CHAPTER I

Properties of Ferromagnetic Materials

Sometimes the best way to realize the value of any object is to try to imagine what would happen if it were taken away. If the iron and steel in dynamo-electric machinery, power and audio-frequency transformers, telephone receivers, relays, loudspeakers, and hundreds of other electromagnetic devices should suddenly lose their magnetic properties, these devices could no longer function properly. It is hard to imagine how without these materials new designs could be made within a reasonable range of space and cost. Obviously, any substance which permits a large flux density for a specified magnetizing force or which makes possible the constraint of flux to definite desired paths is bound to be of inestimable value to the designer. These properties are found in certain forms of iron and its alloys with cobalt, tungsten, nickel, aluminum, and other metals, which are called the *ferromagnetic materials.* Easy to magnetize, such substances when used for the cores of apparatus make possible flux densities which are hundreds or even thousands of times greater than could be conveniently established with a practical coil without the ferromagnetic core.

1. IMPORTANCE OF FERROMAGNETIC MATERIALS

The commercial importance of ferromagnetic materials is indicated by the thousands of tons produced annually, comprising a wide range of physical and magnetic properties. The materials are available commercially in numerous forms such as sheets a few thousandths up to about one-fourth inch thick, as wires a few thousandths up to about one-fourth inch in diameter, as bars of various cross-sectional shapes, and as castings weighing a few ounces up to several hundred tons for use in machines or other devices.

The fields of application of these materials, which are discussed briefly in Art. 6, are so broad and the requirements of each application are so different that engineers, physicists, and metallurgists have had to develop a wide range of ferromagnetic alloys, each having particular qualities valuable in specific applications. The value of these accomplishments can hardly be overestimated, and many of the recent, perhaps startling, developments in the design-technique of electrical machinery have arisen because better materials have been made available by metallurgical research and because the engineer has utilized physical and magnetic properties to better advantage. To emphasize this point, it should be noted that the basic electromagnetic phenomena in a modern

165,000-kva generator are the same as in a 5-kw Edison bipolar generator of a little more than half a century ago. The increase in capacity and the efficient performance achieved in the large machines are due in no small measure to the improvements in the magnetic and other physical properties of steels, and to a better understanding of these properties by engineers.

Engineering utilization of electrical devices containing ferromagnetic materials necessitates quantitative description of the circuit parameters representing the electric-circuit behavior of these devices. In the presence of ferromagnetic materials, an electric-circuit element has a resistance parameter which depends not only upon the magnitude of the current in the circuit but also upon the way in which it varies. The inductance parameter is not only nonlinear but is not even a single-valued function of the current. If in addition it varies with time, the difficulty of describing it exactly can be readily appreciated.

Before any quantitative studies can be made, quantitative data concerning the properties of the ferromagnetic materials must be available, and the manner of using these data toward the desired end must be clearly understood. The major portion of this chapter is therefore devoted to a discussion of the properties of the ferromagnetic materials of chief interest to the electrical engineer. Numerous quantitative data are given, which form a basis for the solution of magnetic-circuit problems to be treated in later chapters. As an aid to a better visualization of the phenomena involved, a theory of magnetism is described in the next article.

2. THEORY OF MAGNETISM[1]

The effort to explain the phenomenon of magnetism and to increase the understanding of many of the nonlinear properties observed for magnetic materials has produced many attempts at a theory of magnetism. One of the earliest was made by Ampère, who suggested about 100 years ago that the magnetization of a substance results from the orientation of molecules containing circulating currents. While Ampère's idea was too vague to be useful except as a philosophical concept, it came surprisingly close to being an introduction to the present theory, which during the past few years has been developed to the stage where it can explain numerous observed effects qualitatively, and some even quantitatively. In spite of these advances, however, developments in the theory still lag far behind the recent improvements in the magnetic properties of the materials used in industry. These improvements have

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[1] The subject matter of this article is taken largely from an excellent summarizing article by R. M. Bozorth, "Present Status of Ferromagnetic Theory," *A.I.E.E. Trans.*, *54* (1935), 1251-1261.

been achieved almost entirely as a result of empirical investigation, and only in comparatively recent times has the theory been developed to the stage where it can serve as a reliable guide to experimentation. Only the briefest qualitative statement of the present theory, which in its details includes many aspects of modern atomic and quantum theory, is given here.

Visualizing the magnetic behavior of actual samples of material in accordance with the present concepts of magnetism involves considering several different subdivisions of matter. The smallest particles concerned are the components of the atom; namely, the nucleus and its associated electrons. Next in size are the atoms. Larger than the atom are the domains, which are subcrystalline particles of varying shapes and sizes having a volume of about 10^{-9} cubic centimeter and containing about 10^{15} atoms. Widely varying numbers of domains are included in a crystal, and all but very special samples of magnetic materials contain many crystals.

2a. *Electrons and Nuclei.* — Magnetism is believed to be basically electrical. When an electric charge q moves with a velocity v, a magnetic field is set up as indicated in Fig. 1 in which v shows the direction of motion and P indicates the point at which $\mathcal{H}$ is to be determined. If the charge is positive, and if the velocity vector and the point P are in the plane of the paper, the direction of $\mathcal{H}$ is away from the reader perpendicular to the plane of the paper and its magnitude is

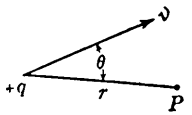

FIG. 1. Moving charge $+ q$ produces a magnetic field in the surrounding space.

$$\mathcal{H} = \frac{qv}{r^2} \sin \theta \qquad [1]$$

In the atom, electrons move in orbits about the heavier nucleus and at the same time each electron, as well as the nucleus, spins[2] about an axis of its own. A spinning electron or a spinning nucleus has a definite moment of momentum (angular momentum) and a definite magnetic moment. For the electron, these moments are in opposite directions and, for the nucleus, in the same direction. An electron in an atom has, in addition to its spin moments, a moment of momentum and a magnetic moment due to its motion in its orbit. The total magnetic moment of an atom is the vector sum of all its component magnetic moments.

2b. *The Atom.* — The latest atom model[3] as conceived by the physicists is pictured as a spinning nucleus composed of protons and neutrons surrounded by definite numbers of spinning electrons performing certain orbital motions. The simplest of the atoms is that of hydrogen having a

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[2] K. K. Darrow, " Spinning Atoms and Spinning Electrons," *B.S.T.J.*, *16* (1937), 319–336.

[3] L. B. Loeb, *Atomic Structure* (New York: John Wiley & Sons, 1938).

proton for its nucleus and a single orbital electron. The atom as a whole has a magnetic moment composed of three parts — the magnetic moment of the positive charge spinning on its axis, that of the negative charge spinning on its axis, and that produced by the negative charge moving in its orbit. The magnetic moment associated with the orbital and spin motions of the electron are of an order of magnitude one thousand times the magnetic moment of the spinning proton. Hence the magnetic effect of the nucleus is difficult if not impossible to detect in experiments with hydrogen atoms unless the magnetic moments of the electron can be in some way neutralized. This neutralization actually takes place in the hydrogen *molecule* since, in the combination of two atoms, the electron spins oppose each other as do the orbital motions. As might be expected, the two proton spins also oppose each other in some of the molecules (parahydrogen), while in the others (orthohydrogen) the proton spins line up in the same direction. Under ordinary conditions, about three-fourths of the molecules are of the ortho type.

According to the above discussion, parahydrogen should not have any magnetic moment at all, but experiments disclose for it the presence of a magnetic moment of the same order of magnitude as that of orthohydrogen but somewhat smaller. The explanation is that the rotating charges precess about the direction of applied magnetic field. An analysis of this precession shows that, regardless of the direction of orbital motion or spin, the precessional motion of all charges is such as to set up a field in opposition to the applied field. In the parahydrogen molecule, then, the only resultant magnetic effect is this weakening of the field due to the precessional magnetic moments. This effect is known as *diamagnetism.* Orthohydrogen has, in addition to this effect, a nuclear spin moment of somewhat larger magnitude.

When a single electron has been removed from the hydrogen molecule, the result is a singly charged hydrogen ion. Here the neutralization of spin and orbital magnetic moments has been destroyed, and the ion tends to align its orbital and spin magnetic moments in the direction of the applied field. This strengthening of the field is known as *paramagnetism.* Both diamagnetic and paramagnetic substances lose their magnetic effects when the external field is removed: the diamagnetic because the precessions about a fixed direction cease when the field is removed; and the paramagnetic because, without an external field, the magnetic moments are so oriented, as specified by quantum considerations, that their sum is zero. The atoms of the noble gases are diamagnetic and so also are certain ions such as Na^{+}, Mg^{++}, and Cl^{-}. The greater number of atoms and ions are paramagnetic.

The properties of the ferromagnetic substances are not determined entirely from their atoms, but the foregoing discussion indicates that the atom of chromium with six excess positive-spin electrons, the atom of iron with four, and the atom of cobalt with three should be good building blocks of which a highly magnetic solid might be built. The facts are, however, that when these atoms are assembled in crystalline structures, the spin orientations are such that chromium is nonferromagnetic, while iron, cobalt, nickel, and certain alloys are highly ferromagnetic. The determining feature[4] is the orientation of the atoms in the crystal lattice.

If this is such as to give a resultant magnetic moment, the material is ferromagnetic. If it is such that the vector sum of the magnetic moments is zero, the material is nonferromagnetic. The orientations in turn depend upon whether the lower potential energy of the crystalline assembly is achieved with the magnetic or the nonmagnetic orientation. Figure 2 shows a curve of the difference ΔW between the potential energy W_u of the unmagnetized arrangement and the potential energy W_m of the magnetized arrangement of atoms in the crystal versus the ratio of atomic separation r_a to the radius r_d of the orbit containing the excess positive-spin electrons. When ΔW is positive, the magnetized state is the stable one, because it is the state of lower potential energy. When ΔW is negative, the unmagnetized state is the stable one. Thus iron, cobalt, and nickel are ferromagnetic but manganese is not.

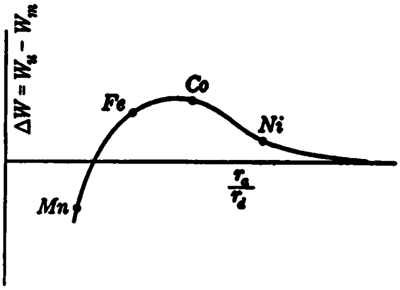

FIG. 2. For ferromagnetic substances, the potential energy of the crystal lattice is less when magnetized than when unmagnetized.

2c. *The Domain.* — The parallel locking of atomic magnetic moments in the crystalline structure extends throughout a limited but somewhat indefinite volume of a ferromagnetic crystal. The reason for this limitation is not completely understood, but experimental evidences are cited in the next article to show that, even when an iron crystal as a whole is unmagnetized, tiny neighboring regions called *domains* are completely magnetized. The individual regions, however, have their magnetic moments in different directions and these moments add to zero over the whole crystal.

▶ Any substance which is made up of these spontaneously magnetized and saturated domains is said to possess *ferromagnetism.*◀

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[4] W. Shockley, "The Quantum Physics of Solids — I," *B.S.T.J.*, *18* (1939), 645–723.

In the crystal structure within a domain, the atoms are arranged in definite orderly fashion. In the iron crystal,[5] for example, the atoms are at the corners of a cube with one at the center as shown in Fig. 3. This arrangement is called a *body-centered cubic lattice.* The grouping in a nickel crystal differs from this by having an atom in the center of each face but none at the center of the cube as shown in Fig. 4. This is called a *face-centered cubic lattice.* A domain in an iron crystal, in the absence of an external magnetizing force, has its atomic magnetic moments all lined up in a single direction, the direction of one of the edges of the cubic lattice. This is called a 100 direction or axis. A diagonal of a face represents a 110 direction. A diagonal of the cube represents a 111 direction and is the one taken by the atomic magnetic moments of the nickel domain.

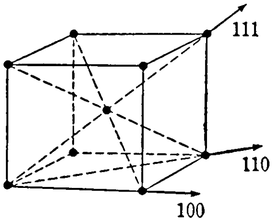

Fig. 3. Body-centered crystal lattice of iron.

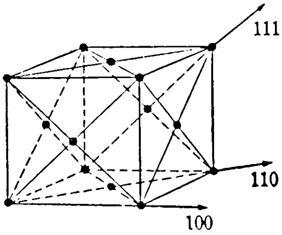

Fig. 4. Face-centered crystal lattice of nickel.

