrument	Dynamometer-type instrument	Permeability and core losses	Outside	Measuring stresses and forces of magnetic materials
Reg. 18,889	a-c. generator or transformer	Electromagnetic induction	Magnetic field	Induced emf. coils	Dynamometer-type instrument	Dynamometer-type instrument	Eddy current losses	One side	Cutting tool tester
1,943,619	Vacuum tube oscillator	Electromagnetic induction	Magnetic field	Induced emf. coils	Vacuum tube oscillator	High-frequency milliammeter	Magnetic losses	One side	Plate and tube tester
1,958,079	a-c. generator or transformer	Electromagnetic induction	Magnetic field	Induced emf. coils	Vacuum tube amplifier	Ammeter	Magnetic field distortion	Top side of rail	Rail tester
1,984,465	Vacuum tube oscillator	Electromagnetic induction	Magnetic field	Induced emf. coils	Wheatstone bridge	Visual or auditory alarm	Eddy current distortion	Outside or one side only	Wire and rod tester
1,992,100	a-c. or d-c. generator	Electromagnetic induction	Magnetic field	Induced emf. coils	Wheatstone bridge circuit	Cathode-ray tube or other indicator	Magnetic field distortion	Outside or one side only	Tube, rod wire tester
2,007,772	a-c. generator or transformer	Electromagnetic induction	Magnetic field	Induced emf. coils	Vacuum tube amplifier	Visual or auditory alarm	Magnetic field distortion	Outside only	Strip, bar, or tube tester
2,010,189	a-c. generator or transformer	Electromagnetic induction	Magnetic field	Induced emf. coils	Vacuum tube amplifier	Cathode-ray oscilloscope	Magnetic permeability	Outside	Tube and bar tester
2,035,672	a-c. generator or transformer	Electromagnetic induction	Magnetic field	Induced emf. coils	Vacuum tube amplifier	Paint spray or marker	Magnetic losses	Outside	Tube and bar tester
2,065,118	Vacuum tube oscillator	Electromagnetic induction	Magnetic field	Two induced emf. coils	Vacuum tube amplifier and thyatron hook-up	Visual or auditory alarm	Magnetic field distortion	Inside and outside, or one side only	Tube tester
2,065,119	Vacuum tube oscillator	Electromagnetic induction	Magnetic field	Induced emf. coils	Vacuum tube amplifier and rectifier	Visual or auditory alarm	Magnetic field distortion	Outside	Plate, tube, and bar tester
2,074,739	a-c. generator or transformer	Electromagnetic induction	Magnetic field	Potential contacts	Vacuum tube amplifier	Recorder and visual indicator	Eddy current distortion	Outside	Cable sheath tester
2,077,161	a-c. generator or transformer	Electromagnetic induction	Magnetic field	Two induced emf. coils	Wheatstone bridge circuit	Voltmeter or potentiometers	Electrical signals	One side	Magnetic material tester
2,084,274	a-c. generator or transformer	Electromagnetic induction	Magnetic field	Two induced emf. coils	Vacuum tube amplifier	Ammeter	Eddy current distortion	One side	Rail tester
2,098,991	a-c. generator	Electromagnetic induction	Magnetic field	Induced emf. coils	Vacuum tube amplifier	Galvanometer-type instrument	Eddy current losses	Outside	Tube and bar tester

