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Basic Magnetic Quantities and the Measurement of the Magnetic Properties of Materials

U.S. DEPARTMENT OF COMMERCE

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Basic Magnetic Quantities and the Measurement of the Magnetic Properties of Materials

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Preface

Since 1909 when the first NBS Circular on Magnetic Testing was issued, successive revisions have been prepared in order to keep up to date with the development of new magnetic materials and methods of testing. Since the last circular, C 456, Magnetic Testing, was issued in 1946 the importance of magnetic materials and testing methods has greatly increased. In view of the many requests for information regarding magnetic quantities, materials, and testing methods, the present revision and extension of the previous circular has been prepared. It supersedes Circular C 456, Magnetic Testing.

Contents

	Page
Preface	II
1. Introduction	1
2. Magnetic quantities and units	1
2.1. Systems of units—dimensions	1
2.2. Basic quantities	2
a. Magnetic induction, B	2
b. Magnetizing force, H	2
2.3. Magnetic constant, Γ_m	2
2.4. Derived quantities	3
a. Magnetic flux, ϕ	3
b. Magnetomotive force, $\mathscr{F}$	3
c. Magnetic reluctance, $\mathscr{R}$	4
3. Magnetic characteristics of materials	4
3.1. Magnetic permeability	4
3.2. Magnetic susceptibility	5
3.3. Classification of materials	5
3.4. Magnetic hysteresis and normal induction	6
3.5. Core loss	7
4. Measurement of static magnetic fields	7
4.1. General principles	7
4.2. Pivoted coil	7
4.3. Pivoted magnet	8
4.4. Ballistic methods	8
a. Ballistic galvanometer	8
b. Intercomparison of mutual inductors and calibration of test coils	10
4.5. Rotating test coil	11
4.6. Bismuth spiral	11
4.7. Hall effect	12
4.8. Saturable core	12
4.9. Nuclear magnetic resonance	12
5. Tests with direct current	12
5.1. Testing of materials	12
5.2. Ring method	14
5.3. Straight bar and solenoid	15
5.4. Permeameters	17
a. MH permeameter	17
b. High-H permeameter	18
c. Fahy Simplex permeameter	19
5.5. Tests of low permeability materials	21
5.6. Magnetic susceptibility	21
5.7. Magnetic standards	23
5.8. Limits of accuracy	23
5.9. Requirements of standard specimens for d-c permeameters	24
5.10. General precautions	24
6. Tests with alternating currents	24
6.1. Core loss and a-c permeability at power frequencies	24
a. Voltmeter-wattmeter methods	25
b. Bridge methods	27
6.2. A–C Measurements at higher than power frequencies	29
7. Typical magnetic properties of materials	30
7.1. Solid core materials	30
7.2. Electrical sheet and strip	30
7.3. Special-purpose materials	31
7.4. Ferrites	32
7.5. Permanent-magnet materials	33
a. Quench-hardened alloys	33
b. Precipitation-hardening alloys	33
c. Work-hardened alloys	34
d. Ceramic magnet materials	35
e. Powder magnets	35
7.6. Feebly magnetic materials	35
8. References	35

Basic Magnetic Quantities and the Measurement of the Magnetic Properties of Materials

R. L. Sanford and I. L. Cooter

This paper gives general information regarding the two basic quantities, magnetic induction, B, and magnetizing force, H, and also the magnetic constant Γ_m (often designated by the symbols μ_v and μ_0). Information is also given regarding the magnetic properties of various materials and methods and apparatus commonly used in the Magnetic Measurements Section for measuring these properties by means of reversed direct current or alternating currents of low frequency. Magnetic measurements peculiar to high frequencies are not discussed. In view of the gradual adoption of the rationalized mksa system of units, this system is included as well as the classical cgs electromagnetic system.

1. Introduction

The work of the Magnetic Measurements Section of the National Bureau of Standards includes (1) testing of specially prepared test specimens intended for use as standards for checking magnetic testing apparatus (2) investigation and development of magnetic testing apparatus (3) calibration of mutual inductors, test coils, and instruments for measuring magnetic fields, and (4) investigations in the field of magnetics such as studies of phenomena associated with nuclear magnetic resonance or the selection and testing of materials suitable to be used as standards of magnetic susceptibility.