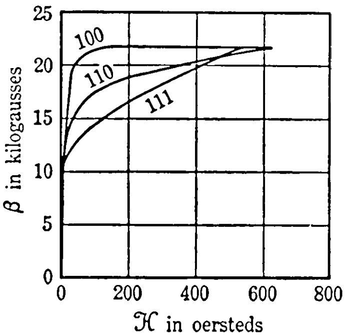

Fig. 5. Magnetization curves for an iron crystal in the directions 100, 110, and 111. *(From footnote reference 1.)*

2d. *The Crystal.* — For study of the behavior of a single crystal, specimens have been prepared which are large enough to be tested in the laboratory for their magnetic properties. When external fields are applied to an iron crystal along the 100 axis, the intrinsic* flux density β reaches a steady value at a small value of the external field $\mathcal{H}$, as shown in Fig. 5. This is explained by supposing that in the unmagnetized state, the domains have a random orientation in the six preferred directions in the crystal, as indicated in Fig. 6a. When the magnetizing force is applied along one of these directions, the domains having magnetic moments in the other five directions shift their moments into the direction of the

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[5] R. M. Bozorth, "The Physical Basis of Ferromagnetism," *B.S.T.J.*, *19* (1940), 1–39.

* Intrinsic flux density is defined on p. 21.

applied field, as indicated in Fig. 6b. This 100 axis is called the direction of easy magnetization. If the field is applied along a face diagonal 110, four of the six magnetic moments first shift to the two directions having components along 110 and then, with increasing field, the moments of all domains are gradually shifted to the field direction. The 110 direction is for an iron crystal the direction of medium magnetization. Finally, if the field is applied along a cube diagonal 111, three of the magnetic moments shift to the three directions having components along 111 and then a further increase in the field brings all the moments into the 111 direction, known as the direction of hard magnetization. The corresponding curves for nickel are shown in Fig. 7.

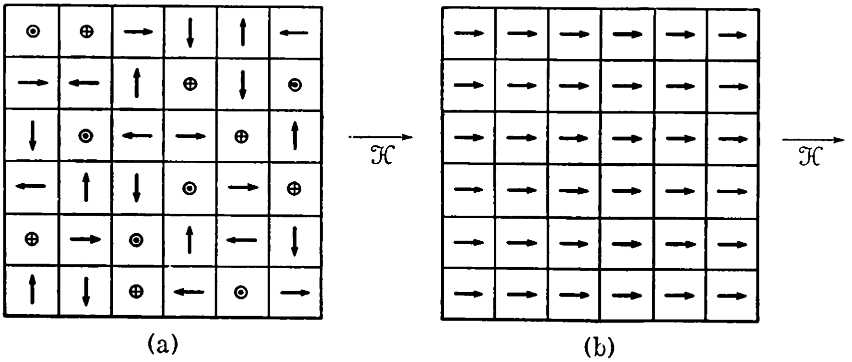


FIG. 6. (a) Domains have magnetic moments in all six 100 directions in an unmagnetized iron crystal; (b) in the same 100 direction when the crystal is fully magnetized in a 100 direction.

The presence of domains is indicated in a striking way by the photographs produced by W. C. Elmore and shown in Fig. 8. The three parts represent three exposures of the same portion of the surface of a cobalt crystal under three different conditions of external field. In Fig. 8a, the crystal is magnetized by the application of an external field; in Fig. 8b, the crystal has been demagnetized and in Fig. 8c the direction of the field has been reversed. The patterns are believed to be produced by the action of the magnetized domains upon a colloidal suspension of iron oxide which is placed on the surface of the crystal and viewed under a microscope. Such arrange-

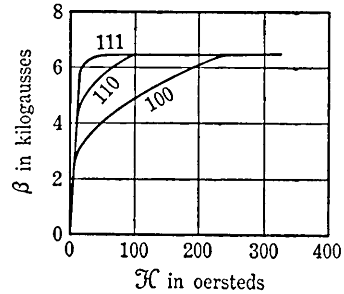
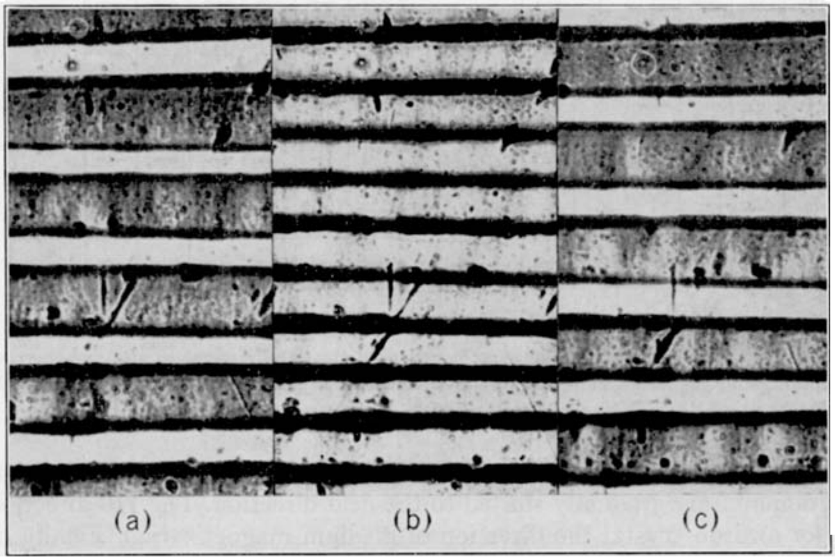


FIG. 7. Magnetization curves for a nickel crystal in the directions 100, 110, and 111. (*From footnote reference 1.*)

ments of the iron particles never take place on nonferromagnetic substances, but are produced by the spontaneously magnetized domains at the surface of an iron or a cobalt crystal even though the crystal as a whole is unmagnetized.



Courtesy W. C. Elmore.

FIG. 8. Powder patterns on a plane surface parallel to the direction of easy magnetization of a cobalt crystal (a) magnetized toward reader, (b) demagnetized, (c) magnetized away from reader.

2e. *Polycrystalline Substances.* — A polycrystalline sample of iron or of a magnetic alloy is composed of many crystals packed rigidly together but with no definite directional alignment of their axes. When no external field is applied, each domain in such materials is spontaneously and completely magnetized in one of its 100 directions. The magnetic moments of the domains in each crystal are distributed equally in the six directions of easy magnetization, with the result that each crystal is in the unmagnetized state. The random alignment of crystals produces a random distribution of magnetic moments throughout the material.

Imposing an external magnetic field is believed to result first in enlarging all domains having magnetic moments in the general direction of the applied field by reducing the size of adjacent domains whose magnetic moments are in less favorable directions. The effect of the supposed enlargement of domains on the magnetic state of the material as observed externally is very small, and predominates only for extremely small applied fields.

As the applied field is increased beyond the extremely small values, a second effect becomes noticeable, in which the magnetic moments of individual domains are aligned in the direction of the preferred crystal axis nearest to that of the impressed field. This effect takes place, not by realignment of the domain as a rigid body, but by realignment of the axes of the spins of the individual electrons within the domain from one stable direction to another stable direction. Throughout any one domain, this realignment of spins takes place simultaneously. As the field continues to be increased from the very small values, the flux density $\mathcal{B}$ is observed experimentally to increase by finite jumps, each increase corresponding to the realignment of spins in one domain. This stepwise buildup, known as the *Barkhausen effect*, is illustrated by the magnified portion of the curve of Fig. 9. Of course, these steps do not occur in any curve actually plotted from experimental data, but the fact that the change in magnetization occurs in jumps can be observed by means of a loudspeaker connected to a coil surrounding the specimen, as shown in Fig. 10. Each reorientation of a domain suddenly changes the flux through the pickup coil and causes a click in the loudspeaker.

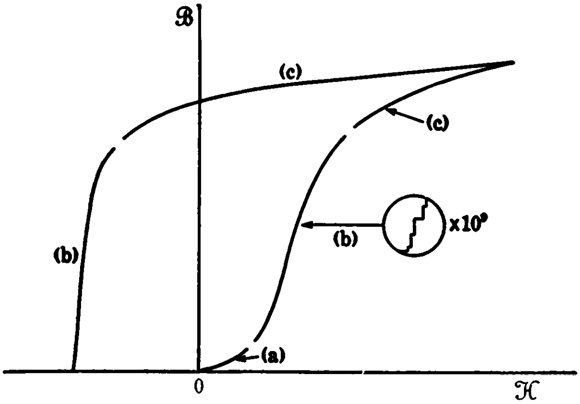


FIG. 9. The three regions of magnetization: (a) boundary displacement, (b) sudden change in orientation, and (c) slow change in orientation. (*From footnote reference 1.*)

Because of the great number of crystal edges not parallel to the direction of the applied field, a third effect becomes apparent with externally applied magnetizing forces greater than those required to align the domain moments along the crystal edges most nearly parallel to the applied field vector. This last mode of magnetization consists of a smooth orientation of all domain moments from the position in line with the crystal edges to the position in line with the direction of the applied field. No sharp demarcation exists between regions (b) and (c) of the curve but the sudden jumps become less frequent as saturation is approached.

The above phenomena can be summarized briefly as follows: When a gradually increasing, but small, magnetizing force is applied to a mass of initially unmagnetized iron, the first mode of magnetization that predominates is caused by the slight growth in the size of domains magnetized in the direction most nearly parallel to the applied field, at the expense of the size of neighboring domains. A small amount of magnetization builds up, and the increase takes place smoothly. The portion of the magnetization curve for which this phenomenon occurs is marked (a) in Fig. 9. As the magnetizing force is increased further, a second mode of magnetization predominates, which is caused by the sudden alignments of groups of spins along the crystal axes most nearly parallel to the impressed field. The region for which this phenomenon principally occurs is marked (b) in Fig. 9. For values of magnetizing force larger than those for which a pronounced Barkhausen effect occurs, the final mode of magnetization predominates. This mode is described as a slow rotation or alignment of the domains into the direction of the field and away from the crystal axes nearest in line with the applied field. The region for which this mode principally occurs is marked (c) in Fig. 9. The first and last modes result in a much smaller change in flux density for a given change in magnetizing force than does the intermediate mode. During the last mode, the iron is becoming magnetically saturated, and, when all the domain moments are aligned in the direction of the applied field, the material is fully magnetized.

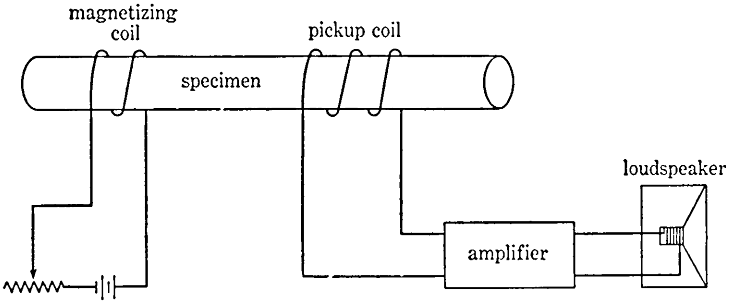


FIG. 10. Circuit connections for demonstration of Barkhausen effect.

Ferromagnetic materials can be magnetized up to intrinsic flux densities ranging from 5,000 to 25,000 gausses, have relative permeabilities of the order of hundreds or thousands, exhibit a pronounced saturation effect, and retain some of their magnetism when the field is removed. Paramagnetic substances have very small positive relative permeabilities and lose all their magnetism when the external field is removed. Diamagnetic substances also respond weakly to magnetization, but their relative permeabilities are less than unity.

Just as the crystal of chromium is nonmagnetic* even though its atom has six uncompensated positive spins, the crystal lattice of iron alloyed with certain other elements may not have pronounced ferromagnetic properties. Alloys of this kind frequently encountered are certain manganese and stainless steels. Specifically, an alloy comprising about 0.3 per cent carbon, 10 per cent manganese, 6.5 per cent nickel, and the remainder iron is essentially nonmagnetic at room temperature. Curiously, however, certain alloys called Heusler alloys, formed from essentially nonmagnetic materials, are observed to exhibit strong magnetic properties. The most highly magnetic of these contains approximately 65 per cent copper, 20 per cent manganese, and 15 per cent aluminum. The best specimens can be magnetized about as easily as low-grade iron. Although they have not found any extensive commercial utilization at the present time, they have properties of marked interest in the development of theories of magnetism.