2, 101, 780 2, 104, 646	a-c. generator or transformer a-c. generator or transformer with or without rectifier	Electromagnetic induction Electromagnetic induction	Magnetic field Magnetic field	Induced emf. coils Induced emf. coils	Dynamometer-type instrument Wheatstone bridge circuit	Dynamometer-type instrument Ammeter	Magnetic losses Magnetic field distortion	Two sides e or side only	Sheet, tube, and bar tester Locomotive axle tester
2, 111, 210 2, 116, 119 2, 124, 577	a-c. generator or transformer a-c. generator or transformer a-c-d-c. generator	Electromagnetic induction Electromagnetic induction Electromagnetic induction	Magnetic field Magnetic field Magnetic field	Induced emf. coils Induced emf. coils Induced emf. coils	Voltmeter Ammeter Vacuum tube amplifier	Voltmeter Ammeter Pen on chart	Eddy current magnetude Magnetic permeability Magnetic permeability	One side only One side One side only	Cable sheath tester Metal sheet tester Conical and cylindrical objects primarily Tube and bar tester
2, 124, 579 2, 150, 922	a-c. or pulsating d-c. a-c. generator or transformer	Electromagnetic induction Electromagnetic induction	Magnetic field Magnetic field	Opposed induced emf. coils Induced emf. coils	Vacuum tube amplifier Cathode-ray oscilloscope or voltmeter	Cathode-ray oscilloscope or voltmeter	Eddy current distortion Eddy current distortion	One side only Outside	Tube and bar tester Tube and bar tester
2, 162, 710	Low-frequency a-c. generator	Electromagnetic induction	Magnetic field	Two coils responsive to asymmetrical distribution of electromagnetic field	Galvanometer and mechanical rectifier	Galvanometer-type instrument	Eddy current distortion	One side only	Metal objects tester
2, 186, 826 2, 208, 145 Re. 21,853	a-c. generator or transformer a-c. generator or transformer a-c. generator or transformer	Electromagnetic induction Electromagnetic induction Electromagnetic induction	Potential drop Magnetic field Magnetic field	Four potential contacts Induced emf. coils Potential contacts	Vacuum tube amplifier a-c. mixer and rectifier Galvanometer-type instrument or strip chart recorder	Strip chart recorder Galvanometer-type instrument Galvanometer-type instrument or strip chart recorder Voltmeter	Eddy current distortion Electrical signals Eddy current distortion	Outside Outside or one side only Outside only	Lead sheath tester Tube and bars tester Thickness tester
2, 245, 568 2, 290, 330	a-c. generator or transformer a-c. generator or transformer	Electromagnetic induction Electromagnetic induction	Magnetic field Magnetic field	Induced emf. coils Induced emf. coils	Quadrature flux emf. discriminator Vacuum tube amplifier	Voltmeter Strip chart recorder	Eddy current losses Phase angles between voltage and current Magnetic permeability	One side only Outside	Examine ferromagnetic articles Tube and bar tester
2, 311, 715 2, 315, 943 2, 329, 810 2, 329, 811 2, 334, 393 2, 340, 150 2, 353, 211 2, 389, 190	Transformer a-c. generator or transformer Vacuum tube oscillator Vacuum tube oscillator Vacuum tube oscillator Induction heating generator a-c. generator or transformer Vacuum tube oscillator	Electromagnetic induction Electromagnetic induction Electromagnetic induction Electromagnetic induction Electromagnetic induction Electromagnetic induction Electromagnetic induction	Magnetic field Magnetic field Magnetic field Magnetic field Magnetic field Thermal Magnetic field Magnetic field	Induced emf. coils Induced emf. coils Induced emf. coils Induced emf. coils Induced emf. coils Visual Induced emf. coils Induced emf. coils	Vacuum tube amplifier Vacuum tube amplifier Heterodyne circuit Visual Balancing system Cathode ray	Galvanometer-type instrument Cathode-ray oscilloscope Frequency meter Visual or auditory alarm Galvanometer-type instrument Cathode-ray oscilloscope	Eddy current losses Eddy current losses Eddy current losses Eddy current losses Magnetic permeability Temperature Eddy current distortion Eddy current losses	One side only Inside and outside Outside only Outside Outside only Inside only One side One side	Rail tester Tube tester Bar and tube tester Tube and bar tester Core sample tester Tube tester Tube and bar tester Test for carbon content of tubes and bars Tube and bar tester
2, 398, 488	a-c. generator or transformer	Electromagnetic induction	Magnetic field	Induced emf. coils	Wheatstone bridge and amplifier	Voltmeter	Magnetic losses	Outside or one side	

TABLE IV.—OPERATIONAL FEATURES OF PATENTED ELECTROMAGNETIC INDUCTION NON-DESTRUCTIVE TESTS (Continued).

Patent No.	Type of Energy Source	Form of Energy Input	Form of Energy Output	Type of Pick-up	Type of Detector	Type of Indicator	Quantity Measured	Required Accessibility	Typical Application
2,489,092	Ultra high frequency oscillator	High frequency electromagnetic waves	High frequency voltage or current a-c. magnetic field	Wave guide pick-up loop	Crystal rectifier	High resistance d-c. galvanometer	Wave guide resonance	One side only	Nonconducting test coating thickness
2,489,920	Electronic oscillator (150-5000)	Electromagnetic induction	Magnetic field	Opposed emf. coils	Vacuum tube phase discriminator	Neon lamps, relays	Magnetic field distortion	Outside or one side only	Linoleum manufacturing metal detector
2,490,554	a-c. generator or transformer	Electromagnetic induction	Magnetic field	Induced emf. coils	Vacuum tube amplifier	Voltmeter	Magnetic field distortion	Outside or one side only	Tube tester
2,491,418	High frequency electronic oscillator	Cavity resonator high frequency field	High frequency a-c. emf.	High frequency probe loop	Electronic amplifier detector	Strip chart recorder	Cavity resonance	Outside only	Sorting, geometry
2,495,627	Multiple-frequency audio oscillator	Electromagnetic induction	Magnetic field	Induced emf. coils	Rectified Wheatstone bridge	d-c. meter	Magnetic field distortion	Outside only	Metal object comparator
2,502,626	Electronic oscillator	Electromagnetic induction	Magnetic field	Opposed induced emf. coils	Vacuum tube amplifier	Plate circuit milliammeter	Magnetic field distortion	Outside or one side only	Automobile tire nail detector