This monograph gives general information regarding magnetic quantities and units, the magnetic characteristics of various materials, and methods and apparatus commonly used in the Magnetic Measurements Section for magnetic testing.

2. Magnetic Quantities and Units

2.1. Systems of Units—Dimensions

For many years magnetic quantities have been expressed in the cgs electromagnetic [1] system of units. In this system the centimeter, gram, and second are taken to be the basic units in which the concepts length, mass, and time respectively are expressed. A three-dimensional system lacks the "resolving power" necessary to distinguish between the magnetic quantities denoted by the symbols B and H. The ratio between these two quantities in empty space, μ_v or μ_0, is arbitrarily assigned the value unity in this system and therefore μ_v or μ_0 is usually omitted from the equations without affecting the *numerical* values.

Another system based on the meter, kilogram, and second as the units of length, mass, and time respectively has been adopted by the International Electrotechnical Commission (IEC) and is rapidly gaining favor. It seems likely that this system eventually will replace the cgs system. In this system the ratio of B to H in empty space is not unity and consequently it cannot be ignored. A fourth dimension in addition to length, mass, and time is required to characterize magnetic and electrical quantities in this system. It must be electric or magnetic in nature. The IEC has chosen electric current, I, as the fourth dimension. When the four dimensions $LMTI$ are applied to magnetic quantities the distinction between B and H is clearly evident.

At the same time that the IEC adopted the mksa (Giorgi) system of units a further step was taken, namely, "rationalization." The object of rationalization is to transfer the factor 4π from linear equations to those having circular symmetry. In the rationalized system, the ratio of B to H in empty space,[2] Γ_m is $4\pi \times 10^{-7}$ h/m. By applying four dimensions to quantities in the cgs electromagnetic system (which is not inherently three-dimensional, as is ordinarily assumed) additional "resolving power" can be gained, the distinction between B and H then becomes clearly evident and mutual consistency between the two systems of units is brought about. The symbols L, M, T, and I denoting length, mass, time, and current respectively may be applied to either system.[3]

[1] There are two other cgs systems, namely the electrostatic system and the gaussian system, but in this monograph cgs means cgs electromagnetic unless otherwise specified.

[2] Since this is a true definitional constant, whereas the symbol μ denotes relationships usually not constant, the symbol Γ_m is used instead of μ_v or μ_v to avoid confusion.

[3] Many writers consider Q (quantity of electricity) to be a more simple concept than current and use it as the fourth dimension. The dimensions then are $LMTQ$.

2.2. Basic Quantities

There are two basic magnetic quantities and a constant from which all other magnetic quantities are derived. They are magnetic induction, B (often called flux density), magnetizing force or magnetizing field, H (also called magnetic field strength or magnetic intensity), and the magnetic constant Γ_m.

a. Magnetic Induction, *B*

A current-carrying conductor in a magnetic field experiences a mechanical force, the magnitude of which depends upon the magnitude of the current and the field, the length of the conductor and its orientation in the field. This dependence on direction and magnitude identifies the field as a vector field. Its direction is considered to be the direction of the conductor for which the mechanical force is zero. The quantity measured by the mechanical force experienced by a current-carrying conductor in a magnetic field is called *magnetic induction*, B.

If a linear conductor is perpendicular to the direction of the field and the field is uniform along its length

$$B=F/Il$$

where B=magnetic induction
F=mechanical force
I=current
and
l=length of the conductor.

There is another phenomenon by which the presence of a magnetic field can be detected and its magnitude determined. If a conducting loop or coil is placed in a magnetic field and the strength of the field is varied, the orientation of the coil in the field is changed or the coil is removed from the field, an electromotive force will be induced in the coil during the change. At any instant while a change is taking place

$$e=Na\ dB/dt$$

where e=instantaneous induced emf
N=number of turns in the coil
a=average area of the turns
B=magnetic induction
t=time.