The preceding remarks concerning the phenomena of magnetization apply chiefly to single ferromagnetic crystals and isotropic assemblies of these crystals in an unstrained condition. A sample of iron comprising many crystals oriented wholly at random and free from strains has properties that are an average or composite of magnetization in all directions of a single crystal. Frequently, however, the polycrystalline ferromagnetic materials used in engineering are not strain free, nor are they isotropic; that is, their crystal axes are not always distributed equally in every direction. Rolled sheet steel is a good illustration of this condition and frequently exhibits widely different magnetic properties for different directions of magnetization.†

The subject of strains is closely connected with certain aspects of ferromagnetic theory. For instance, the magnetic forces in a crystal occurring as a result of the spins of the electrons are balanced by the electric forces occurring as a result of the electric charges on the electrons. When a rearrangement of the magnetic vectors occurs, the balance between the magnetic and electric forces is disturbed. Consequently, the physical dimensions of the material are observed to vary. This phenomenon is one of many effects which have to do with strains, mechanical or magnetic, and are referred to collectively as *magnetostriction.* The magnetostrictive properties of iron are opposite to those of nickel. The effect of mechanical tension on iron is to increase the magnetization for a specified magnetizing force, whereas the effect of mechanical compression is to decrease it. With nickel, the effect of tension is to decrease the magnetization for a specified magnetizing force, whereas the effect of compression is to increase it. With iron, the length of the material

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* See p. 7.

† See footnote 1, Ch. III.

increases as the magnetization is increased (positive magnetostriction), whereas with nickel the length decreases (negative magnetostriction). The limiting values of magnetostriction occur simultaneously with the magnetic saturation of the material. The curve of Fig. 11 shows the saturation magnetostriction properties of the iron-nickel alloys commonly known as Permalloys.

Strains are produced in a material in several ways, such as by cold working, by the presence of impurities in the material which give rise to crystal lattice distortion (chemical strain), or by magnetostriction (latent or residual strain). Where permanence of magnetization is desired, high internal strain is beneficial, because the larger the strain the more stable is the direction of the magnetization of the domain. This condition is well borne out in permanent magnets, which frequently exhibit magnetic hardness simultaneously with the physical hardness that is typical of a metal with large internal strain.

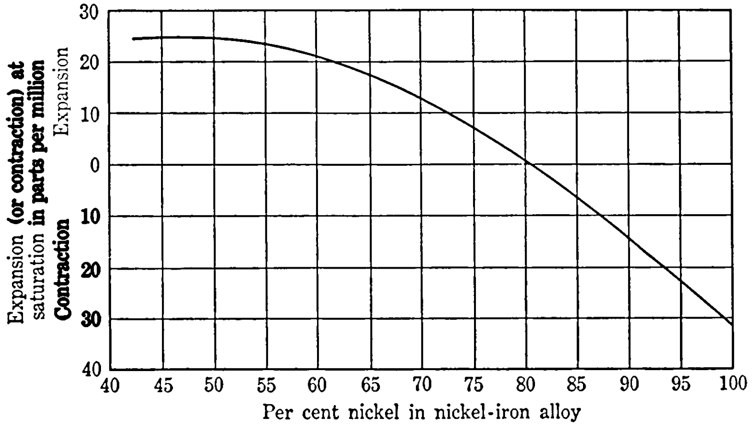

Fig. 11. Saturation magnetostriction of the nickel iron alloys. (*From footnote reference 1.*)

On the other hand, when ease of magnetization is desired — that is, when a material is to have a large permeability — negligible internal strain or magnetostrictive effect is desirable. This condition is well illustrated by the data of Fig. 11, since the nickel-iron alloys which show small magnetostriction exhibit large permeabilities. Actually, the largest relative permeability thus far obtained, about 600,000, occurred when an alloy of 65 per cent nickel and 35 per cent iron was heated first in hydrogen for 18 hours at about 1,400 degrees centigrade to remove the nonmetallic impurities and to relieve the chemical strain and next at about 650 degrees for one hour, and then was cooled in hydrogen under the influence of a field intensity of about 16 oersteds. This treatment appears to have oriented the directions of the magnetostrictive strains (latent or residual strain) so as to give the easy axes of magnetization in the direction of the applied field.

3. GENERAL PROPERTIES OF MAGNETIC MATERIALS

At present, the scope of the theory of magnetism is insufficient to allow prediction of the magnetic properties of materials on purely theoretical considerations, even when the composition of the material is accurately known. This insufficiency of the theory is not a very serious disadvantage, for even were such a prediction possible the procedure involved in the prediction would probably not be sufficiently simple to find extensive use. The customary procedure for determining the properties of magnetic alloys is to make measurements of each property on samples of each kind of material manufactured. Frequently, a few measurements are made at the mill on samples drawn from each batch as manufactured. The data so obtained are then used to prepare characteristic curves for the particular material. Finally when the material is fabricated into various forms for inclusion as constituent elements of a particular device, the performance of the device, or its parameters as a circuit element, can usually be computed from these characteristic curves with an accuracy sufficient for most engineering purposes.

Ferromagnetic materials are characterized by one or more of the following attributes:

(a) **They can be magnetized much more easily than other materials. This characteristic is indicated by a large relative permeability μ/μ_0.**
(b) They have a high maximum intrinsic flux density β_{max}.
(c) They are magnetized with widely different degrees of ease for different values of magnetizing force. This attribute leads to a nonlinear relation between flux density $\mathcal{B}$ and magnetizing force $\mathcal{H}$.
(d) An increase in magnetizing force produces in them a change in flux different from the change produced by an equal decrease in magnetizing force. This attribute indicates that the relationships expressing the flux density and the permeability μ as functions of magnetizing force are nonlinear and multivalued.
(e) They retain magnetization when the magnetizing force is removed.
(f) They tend to oppose a reversal of magnetization after once being magnetized.

The degree to which certain of these characteristics are important in particular applications of magnetic materials depends upon the circumstances encountered in each application.

Of the materials available, iron finds the most extensive use. Its permeability is large and its cost per pound is least of all the ferromagnetic materials available. In its commercially pure form, it is used frequently in the structures of numerous machines. It is used also as the base element for practically all the ferromagnetic alloys. Probably the alloy produced in the largest quantity is that composed of essentially pure iron and between 1 and 4 per cent of silicon, depending upon the purpose for which the material is required. When this alloy is given a particular heat treatment, a material is obtained which, compared with iron, has better magnetic properties at low values of magnetizing force and larger resistivity. As shown later, both these properties are desirable. This alloy is rolled into sheets and strip, principally in the thickness range 0.014 to 0.025 inch, and annealed; it is designated in the trade literature as silicon steel sheets and strip. The sheet form is convenient for punching into many shapes used in the construction of electromagnetic apparatus. Typical shapes of punchings are shown in Fig. 12.

The silicon sheet steels used in the electrical industry are known among steel manufacturers[6,7] and electrical designers by certain descriptive names.

Field grade sheets contain about one-fourth of 1 per cent silicon and have a resistivity of about 16 microhm-centimeters. This grade is used for small low-priced motors.

Armature grade sheets contain about one-half of 1 per cent silicon and have a resistivity of about 19 microhm-centimeters. This grade is relatively soft and for this reason easy to punch. It is used in small motor and generator field poles, armatures, and other devices in which high flux densities are required but core losses are not of great importance.

Electrical grade sheets contain about 1 per cent silicon and have a resistivity of about 26 microhm-centimeters. This grade is widely used in commercial motors and generators of small and moderate sizes and medium efficiencies, and in transformers, relays, and other devices designed for intermittent operation.

Motor grade sheets contain about 2.5 per cent silicon and have a resistivity of approximately 42 microhm-centimeters. This material is used in medium-size motors and generators of good efficiencies, in control apparatus, and in inexpensive radio transformers.

Dynamo grade sheets contain about 3.5 per cent silicon and have a resistivity of about 50 microhm-centimeters. This grade is used in high-

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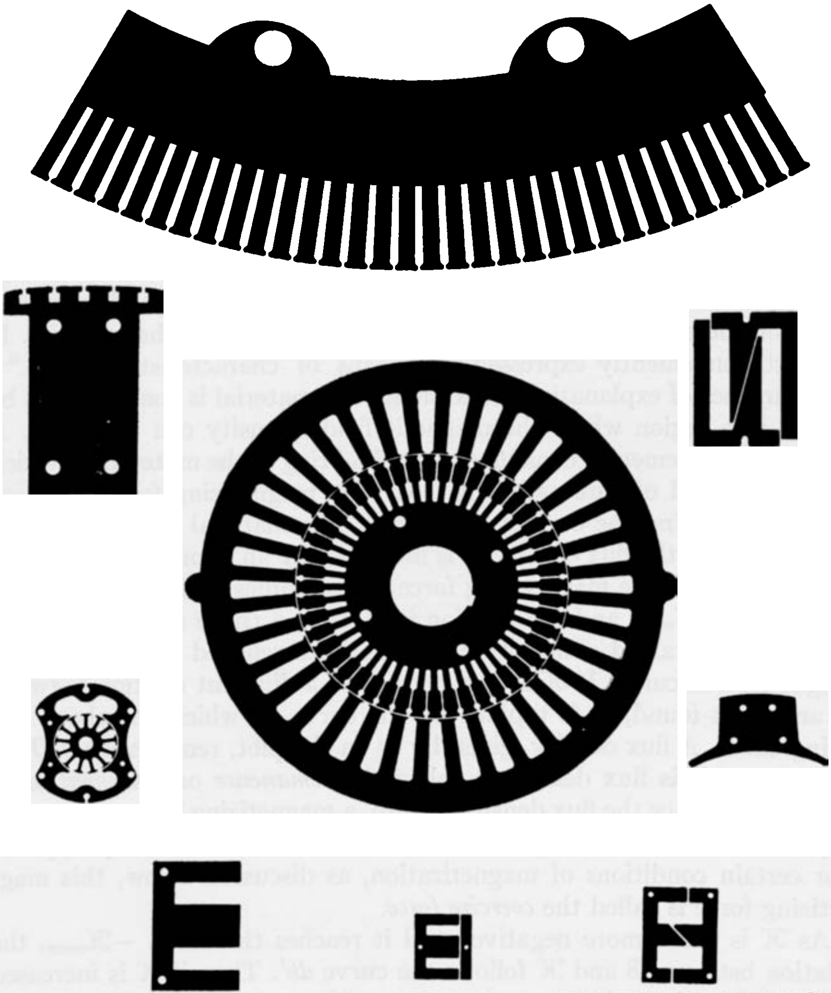
[6] Carnegie-Illinois Steel Corporation, Pittsburgh, Pa., *Electrical Steel Sheets, Technical Bulletin No. 2* (1941).

[7] Allegheny Steel Co., Brackenridge, Pa., *Magnetic Core Materials Practice* (1937).

efficiency motors and generators, small power-distribution transformers, and radio transformers.

Several *transformer grades* are available, the principal ones being designated 72 (radio C), 65 (radio B), 58 (radio A), and 52. The numbers are the core losses of 29-gauge sheets in hundredths of watts per pound at 60 cycles per second as found by the standard Epstein test described in Ch. V. The silicon content increases as the losses decrease. These sheets are used primarily for power and radio transformers, and for large high-efficiency alternators, motors, and synchronous condensers.



Courtesy Carnegie-Illinois Steel Corp.

FIG. 12. Typical lamination punchings.

Because of the multitude of ferromagnetic alloys available at the present time, to mention the properties of more than a few of those frequently encountered would be impractical. Certain properties of a selected group of the more common alloys, and some of their fields of usefulness are discussed in Art. 6; but, before these matters are considered, the properties of the magnetization curves of typical ferromagnetic materials when subjected to a direct magnetizing force will be investigated more fully.

4. CHARACTERISTICS AND MAGNETIZATION CURVES OF MAGNETIC MATERIALS

The relation between the magnetizing force $\mathcal{H}$ and the flux density or magnetic induction $\mathcal{B}$ which it produces in a ferromagnetic material is of considerable importance in the engineering uses of the material. It is most conveniently expressed by means of characteristic curves.[8, 9] For purposes of explanation, a ferromagnetic material is considered to be placed in a region where the magnetic field intensity can be varied. A possible arrangement[10] consists of a toroidal ring of the material on which is wound a coil of wire as in Fig. 13a. The magnetizing force is varied through changing the current in the coil. The material is originally demagnetized. If the flux density $\mathcal{B}$ is measured by an appropriate method, as a function of the magnetizing force $\mathcal{H}$ for values of $\mathcal{H}$ up to a maximum, say $+\mathcal{H}_{max}$, and the relation is plotted, a curve similar to *oab* of Fig. 13a is obtained. This curve is sometimes referred to as the *rising* magnetization curve. If $\mathcal{H}$ is now decreased, a different relation between $\mathcal{B}$ and $\mathcal{H}$ is found, as is typified by the curve *bc*, which lies above the rising curve. A flux density, given by *oc* on the plot, remains when $\mathcal{H}$ is made zero. This flux density is called the *remanence* or *remanent magnetism*. To reduce the flux density to zero, a magnetizing force *od* must be applied in the direction opposite to that of the force formerly applied. For certain conditions of magnetization, as discussed below, this magnetizing force is called the *coercive force*.

As $\mathcal{H}$ is made more negative until it reaches the value $-\mathcal{H}_{max}$, the relation between $\mathcal{B}$ and $\mathcal{H}$ follows the curve db'. Then if $\mathcal{H}$ is increased from $-\mathcal{H}_{max}$ through zero to the value $+\mathcal{H}_{max}$, the curve follows a path such as $b'c'd'e$. The point *e* differs from the point *b* by a small amount, and the path does not yet form a closed loop. If $\mathcal{H}$ is varied through

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[8] F. Bitter, *Introduction to Ferromagnetism* (New York: McGraw-Hill Book Co., Inc., 1937).

[9] Carnegie-Illinois Steel Corporation, Pittsburgh, Pa., *Electrical Steel Sheets, Technical Bulletin No. 2* (1941).

[10] Thomas Spooner, *Properties and Testing of Magnetic Materials* (New York, McGraw-Hill Book Co., Inc., 1927), Chs. xv and xvii.

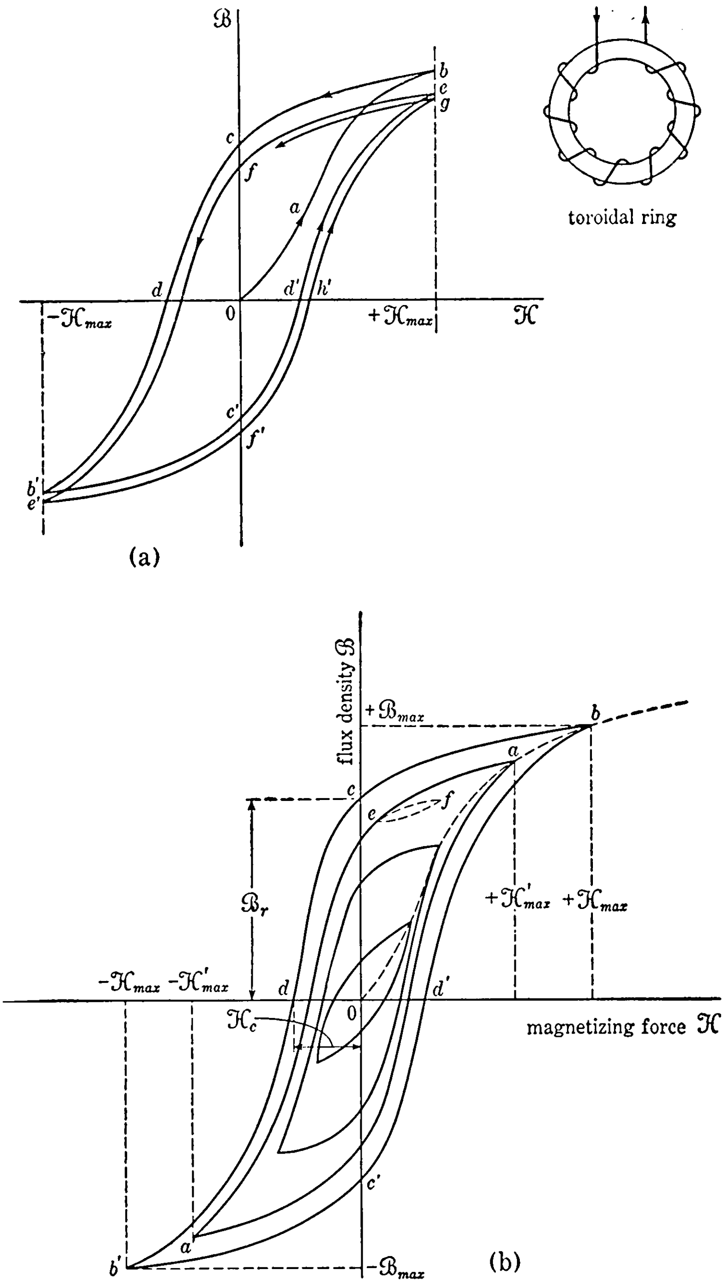

FIG. 13. (a) $\mathcal{B}(\mathcal{H})$ curves from initially unmagnetized sample. (b) Typical hysteresis loops.

another cycle between the same limits of $\mathcal{H}$, the relation between $\mathcal{B}$ and $\mathcal{H}$ follows the path *efe′f′h′* to *g*. As the variation in $\mathcal{H}$ is carried through additional identical cycles, the path gradually approaches a fixed curve. Finally, after many cycles the path becomes a closed loop, as indicated by the loops of Fig. 13b. If the positive and the negative values of $\mathcal{H}_{max}$ are equal, the loop is symmetrical about the origin. The steel is then in its symmetrically cyclically magnetized condition, sometimes abbreviated to *cyclic condition,* for the particular numerical value $\mathcal{H}_{max}$.

Mention has already been made that the values of $\mathcal{B}$ on the falling curve are greater than those on the rising curve. Thus the material has the property of tending to oppose a change in the value of the flux density. This property is known as *hysteresis*, which is a term meaning *a lagging behind.* The closed loop obtained when the magnetizing force is taken through a complete cycle of values is known as a *hysteresis loop.* Although the word hysteresis implies a time lag, the hysteresis phenomenon does not depend on time but only on whether the magnetizing force is decreasing or increasing. If at any instant the magnetizing force is raised to a new value, and the magnetic material is not jarred, the flux density apparently never increases above or settles below its new initial value. The hysteresis phenomenon results in a dissipation of energy, called *hysteresis loss*, within the material when cyclic variations of magnetizing force are considered. The distinction between hysteresis loss and the above hysteresis phenomenon is explained in Ch. V.

If the magnetic material is subject to a cycle involving smaller values of $\mathcal{H}$ and $\mathcal{B}$, as from $+\mathcal{H}'_{max}$ to $-\mathcal{H}'_{max}$, a smaller hysteresis loop *aa′a*, Fig. 13b, is obtained. If the magnetizing force is not varied continuously in one direction between the maximum values of $\mathcal{H}$, small internal loops are introduced. If, for example, after descending from point *a*, Fig. 13b, to *e* at which $\mathcal{H}$ is equal to $\mathcal{H}_e$, $\mathcal{H}$ is increased to $\mathcal{H}_f$ and then brought back to $\mathcal{H}_e$, a loop *ef* is introduced into the curve.

When the properties of different magnetic materials are compared, some of the properties are denoted by special terms. Those of major interest in this part of the treatment are (a) remanence, (b) residual flux density or residual induction, (c) retentivity, (d) coercive force, and (e) coercivity. The usually accepted definitions[11] of these terms are as follows:

(a) *Remanence* is the flux density, or magnetic induction, which remains in a magnetic material after the removal of an applied magnetizing force.

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[11] These definitions are in substantial agreement with the definitions of the American Society for Testing Materials standards A 34.

(b) *Residual flux density,* or *residual induction* $\mathcal{B}_r$, in a magnetic material is the value of the flux density for the condition of zero magnetizing force, when the material is being symmetrically cyclically magnetized. It is distinguished from *remanence* by the symmetrically cyclic requirement.

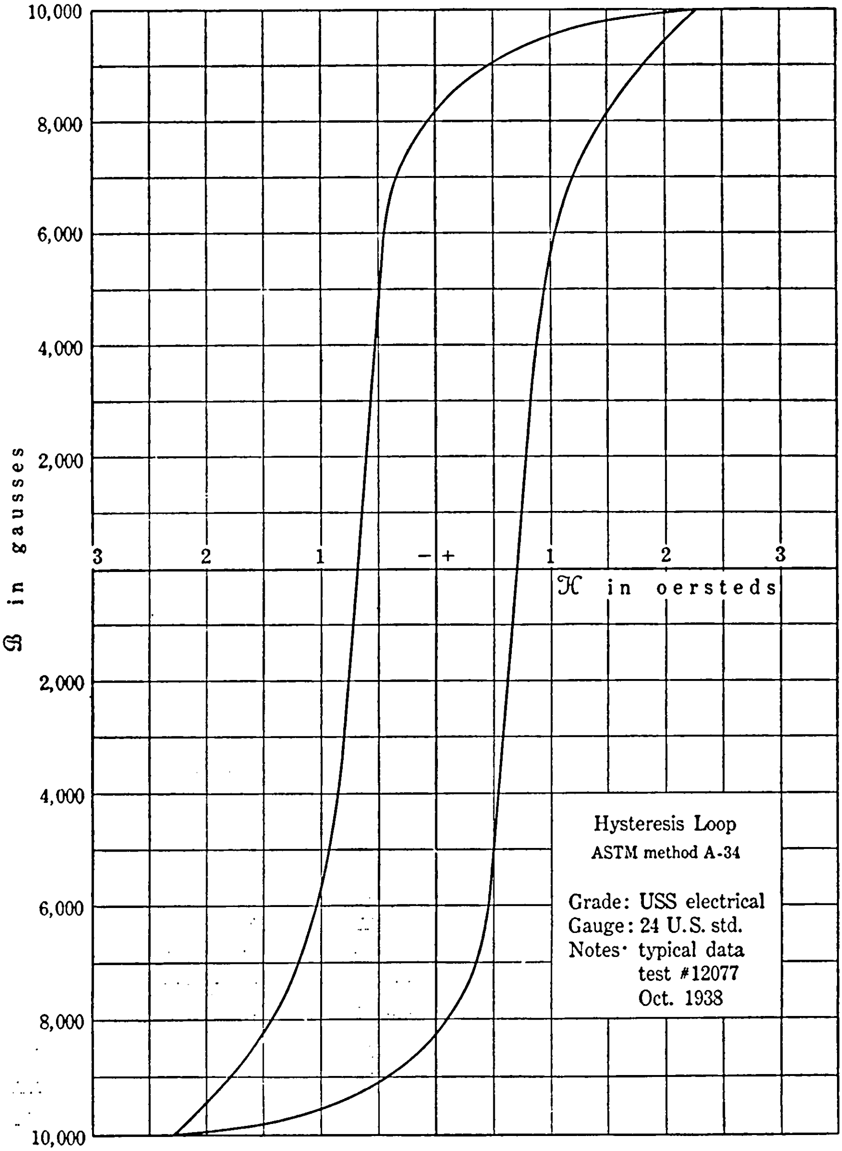
(c) *Retentivity* is the flux density that remains in the material after a magnetizing force sufficient to cause saturation flux density or saturation induction has been removed.

(d) *Coercive force* $\mathcal{H}_c$ for a magnetic material is the magnitude of the magnetizing force at which the flux density is zero when the material is being symmetrically cyclically magnetized.

(e) *Coercivity* is the coercive force required to reduce the flux density in the material to zero from a condition corresponding to saturation flux density or saturation induction.

The foregoing discussion shows that the flux density associated with a given magnetizing force is not single valued. It can have any value between certain limits, depending on the history of the material. In many magnetic problems, the history of the material is unknown. Existing magnetization may then have occurred by an increase of the magnetizing force from a small value up to the value under consideration, or by a decrease from a larger value. Many magnetic calculations are therefore performed using a magnetization curve, called *the normal magnetization curve,* which is obtained by drawing a single-valued curve through the tips of a series of increasingly larger symmetrical hysteresis loops. Such a curve is shown as *oab* in Fig. 13b.