Provided that B is uniform over the area a, the total change in induction, ΔB, in a given time is

$$\Delta B=\frac{1}{Na}\int_{t_1}^{t_2} edt.$$

The units for the cgs and mksa (Giorgi) systems are as follows:

Symbol	cgs	mksa (Giorgi)
B	gauss	tesla
F	dyne	newton
I	abampere	ampere
l	centimeter	meter
e	volt	volt
a	square centimeter	square meter
t	second	second

The dimension [4] of magnetic induction is

$$[B]=MT^{-2}I^{-1}.$$

b. Magnetizing Force, *H*

In view of the general acceptance of the concept that the magnetic behavior of materials is due to the presence within them of electrons in motion (spins or rotations) it is reasonable to conclude that magnetism is simply one of the manifestations of an electric current. Magnetic induction at a given point must therefore be due to the influence of electric currents. The magnetizing influence of an electric current is proportional to its magnitude and depends upon its geometrical configuration. The measure of the ability of an electric current to produce magnetic induction at a given point is called the magnetizing force (magnetic field strength or magnetic intensity), H.

At the middle of a very long uniformly wound solenoid

$$H=KNI/l$$

where H=magnetizing force
K=a constant depending on the system of units
N=number of turns
I=current
l=axial length of the solenoid.

The units for the two systems are as follows:

Symbol	cgs	mksa (Giorgi)
H	oersted	Ampere-turn per meter
K	4π	1
N	turn	turn
I	abampere	ampere
l	centimeter	meter

The dimension of magnetizing force is

$$[H]=L^{-1}I.$$

2.3. Magnetic Constant, Γ_m

The magnetic constant for any system of units is the proportionality factor in the expression relating the mechanical force between two currents

[4] The square brackets in a dimensional equation denote "the dimension of."

to their intensities and geometrical configurations. In differential form this may be written

$$d\mathbf{F}=\Gamma_m I_1 I_2 d\mathbf{l}_1 \times (d\mathbf{l}_2 \times \mathbf{r}_1)/nr^2$$

where

Γ_m is the magnetic constant

dF is the element of force of a current element

$I_1 dl_1$ on another current element

$I_2 dl_2$ at a distance r.

r_1 is a unit vector in the direction from l_1 to l_2

n is a dimensionless factor which is unity in unrationalized systems and 4π in rationalized systems.

The magnetic constant is also equal to the ratio of the magnetic induction, B, to the corresponding magnetizing force, H, in a vacuum. For this reason it is often called the permeability of space (or vacuum) and denoted by the symbol μ_v or μ_0. Since the symbol μ, with or without subscripts is used to denote several different relationships between B and H which in general are not constant, the symbol Γ_m is used to denote the magnetic constant. The value of Γ_m determines the system of units employed. In the classical cgs system the value of Γ_m is unity and it is a numeric. In the rationalized mksa (Giorgi) system its value is $4\pi \times 10^{-7}$ and the dimension is $LMT^{-2}I^{-2}$ (henries per meter).

2.4. Derived Quantities

The principal derived quantities are associated with the idea of a *magnetic circuit*, somewhat, but not exactly, analogous to an electric circuit. It is a magnetic structure which may contain one or more airgaps or other "nonmagnetic" materials and designed to contain certain continuous lines of magnetic induction. Ideally, none of the induction would escape from the circuit. However, since there is no insulator for magnetism, this ideal condition is rarely if ever realized. The magnetic flux which escapes from a magnetic circuit is called *leakage flux* or simply *magnetic leakage.*

a. Magnetic Flux, ϕ

Given a plane surface or cross section within the boundaries of which there is a uniformly distributed field of magnetic induction, B everywhere having a direction normal to the plane of the surface, the product of the induction, B, by the area, A, is the magnetic flux.

$$\phi=BA$$

where

ϕ=magnetic flux

B=magnetic induction uniformly distributed and normal to the plane of the surface of which

A=area.

If the induction is not uniformly distributed over the area, the surface integral of the normal component of B over the area is the magnetic flux

$$\phi=\iint \mathbf{B}\cdot d\mathbf{A}$$

where

ϕ=magnetic flux

B=Magnetic induction

and

dA=an element of area.