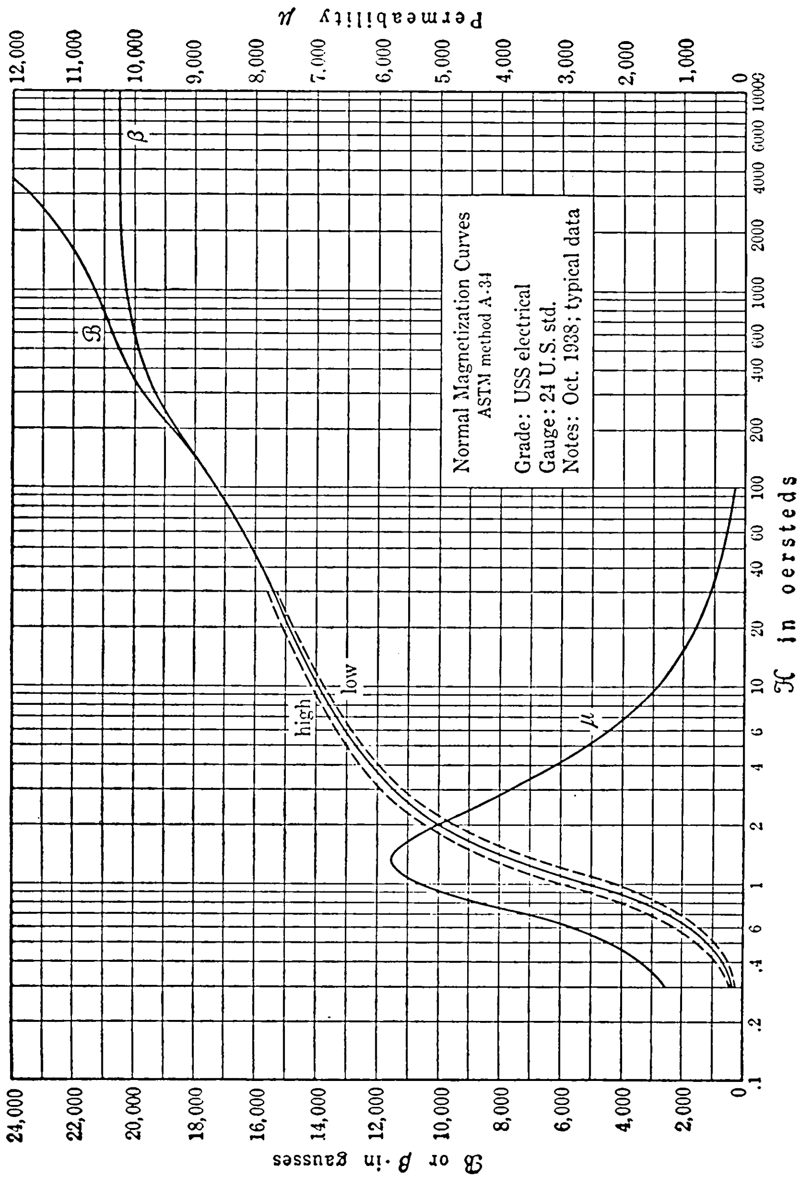
Figure 14a shows a typical hysteresis loop for 24-gauge electrical-grade sheet steel. The co-ordinates are in aemu; that is, the magnetizing force is given in gilberts per centimeter, or oersteds, and the flux density is in flux lines per square centimeter, or gausses. The curve of Fig. 14a shows the relationship between $\mathcal{B}$ and $\mathcal{H}$ [herein abbreviated to $\mathcal{B}(\mathcal{H})$] for a maximum induction of 10,000 gausses, which is the flux density at which the hysteresis loops, residual induction $\mathcal{B}_r$, and coercive force $\mathcal{H}_c$, of electrical sheet steels are compared according to standards of the American Society for Testing Materials. From Fig. 14a it is seen that the value of $\mathcal{B}_{r10}$ for electrical-grade sheet steel is observed to be 8,100 gausses, and the value of $\mathcal{H}_{c10}$ is 0.7 oersted. In Fig. 14b is shown a typical normal magnetization curve of the same grade of electrical sheet steel as represented by the data of Fig. 14a. The co-ordinates of this curve are also expressed in aemu. This grade of material does not become saturated until $\mathcal{B}$ approaches 20,500 gausses as shown by the curve of *intrinsic* flux density β. The intrinsic flux density β is $\mathcal{B}$ minus $\mu_0\mathcal{H}$, and is a measure of that part of the flux density attributable to the ferromagnetic characteristic of the material. When the material becomes saturated, it can make no further contribution to the flux density; hence as $\mathcal{H}$ is



Courtesy Carnegie-Illinois Steel Corp.

FIG. 14a. Hysteresis loop.

increased beyond the values which saturate the material, the slope of the $\mathcal{B}(\mathcal{H})$ curve becomes μ_0, the permeability of free space, and β be-



Courtesy Carnegie-Illinois Steel Corp.

Fig. 14b. Curves of flux density and permeability.

comes constant. With most ferromagnetic materials, the difference between *normal flux density* $\mathcal{B}$ and *intrinsic flux density* β is negligible until saturation conditions are approached.

The *static permeability* μ of the material is defined by the relation

$$\mu = \frac{\mathcal{B}}{\mathcal{H}}, \qquad [2]$$

in which $\mathcal{B}$ is the total flux density and $\mathcal{H}$ is the magnetizing force, $\mathcal{B}$ and $\mathcal{H}$ being related by the normal magnetization curve. In other words, the static permeability (as distinguished from the dynamic or incremental permeability defined in Ch. VI) at any point on the magnetization curve is the slope (gausses/oersteds) of a line drawn through the origin to the point on the normal magnetization curve. In Fig. 14b, a curve of static permeability is shown as a function of the magnetizing force $\mathcal{H}$. Static permeability and its reciprocal, called *reluctivity,* are sometimes useful quantities, but, for most practical engineering work involving calculations on magnetic circuits, the characteristic curves giving the relation between $\mathcal{B}$ and $\mathcal{H}$ contain the same information in a more useful form.

The general form of the hysteresis loop of nearly all the ferromagnetic materials is similar to that shown in Fig. 14a. The proportions of such a loop frequently vary considerably among different materials, and, for a given material, vary with the heat treatment and mechanical working to which the material is subjected. Normal intrinsic magnetization curves for a wide variety of magnetic materials are shown in Fig. 15a. Figure 15b shows hysteresis loops for some of the typical permanent-magnet materials. The chief purpose in presenting the curves of various materials on the same sheet and to the same scale is to facilitate comparison of the magnetic properties among these materials.

Representative properties for a selected group of magnetic materials are given in Table I. These figures represent an average of values for the various materials given by several sources.[12] In this table, the magnetically soft materials are arranged in order according to their maximum permeabilities, the material having highest permeability appearing at the top. This order is also essentially that of decreasing relative magnetic softness, a magnetically soft material having a relatively narrow hysteresis loop and hence a small coercivity, usually less than about 3 oersteds. Magnetically soft materials are used in devices where high permeabilities are desired, and where the materials are subjected to alternating fields. Magnetically hard materials are used for permanent magnets; their uses are discussed in Ch. IV.

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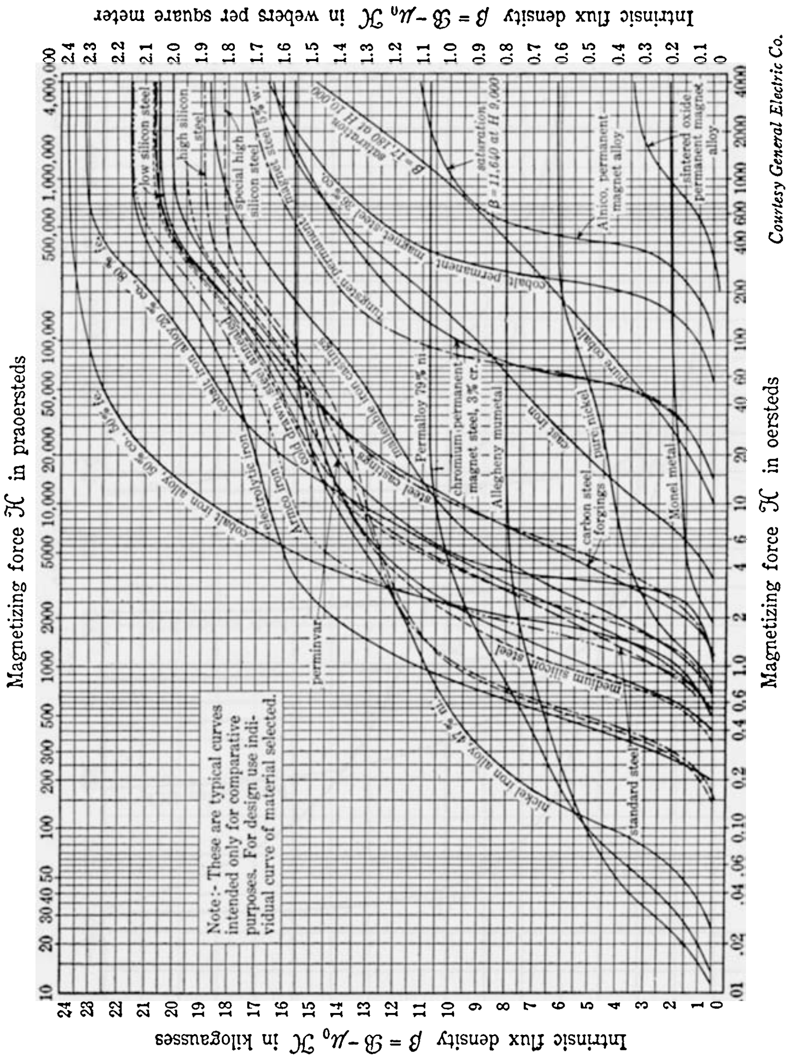
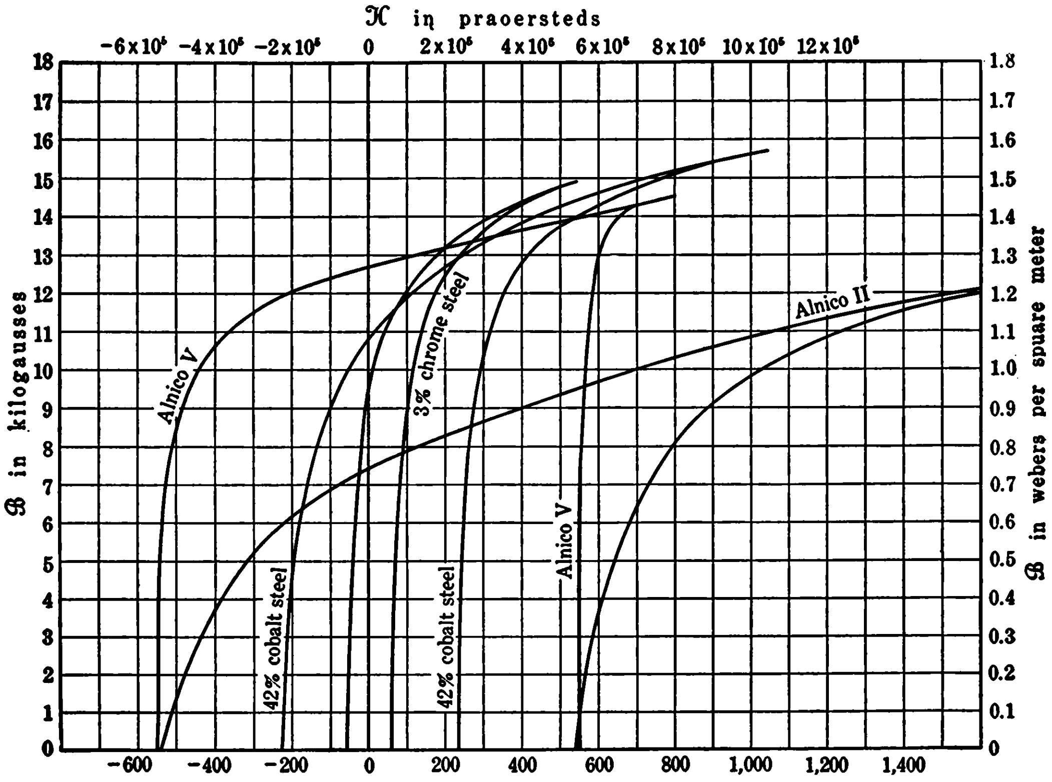
[12] V. E. Legg, " Survey of Magnetic Materials and Applications in the Telephone System," *B.S.T.J.*, *18* (1939), 438–464.



Courtesy General Electric Co.

FIG. 15a. Normal d-c magnetization curves for various magnetic materials.



Courtesy General Electric Co.

FIG. 15b. **Typical hysteresis loops for permanent-magnet materials.**

TABLE I—REPRESENTATIVE PROPERTIES OF FERROMAGNETIC **MATERIALS‡**

Magnetically Soft Materials	*Elements*	*Composition*	*Intrinsic Saturation* β_{max}	*Residual Flux Density* $\mathcal{B}_r$	*Coercive Force* $\mathcal{H}_c$	*Typical Maximum Perme-ability* μ_{max}	*Typical Initial Perme-ability* μ_i	*Cost*
		approx. parts per 100	*kilogausses*	*kilogausses*	*oersteds*	*kilogausses/oersted*	*kilogausses/oersted*	*cents/lb*
Magnetic Iron (Purified in H) .	Fe	99.98	21.5	13.6	0.05	275.	25.	7
Sendust	Fe, Si, Al	85, 9.5, 5.5	10.0	5.0	0.05	120.	30.	3
78.5 Permalloy	Ni, Fe, Mn	78.5, 20.9, 0.6	10.7	6.0	0.05	105.	9.	28
Hipernik	Fe, Ni	50, 50	15.0	7.5	0.06	90.	6.	18
Mumetal	Ni, Fe, Cu, Mn	74, 20, 5, 1	8.5	6.0	0.05	80.	7.	27
4–79 Mo-Permalloy	Ni, Fe, Mo, Mn	79, 16.4, 4, 0.6	8.5	5.0	0.05	72.	22.	32
High-Silicon Steel	Fe, Si	95.5, 4.5	19.0	5.0*	0.5*	8.3	0.750	8
Low-Silicon Steel	Fe, Si	99, 1	21.0	8.5*	0.7*	5.2	0.350	7
Permendur	Fe, Co	50, 50	24.5	14.0	2.0	5.0	0.800	69
7–70 Perminvar	Ni, Fe, Co, Mn	70, 22.4, 7, 0.6	12.5†	2.4†	0.6†	4.0†	0.850	35
45–25 Perminvar	Ni, Fe, Co, Mn	45, 29.4, 25, 0.6	15.5†	3.3†	1.4†	1.8†	0.365	50
Conpernik	Fe, Ni	50, 50	15.0	. . . .	. . . .	1.0	0.175	18
Cast Steel	Fe, C	. . . .	20.0	. . . .	5.0*	1.0	0.175	1
Cast Iron Annealed	Fe	. . . .	16.0	5.5	11.0*	0.3	0.125	1
12.5–80 Mo-Permalloy	Ni, Mo, Fe	80, 12.5, 7.5 (Loses magnetic properties at 40 degrees C.)					9.	40

* $\mathcal{B}_r$ and $\mathcal{H}_c$ from $\mathcal{B}_{max}$ = 10 kilogausses instead of from saturation. † These are not the conditions under which Perminvar is useful. See p. 28.

Magnetically Hard Materials	*Elements*	*Composition*	*Retentivity*	*Coercivity*	$(\mathcal{B}\mathcal{H})_{max}$	*Cost*		
		approx. parts per 100	*kilogausses*	*oersteds*		*cents/lb*		
Alnico V Cast	Fe, Co, Ni, Al, Cu	51, 24, 14, 8, 3	12.5	550	4.5×10^6	56		
Honda Metal	Fe, Co, Ni, Ti, Al	45, 27, 18, 6.7, 3.3	7.1	780	2.0	53		
Alnico II Cast	Fe, Ni, Co, Al, Cu	54.5, 17, 12.5, 10, 6	7.2	540	1.6	26		
Alnico I Cast	Fe, Ni, Al, Co	63, 20, 12, 5	7.3	430	1.4	17		
Mishima Metal	Fe, Ni, Al	58, 29, 13	6.0	550	1.4	14		
Remalloy	Fe, Mo, Co	71, 17, 12	10.5	250	1.1	33		
Cobalt Steel	Fe, Co, C	64, 35, 1	9.5	260	1.05	62		
Tungsten Steel	Fe, W, C	93, 6, 1	10.0	80	0.34	9		
Chrome Steel	Fe, Cr, C, Mn	96, 3, 1, 0.4	9.7	65	0.30	1		

‡Data for Table I taken chiefly from reference 12, p. 24.

The characteristics tabulated for the magnetically soft materials are: the maximum intrinsic flux density β_{max}, the residual flux density $\mathcal{B}_r$, the coercive force $\mathcal{H}_c$ (also the retentivity and the coercivity respectively since the symmetrical cyclic magnetization was carried to saturation, except as noted), the maximum and initial permeabilities μ_{max} and μ_i, and the cost of the raw material. The characteristics tabulated for the magnetically hard materials are the retentivity, the coercivity, the maximum value of the product of $\mathcal{B}$ and $\mathcal{H}$ occurring between the points $\mathcal{H} = 0$ and $\mathcal{H} = -\mathcal{H}_c$, and the cost. The product $(\mathcal{B}\mathcal{H})_{max}$ is a measure of the effectiveness of the material for use in permanent magnets; its significance is discussed in Ch. IV. The composition of the alloys in parts per hundred is given for both hard and soft materials. Inadvertent impurities are not indicated, although they frequently produce serious effects. Almost all the materials mentioned in the table are commercially available, but a few are in the stage of laboratory development.

The extent of the dependence of certain of the magnetic properties of all ferromagnetic materials on the heat treatment to which they are subjected cannot be overemphasized. A discussion of the heat-treatment procedure[13] is beyond the scope of this textbook, but the importance of the treatment may be illustrated by the fact that Hipernik and Conpernik, although having the same composition, display widely different magnetic properties. The differences are brought about wholly by a difference in the heat treatment to which each material is subjected. The Perminvars maintain a practically constant permeability μ_i if not magnetized above about 1,000 gausses. Magnetization above this value destroys the property of constant permeability and this can be restored only by further heat treatment. Of the characteristics tabulated, the maximum intrinsic flux density is the one subject to the least variation. It is dependent chiefly on the percentage of ferromagnetic material present in the alloy. The degree to which the other characteristics are subject to variation increases in the order, residual induction, coercive force, and permeability.

From the curves of Figs. 15a and 15b and the data of Table I, the material best suited from the magnetic point of view for any specific purpose can be chosen. Whether the material should be used depends, of course, on numerous other factors such as availability, cost, mechanical strength, and machinability. Characteristics of magnetic materials subjected to alternating fields are given in Ch. V. Additional magnetic data on commercial materials may be obtained from the manufacturers or from the literature.

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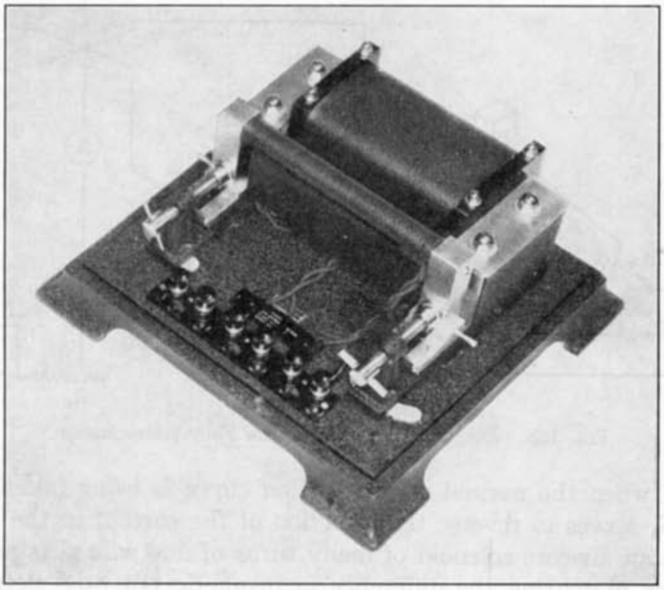
[13] C. E. Webb, "Recent Developments in Magnetic Materials," *I.E.E.J.*, *82* (1938), 303–323.

5. MAGNETIC TESTING

The normal magnetization curve and a family of hysteresis loops for a magnetic material give the information necessary for the solution of problems involving the use of the material in direct-current applications. In order to get these curves experimentally, some kind of permeameter[14] is required in which a sample of the material can be tested.

Of the many types of permeameter, only those most commonly used will be described here. These are the *Fahy simplex* permeameter, which gives good precision up to magnetizing forces of 300 oersteds, and with an adapter up to 1,000 oersteds, and the *high-$\mathcal{H}$* permeameter, which permits a range up to 5,000 oersteds.



Courtesy Mr. Frank P. Fahy.

FIG. 16a. The Fahy simplex permeameter.

The Fahy simplex permeameter is pictured in Fig. 16a and is represented diagrammatically in relation to its associated equipment in Fig. 16b. The circuit shown is somewhat simpler than the actual laboratory layout, since the object of this treatment is to set forth the method of testing rather than to stress the technique of manipulation. The ballistic galvanometer is first calibrated by the adjustment of its resistances R_S, R_B, and R_H, so that a change of some convenient unit of flux density in coil B (called the $\mathcal{B}$-coil) or a change of some definite unit of field

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[14] R. L. Sanford, "Magnetic Testing," *Circ. Nat. Bur. Stand.* C415 (1937).

intensity in coil H (called the $\mathcal{H}$-coil) produces a galvanometer deflection of one main scale division. This calibration requires the use of a standard mutual inductor not shown in the diagram.

The specimen S to be tested is clamped between the solid iron posts P and the ends of the laminated iron yoke Y, forming a magnetic circuit in which flux is set up by the magnetomotive force of coil M. The current in this magnetizing winding is supplied from a steady direct-current source and can be adjusted by the variable resistor R_M. The switch S_2 is closed when the normal magnetization curve is being taken and the switch S_1 serves to reverse the direction of the current in the coil. The coil H is an air-core solenoid of many turns of fine wire that provides a means for measuring the difference in magnetic potential between the posts P. This difference in magnetic potential divided by the distance between posts is the magnetizing force $\mathcal{H}$ in the specimen.

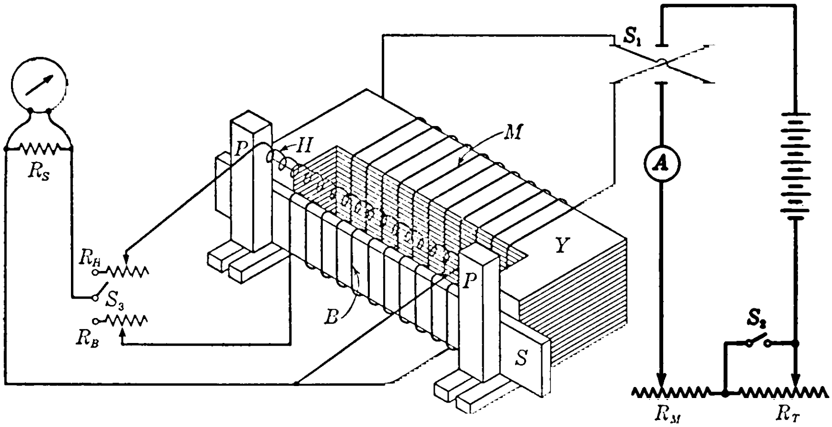


FIG. 16b. Diagram of connections for Fahy permeameter.

Before data for the normal $\mathcal{B}(\mathcal{H})$ curve are taken, the sample is demagnetized, and, with switch S_2 closed, rheostat R_M is set for the lowest point on the curve. Switch S_1 is placed in either closed position and S_3 is left open. The current in coil M is reversed several times by means of switch S_1 in order to put the sample in cyclically magnetized condition. Switch S_3 is now closed in the lower position and S_1 is moved from one pair of contacts to the other. The deflection of the ballistic galvanometer then indicates the change in flux density $\mathcal{B}$ in the sample. A repetition of the process with S_3 in the upper position, using the same value of magnetizing current as before, gives the corresponding change in magnetizing force $\mathcal{H}$ in the sample. Other points on the curve can be obtained through increasing the current in coil M, putting the sample in cyclic condition by several reversals of S_1, and then taking data as for the first point. The normal magnetization curve is the locus of points plotted from these data as indicated by the broken line in Fig. 17.