It is important to note that although both B and A are vectors, ϕ is a scalar and cannot have direction.

The units in the cgs and rationalized mksa systems are

Symbol	cgs	mksa
ϕ	maxwell	weber
B	gauss	tesla
A	cm^2	m^2

The dimension of magnetic flux is

$$[\phi]=L^2MT^{-2}I^{-1}.$$

b. Magnetomotive Force, $\mathscr{F}$

In a magnetic circuit, the line integral of the magnetizing force around the circuit is called the magnetomotive force. It is proportional to the total ampere-turns linked with the circuit.

$$\mathscr{F}=KNI$$

where

$\mathscr{F}$=magnetomotive force

N=number of turns

I=current

and

K=a constant depending on the system of units.

The units for the two systems are

Symbol	cgs	mksa
$\mathscr{F}$	gilbert	ampere-turn
N	turn	turn
I	abampere	ampere
K	4π	1

The dimension of magnetomotive force is $[\mathscr{F}]=I$.

c. Magnetic Reluctance, $\mathscr{R}$

The magnetic flux resulting from a given magnetomotive force acting on a magnetic circuit is determined by the magnetic reluctance $\mathscr{R}$, of the circuit. Thus

$$\phi=\mathscr{F}/\mathscr{R}$$

where

$$\phi=\text{flux}$$

$$\mathscr{F}=\text{magnetomotive force.}$$

and

$$\mathscr{R}=\text{magnetic reluctance.}$$

The units are

Symbol	cgs	mksa
ϕ	maxwell	weber
$\mathscr{F}$	gilbert	ampere-turn
$\mathscr{R}$	(5)	----------

The dimension of reluctance is $[R]=L^{-2}M^{-1}T^{2}I^{2}$.

TABLE 1. *Magnetic quantities and units*

Quantity and dimension (mksa)	Symbol	cgs Unit [a]		Name of rationalized mksa unit	To convert cgsem values to rationalized mksa values, multiply by
		Name	Equation		
Induction $MT^{-2}I^{-1}$	B	gauss	$B=\frac{F}{Il}$ (I in abamperes)	tesla (weber/m²)	10^{-4}
Magnetizing force $L^{-1}I$	H	oersted	$H=\frac{4\pi NI}{10l}$ (I in amperes)	ampere-turn per meter	$\frac{10^{3}}{4\pi}=79.58$
Magnetic Constant $LMT^{-2}I^{-2}$	Γ_m		$\Gamma_m=\frac{B}{H}$ (in vacuum)		$4\pi\times10^{-7}=12.57\times10^{-7}$
Flux $L^{2}MT^{-2}I^{-1}$	ϕ	maxwell	$\phi=\iint_A BdA$	weber	10^{-8}
Magnetomotive Force I	$\mathscr{F}$	gilbert	$\mathscr{F}=\int Hdl$	ampere-turn	$10/4\pi=0.7958$
Reluctance $L^{-2}M^{-1}T^{2}I^{2}$	$\mathscr{R}$		$\mathscr{R}=\frac{\mathscr{F}}{\phi}$		$10^{9}/4\pi=79.58\times10^{6}$
Normal permeability $LMT^{-2}I^{-2}$	μ		$\mu=\frac{B}{H}$		$4\pi\times10^{-7}=12.57\times10^{-7}$
Relative Permeability (dimensionless)	μ_r		$\mu_r=\frac{\mu}{\Gamma_m}$		(a)
Susceptibility (dimensionless)	k		$k=\frac{\mu_r-1}{4\pi}$		$4\pi=12.57$

[a] In this table, "cgs unit" refers to the unrationalized cgs electromagnetic system.

3. Magnetic Characteristics of Materials

3.1. Magnetic Permeability

Magnetic permeability, denoted by a symbol μ, with or without certain subscripts, is a term used to express various relationships between magnetic induction, B, and magnetizing force, H, in a material under specified conditions. The simplest relationship is the ratio of induction to the corresponding magnetizing force.

$$\mu=B/H.$$

This is usually called absolute permeability or simply the permeability. The term has a specific significance, however, only under certain definite conditions. For certain types of material the ratio is constant, not depending upon the degree of magnetization. For other materials the ratio depends upon the induction. If the corresponding values of B and H are determined by a standardized normal procedure (to be described later) the ratio of B to H is called the normal permeability. This is generally denoted by the symbol μ, without subscripts. It relates only to points on the normal induction curve. The symbol μ with various subscripts denotes either the normal permeability at specified values of B or H or the ratio of certain changes in B to the corresponding changes in H. In this discussion, the term permeability (symbol μ) denotes normal permeability.

Permeability has the dimension

$$[\mu]=LMT^{-2}I^{-2}$$

in the rationalized mksa system.

The symbol μ_r denotes the quantity called relative permeability. It is the ratio of the permeability of a material to that of space (or vacuum). Or it may be defined as the ratio of the permeability of a material to the magnetic constant.

$$\mu_r=\mu/\Gamma_m$$

Since this is the ratio of two quantities having the same dimensions, μ_r is seen to be a dimension-

[5] Previous to 1930 the cgs unit of reluctance was called the oersted, but the International Electrotechnical Commission, in 1930 adopted the name oersted for the cgs unit of magnetizing force, leaving the unit of reluctance without a name.

less ratio and its value is independent of the system of units. The absolute permeability is the relative permeability multiplied by the value of Γ_m pertinent to the system of units employed. In the cgs system, the value of Γ_m is unity so that the numerical value of the absolute permeability in this system is the same as that of the relative permeability. It is for this reason that in the cgs system the normal permeability is considered also to be a dimensionless ratio which leads to the conclusion that B and H are quantities of the same kind.

3.2. Magnetic Susceptibility

The magnetic induction, B, in a material due to a magnetizing force, H, is made up of two components, that induced in the space alone, $\Gamma_m H$, and that due to the magnetization[6] of the specimen, B_i. That is

$$B=\Gamma_m H+B_i.$$

The ratio of these two components is called the magnetic susceptibility, k

$$k=B_i/\Gamma_m H$$

since

$$B_i=B-\Gamma_m H$$

$$k=B_i/\Gamma_m H=(B/\Gamma_m H)-1=\mu_r-1.$$

This differs from susceptibility in the classical cgsem system by the factor 4π because in the cgsem system in which $\Gamma_m=1$, the equations are customarily written

$$B=H+4\pi J$$

$$J=(B-H)/4\pi$$

and

$$k=J/H=(B-H)/4\pi H=(\mu-1)/4\pi.$$

J is called intensity of magnetization and has the dimensions of magnetic induction. The ratio of J to H, therefore, has the dimensions of permeability although susceptibility is actually a dimensionless constant. However, in the cgsem system only three dimensions are employed, B and H are considered to be quantities of the same kind, and μ is a dimensionless ratio. In the mksa system as has been previously noted Γ_m is not unity and therefore in vacuum B is not equal to H, their ratio is not unity and so neither the values nor the dimension of Γ_m can be ignored as they are in the classical cgsem system.

Susceptibility is used to characterize materials whose permeability differs from unity by only a very small amount. The susceptibility of a material divided by its density, ρ, is called its mass susceptibility, χ.

[6] The component due to the magnetization of the specimen is called the intrinsic induction, B_i.

$$\chi=k/\rho$$

The mass susceptibility multiplied by the atomic weight A is called atomic susceptibility, χ_A.

$$\chi_A=\chi A$$

3.3. Classification of Materials [32]

The magnetic properties of materials result from the motions of electric charges within them. The motions are either rotation in orbits or spins about the axis of the charges. These motions constitute equivalent electric currents and therefore produce magnetic fields. The field-producing effect of an orbit or spin is called its *magnetic moment*. It is a vector whose direction is that of the axis of spin or of the normal to the plane of the orbit and whose magnitude is the product of the equivalent current and the area enclosed by its path. The magnetic moment of a magnetized body is the vector sum of its internal moments. Dimensionally, $[m]=L^2I$ where m is the magnetic moment.