When a hysteresis loop is to be determined, the cyclic condition is first established at the desired value of $\mathcal{B}_{max}$. The rheostat R_T is set to

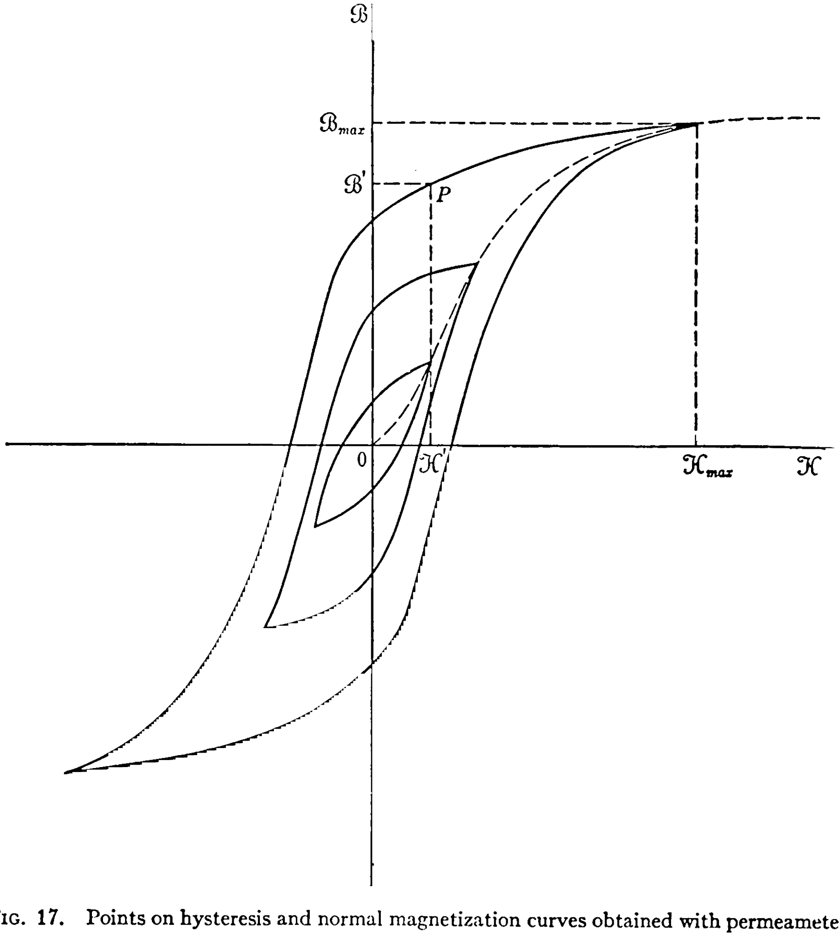


FIG. 17. Points on hysteresis and normal magnetization curves obtained with permeameter

give a small decrease in the reading of ammeter A when S_2 is opened. With S_3 in the lower position, S_2 is opened and the galvanometer deflection is noted. The reading indicates the change in $\mathcal{B}$ as it is decreased from $\mathcal{B}_{max}$. This will give the value $\mathcal{B}_{max} - \mathcal{B}'$ as indicated in Fig. 17. The cyclic condition at the tip of the loop is now restored through reversing S_1, closing S_2, and then reversing S_1 again. If, with S_3 in the upper position, S_2 is again opened, the value $\mathcal{H}_{max} - \mathcal{H}'$ is obtained. Points farther down the loop can be obtained in the same way by the use of larger values of resistance R_T, each reading being made from a cyclical condition at the tip of the loop. This makes it possible to establish identical initial conditions for the $\mathcal{B}$ and $\mathcal{H}$ readings and also to avoid cumulative errors which would accrue in going from point to point.

When the points on the hysteresis loop are near the horizontal ($\mathcal{H}$) axis, small errors in the determination of $\mathcal{B}$ are not of much consequence, because the curve is nearly vertical, but errors in $\mathcal{H}$ are of importance. The method just described for the determination of $\mathcal{H}$ is likely to introduce a considerable error in this region, since the values of $\mathcal{H}$ are found through taking the difference between $\mathcal{H}_{max}$ and another large value $\mathcal{H}_{max} - \mathcal{H}$ determined from the test. Greater precision in these values of $\mathcal{H}$ is obtained by the use of an attachment which makes possible the measurement of $\mathcal{H}$ directly at a fixed magnetization of the specimen through quickly rotating the coil H 180 degrees. Not only is greater precision possible in a single reading by the use of this device, but several readings of $\mathcal{H}$ can be taken without changing the magnetic condition of the specimen.

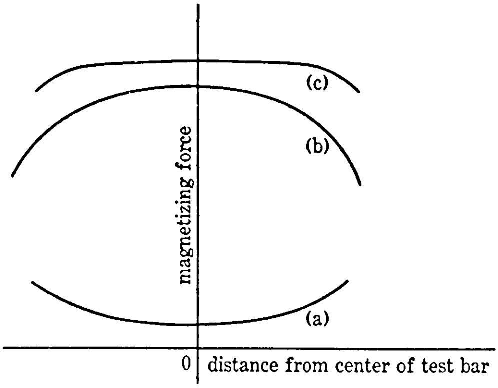
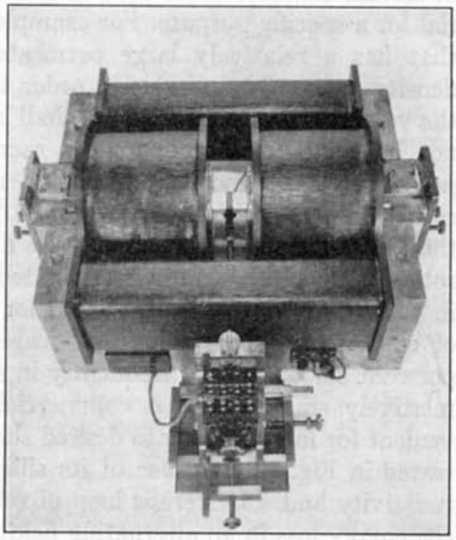


Fig. 18. Distribution of magnetizing force $\mathcal{H}$ along test bar for: (a) coil on yoke, (b) coil surrounding specimen, (c) combination of (a) and (b).

Since a considerable difference in magnetic potential exists between the ends of the test bar, a leakage of flux away from the bar through the surrounding air is bound to occur. For this reason, the flux density decreases along the bar from the ends toward the center with a corresponding decrease in magnetizing force as shown in curve (a) of Fig. 18. The greater the total applied magnetomotive force, the greater will be this leakage and resulting nonuniformity in $\mathcal{H}$ along the specimen. For magnetizing forces greater than 300 oersteds, this effect becomes great enough to interfere with the precision of the instrument. The recognition of this situation and the need for testing the new hard permanent-magnet alloys led to the development of the super-$\mathcal{H}$ adapter. This device is clamped against the yoke Y in place of the sample and auxiliary posts P and holds near its center a short length of test material and an accompanying short $\mathcal{H}$-coil. Magnetizing forces up to 2,500 oersteds can be applied to the sample without overheating the apparatus, but the precision of the measurements above about 1,000 oersteds is doubtful.

The curve (b) of Fig. 18 shows the variation of magnetizing force along a specimen when the magnetizing coil is a solenoid surrounding the specimen rather than a winding on the yoke. Here the value of $\mathcal{H}$ is greatest near the center and drops off toward the end. Curve (c) represents a combination of these two curves and indicates that, with a part of the magnetizing winding on the yoke and a part surrounding the specimen, a uniform field can be obtained over a considerable length about the center of the test bar. This principle is used in the Babbitt[15] permeameter, which gives good precision up to 1,000 oersteds.

The most recent development is the Sanford-Bennett[16, 17] high-$\mathcal{H}$ permeameter of the U. S. Bureau of Standards. This instrument is claimed to measure both $\mathcal{B}$ and $\mathcal{H}$ in small samples (up to cross-sectional dimensions 0.75 in. × 1.5 in.) for magnetizing forces up to 5,000 oersteds with an error not exceeding 1 per cent. Values of $\mathcal{H}$ up to 9,000 oersteds can be used without overheating the instrument or the sample, but the precision for the higher values has not yet been determined. Figure 19 shows this permeameter. The two large coils in the center surround the pole pieces and comprise the main magnetizing winding. Each of these coils has 2,690 turns of 14 AWG silk-enamel wire. Each of the auxiliary or yoke coils has 1,600 turns. Several $\mathcal{B}$-coils are available in order that one may be chosen which fits snugly around the sample to be tested. Each of these coils has 25 turns of fine wire wound on a thin brass shell. This is clearly visible at the middle of the picture, as is also the $\mathcal{H}$-coil just beneath the $\mathcal{B}$-coil. The device at the front is a motor-driven rotator for the $\mathcal{H}$-coil, in order that $\mathcal{H}$ may be measured at a fixed magnetization



Courtesy National Bureau of Standards.

FIG. 19. The Sanford-Bennett high-$\mathcal{H}$ permeameter.

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[15] B. J. Babbitt, "An Improved Permeameter for Testing Magnet Steel," *J.O.S.A.* and *R.S.I.*, *17* (1928), 47–58.

[16] R. L. Sanford and E. G. Bennett, "An Apparatus for Magnetic Testing at High Magnetizing Forces," *J. Res. Nat. Bur. Stand.*, *10* (1933), 567–573.

[17] R. L. Sanford and E. G. Bennett, "An Apparatus for Magnetic Testing at Magnetizing Forces up to 5,000 Oersteds," *J. Res. Nat. Bur. Stand.*, *23* (1939), 415–425.

of the specimen. The instrument connections are essentially the same as for the Fahy simplex permeameter.

6. ENGINEERING UTILIZATION OF FERROMAGNETIC MATERIALS

A detailed study of the data of Figs. 15a and 15b and Table I shows that the various alloys mentioned display the characteristics typical of ferromagnetic materials to markedly varying degrees. The predominance of certain characteristics determines the usefulness of a particular material for a specific purpose. For example, for an electromagnet, a material that has a relatively large permeability and a large saturation flux density is usually desirable in order that the magnetomotive force and the volume of material required shall be small. But these properties must not be achieved at too great a sacrifice of the desirable mechanical properties, or at too large a cost. A relatively pure iron or low-silicon-content sheet steel is frequently used for such purposes. However, when the flux is varying with time, as it does in transformers, reactors, and rotating machines, energy is dissipated in the iron in a manner explained in Ch. V. Because of heating, and for economic reasons, this dissipation of energy must be small. Electrical-sheet steel with between 2 and 4 per cent silicon is used frequently in such devices. Its cost per pound is relatively small and it is commercially available in many forms convenient for fabrication into desired shapes. Some of these forms are illustrated in Fig. 12. Because of its silicon content, it has relatively high resistivity and a hysteresis loop of relatively small area,* which reduce the energy loss in an alternating field. When more than about 4 per cent of silicon is used, the improvement in the magnetic properties is negligible, and the material becomes brittle and difficult to punch into desired shapes. Manufacturing difficulties are then increased.

In some communications equipment, a material having an extremely high permeability is desirable. For such applications, certain nickel-iron alloys, known as Permalloys[18,19] (*perm*eability *alloy*) or Hipernik in the United States, or a nickel-iron-copper alloy, known as Mumetal[20] and developed in England, may be used. The use of these alloys involves an increased cost per pound of material but not of cost per unit of inductance.

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* Representative values of core loss for symmetrical cyclic magnetization and representative values of resistivity for average samples of various materials are tabulated in Art. 3, Ch. V.

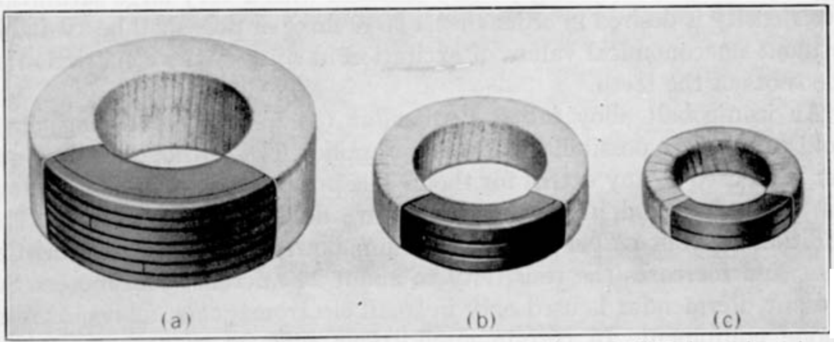
[18] G. W. Elmen, "Magnetic Alloys of Iron, Nickel, and Cobalt," *A.I.E.E. Trans.*, *54* (1935), 1292–1299.

[19] V. E. Legg and F. J. Given, "Compressed Powdered Molybdenum Permalloy for High-Quality Inductance Coils," *B.S.T.J.*, *19* (1940), 385–406.

[20] W. F. Randall, "Nickel-Iron Alloys of High Permeability with Special Reference to Mumetal," *I.E.E.J.*, *80* (1937), 647.

The large permeability of these alloys is chiefly the result of their having been subjected to a particular heat-treatment procedure, for which careful control is necessary. Also, their permeability is very susceptible to strains introduced by mechanical working; hence their use may increase manufacturing problems.

In Ch. V an analysis is presented showing that eddy-current loss can be reduced through building ferromagnetic cores of laminated sheets insulated from each other by their surface oxides or by an insulating lacquer. Another method of reducing eddy currents is to reduce the material to a powder and then to insulate the particles from one another by an insulating substance tough enough to withstand the forces of compression when the powder is molded into the cores of various shapes. Figure 20 is indicative of the advance given to this art by the engineers and physicists of the Bell System during the past 20 years.



Courtesy Bell Telephone Laboratories.

FIG. 20. Reduction in size of compressed-powder loading-coil cores in 20 years: (a) iron, (b) 80-Permalloy, and (c) 2-81 Mo-Permalloy.

In certain other communications problems, extreme constancy of permeability throughout the working range is imperative. A nickel-iron-cobalt alloy known as Perminvar (*perm*eability *invar*iable) and a nickel-iron alloy known as Conpernik possess this property at relatively low flux densities. Unfortunately, the permeability of these alloys is low. They have the unique properties of negligible residual magnetism and of negligible coercive force throughout their useful range. Perminvar has a low resistivity, of the order of 20 microhm-centimeters, but by the addition of about 7 per cent of molybdenum its resistivity is increased by a factor of about four without appreciable sacrifice of its magnetic properties.

When a material is to be used in rotating machinery, one having properties different from the above is required. Mechanical strength becomes important, since in the rotors of turbo-alternators, centrifugal forces are often large and a material with large tensile strength is then essential. When the magnetizing forces are essentially constant, solid steel forgings of nickel steel or nickel-chromium steel are often used. These alloys possess the high values of saturation flux density desired in steels for these applications. In the parts of the machine where the flux is alternating, as it is in the neighborhood of the alternating-current windings, the resulting energy losses are of considerable concern. For these parts, a suitable silicon steel is used.

In rotating-armature machines, a special problem arises. The flux density in the teeth is large, and a material with a very large saturation flux density is desired in order that a large flux per pole shall be available without uneconomical values of excitation in spite of the constriction at the roots of the teeth.

An iron-cobalt alloy called Permendur (*perm*eability *endur*ing) may hold interesting possibilities for these applications, although it has not yet been used to any extent for them. The present high cost of this alloy, its brittleness, and its low resistivity are deterrents to wide use. The addition of about 1.7 per cent of vanadium, however, decreases the brittleness, and increases the resistivity to about 24 microhm-centimeters. At present, Permendur is used only in small electromagnets, relays, or telephone equipment. In certain applications such as in aeronautical or other equipment where space or weight is at a premium, the item of its cost should not be a serious one. The important factors are the relation between the cost per pound of the material, the cost per pound of the finished article, and the percentage by weight of the material in the finished article.

When ferromagnetic materials are used as permanent magnets, other properties become primary in importance. Permanent-magnet applications usually are in instruments, meters, and small motors or generators, where the cost per pound of the finished product is relatively large. The magnets are subject frequently to severe mechanical shock, to alternating fields, and to moderate changes in temperature. The mechanical strength of the magnets is usually considerably in excess of that necessary. The coercivity and retentivity of the material become, in a general way, the figures of merit. For many applications, the determining factor is the maximum value of the product ($\mathcal{BH}$) along the demagnetization curve between $\mathcal{H}$ equals 0 and $\mathcal{H}$ equals $\mathcal{H}_c$ as is explained in Ch. IV. This product is tabulated as $(\mathcal{BH})_{max}$ in Table I for those materials that are suitable for use as permanent magnets.

During the early days of the electrical industry, the carbon steels used for permanent magnets were seriously weakened magnetically by vibration, alternating fields, and temperature variations, and were therefore of little use where constancy of field was desired. The development of tungsten-steel and chromium-steel alloys provided improved permanent-magnet materials which still find wide application where the cost of the material is of major importance and space is not. These steels are subject to the same kind of defects as carbon steel but to a lesser degree.

The development of cobalt steel provided a material superior magnetically to either tungsten or chromium steel. Not only can stronger fields be produced by a cobalt-steel magnet, but alternating fields and mechanical vibration have relatively little effect on its permanency. Recently has come the development of other alloys containing chiefly iron, nickel, cobalt, and aluminum. These alloys, which are known by the trade name Alnico in the United States and Nipermag in England, are less expensive to produce and lighter in weight than cobalt steel, and yet have better magnetic properties. The alloy Alnico[21] is produced with various compositions, an average composition being about 20 per cent nickel, 12 per cent aluminum, 5 per cent cobalt, 0.4 per cent manganese plus silicon, and the remainder iron. It has a large $(\mathcal{BH})_{max}$ and its properties are changed only slightly by vibration, alternating fields, or even a surprisingly wide range of temperature variation. The use of this alloy introduces a new problem, however, for it cannot be machined readily and frequently must be cast in the form in which it is to be used. Hence use of it may involve a complicated manufacturing problem. This problem has been partly solved by sintering,[22] a process in which the powdered constituents are diffused together at high temperature and under tremendous pressure. Some of the parts formed with considerable accuracy by this process are shown in Fig. 21. Larger elements, as well as the ones shown, are commercially available and can be combined with soft iron or steel in the construction of magnetic devices.

Certain other alloys, and also the oxides of iron and iron-cobalt, show desirable properties as permanent magnets. The oxide magnets must be molded and are relatively brittle. Future developments in this part of the art may yield useful products. In many devices, no single ferromagnetic material is adequate. For example, the modern telephone receiver shown in Fig. 22 has Remalloy permanent magnets, 45-Permalloy pole pieces, and a Permendur diaphragm.

In certain devices, such as relays, resistors, and transformers, a material having magnetic properties very sensitive to temperature can be used to advantage. This condition has only recently become of engineering importance, although the change in the magnetic property with temperature has been of theoretical significance since the era of early attempts to formulate a theory of ferromagnetism. By appropriate composition, an alloy is obtained having the temperature at which it ceases to be ferro-

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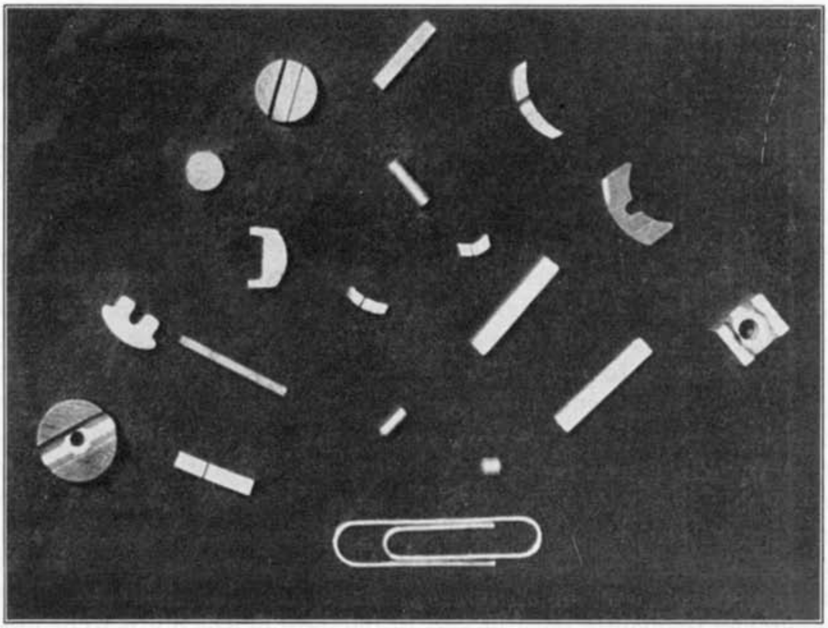
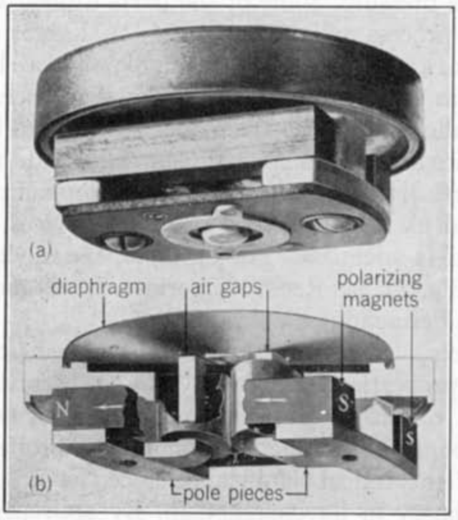
[21] J. Q. Adams, "Alnico — Its Properties and Possibilities," *G.E. Rev.*, *41* (1938), 518–523.

[22] G. H. Howe, "Sintering of Alnico," *Iron Age*, *145* (1940), 27.



Courtesy General Electric Co.

FIG. 21. Representative collection of small Alnico magnets. Paper clip included to indicate size.



Courtesy Bell Telephone Laboratories.

FIG. 22. Magnetic circuit of telephone receiver.

magnetic (that is, its Curie point) in a useful range for many engineering applications. Alloys having this property are used for the temperature-sensitive element in temperature-sensitive reactors, contactors, and transformers. The possibilities for useful application of alloys of this kind may be better appreciated when it is realized that an alloy[23] comprising approximately 35 per cent nickel, 5 per cent chromium, 60 per cent iron, and 0.3 per cent silicon, appropriately heat-treated, has a saturation flux density of about 6,000 gausses at a temperature of 60 degrees centigrade but is essentially nonmagnetic at 160 degrees. Another of these alloys, 12.5–80 Mo-Permalloy, becomes nonmagnetic at 40 degrees centigrade, or slightly above normal room temperature.

The magnetic properties of many ferromagnetic materials change gradually with time, a phenomenon known as aging. All the steels behave this way to some extent since their iron-carbon compounds are not stable, but change from one form to another with time. The changes may proceed rapidly at high temperatures, but appropriate sudden cooling as part of the heat treatment can so retard the rate that the whole effect is distributed over a period of years. However, the aging cannot be completely stopped. The silicon steels show only a slight aging effect because of the reaction occurring among the silicon, oxygen, and carbon during their production.

While the effects of aging on the magnetic properties of all steels are important, usually causing a decrease in the permeability and an increase in coercivity of magnetically soft materials, the effects are especially serious when they occur in magnetically hard steels used for magnets in instruments and meters. Here the strength of the magnet is decreased, and the accuracy of the device is impaired by even a very small change in the strength. The usefulness of the magnetically hard carbon steels can be increased by artificial aging. For example, if the steel is subjected to a temperature of about 100 degrees centigrade for several hours, a rapid aging and considerable change in strength occur. The subsequent rate of change of magnetic strength at normal room temperature is then greatly reduced.

Many of the newer alloys do not contain carbon in significant amounts and are not subject to these aging effects. Some of the compounds formed, notably Alnico, are stable even up to temperatures above 600 degrees centigrade. Welding is even possible with some of these alloys after they have been heat-treated, without appreciably impairing their desired magnetic properties. The advantages offered by such alloys for manufacturing processes may therefore be readily appreciated.

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[23] L. R. Jackson and H. W. Russell, " Temperature-Sensitive Magnetic Alloys and Their Uses," *Instruments*, *11* (1938), 280–282.

PROBLEMS

1. Describe briefly any new developments in the theory of magnetism which have appeared in the periodical literature in the fields of physics and electrical engineering since this textbook was published.

2. Give the physical properties including characteristic curves of any important ferromagnetic materials not included in this chapter.

3. A strip of specially treated stainless steel (18% chromium, 8% nickel), when first placed under a powerful permanent magnet, shows very little tendency to be lifted, but, after the lapse of about one and one-half minutes, is strongly attracted to the poles of the magnet. The special treatment consists in removing the nitrogen from the metal and quenching in water from a temperature of 1,100 F. The magnetic experiment is performed immediately after quenching. How can this change in magnetic properties be explained? Does your explanation indicate that the strip regains its nonferromagnetic properties when removed from the magnetic field?[24]

4. When a sinusoidal voltage of 2,300 v effective value is applied at the primary terminals of a transformer, the maximum flux density in the core is 1 weber per sq m. The data for the hysteresis loop of the steel in the transformer core are given in the following table:

$\mathcal{B}$ *in webers/sq m*	$\mathcal{H}$ *in praoersteds*
−1.00	−3,750
−0.92	−1,500
−0.77	0
−0.50	+1,400
−0.20	+2,100
0.00	+2,350
+0.45	+2,500
+0.75	+2,950
+1.00	+3,750

Plot, on the same horizontal axis, a complete cycle of sinusoidal voltage and the corresponding cycles of flux density and magnetizing force. Use a horizontal scale of 40 degrees = 1 in. Use vertical scales of 1,000 v = 1 in., 0.40 weber per sq m = 1 in., and 1,000 praoersteds = 1 in. The waveform of $\mathcal{H}$ is similar to that of the magnetizing current of the transformer described in Ch. VI.

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[24] See "Magnetic Delay," *G.E. Rev.*, *45* (1942), 245, 246.