In the past, materials have been classified as diamagnetic, paramagnetic, or ferromagnetic. However, two other classes are now recognized, namely, antiferromagnetic and ferrimagnetic. The magnetic properties of a single atom depend upon the relative locations and directions of spins of its electrons. The spin of the nucleus and orbital motion of the electrons constitute such small parts of the magnetic moment that they can generally be neglected. The moments of two electrons in the same orbit or shell whose spins are in opposite directions mutually cancel. An atom has a permanent magnetic moment if there is an excess of spins in one direction.

The magnetic properties of materials composed of associated atoms depend upon the arrangement of the atoms with respect to each other. This determines the kind of interactions between their magnetic moments. The forces of interaction (also called exchange forces) are functions of the ratio of the distance between atoms to the diameter of the orbit or shell in which the uncompensated spins are located.

Diamagnetic materials have no permanent magnetic moment. However, moments are induced by the influence of a magnetic field. The induced moments have a direction opposite to that of the inducing field. Consequently the relative permeability is less than unity. The diamagnetic susceptibility is negative. The diamagnetic susceptibility is very small, not more than a few parts in a million, and usually independent of temperature and applied magnetic field. It is probably present in all materials but usually masked by other larger effects.

Paramagnetic materials have a permanent magnetic moment but the interatomic spacing is so great that there is negligible atomic interaction. The relative permeability is greater than unity so the susceptibility is positive. Although the effect is greater than the diamagnetic effect, it is still very small, not more than a few parts in a hundred thousand. There are two kinds of paramagnetism called strong and weak. Except for high fields of the order of 10^4 gausses (1 tesla) or higher the strong paramagnetic susceptibility is constant with field at a given temperature but varies inversely with temperature at a given field. Weak paramagnetism is due to the effect of conduction electrons in conducting metals and is practically independent of temperature.

Ferromagnetic materials have a relative permeability greater than unity and generally very high. The permeability is not constant but depends upon the degree of magnetization. Ferromagnetic materials exhibit hysteresis, that is, the induction corresponding to a given magnetizing force depends upon previous magnetic history. Furthermore, the intrinsic induction approaches a limiting or saturation value as the magnetizing force is increased indefinitely. Ferromagnetism has sometimes been called a special case of paramagnetism but in view of the differences in the processes involved, it should not be so classified.

Ferromagnetic materials are temperature-sensitive and when the material is heated, the temperature at which it is transformed from the ferromagnetic condition to the paramagnetic condition is called the Curie temperature.

In ferromagnetic materials, the interatomic distances compared to the diameter of the orbit or shell in which the uncompensated spins are located are such that neighboring atoms have their magnetic moments alined parallel and in the same direction. This is called positive interaction. Not all of the moments in a body are oriented in the same direction. Instead, they are lined up in groups called domains which act as magnetic entities. Each domain is spontaneously magnetized to saturation but because they are oriented in various directions the resultant magnetization in any direction may be anything from zero to the saturation value at which all domains would be oriented in the direction of the applied field.

Antiferromagnetic materials are those whose interatomic distances are less than the critical value so that the magnetic moments of neighboring atoms line up parallel to each other but in opposite directions, that is, antiparallel. The susceptibility of these materials is so low that they might easily be mistaken for paramagnetic materials. The experimentally distinguishable characteristic is that the susceptibility increases instead of decreasing as the temperature is raised until the thermal agitation destroys the interaction. Above this temperature the material becomes paramagnetic. This is analogous to the Curie point in ferromagnetic materials but is called the Neèl point for this class of materials.

Ferrimagnetic materials are those in which unequal magnetic moments are lined up antiparallel to each other leaving a net permanent moment. Permeabilities are of the same order of magnitude as those of ferromagnetic materials but are lower than they would be if all the atomic moments were parallel and in the same direction.[7] Under ordinary conditions the magnetic characteristics of ferrimagnetic materials are quite similar to those of ferromagnetic materials.

3.4. Magnetic Hysteresis and Normal Induction

One of the important characteristics of ferromagnetic materials is the phenomenon of magnetic hysteresis. This phenomenon is illustrated in figure 1. If a demagnetized specimen is subjected to the influence of a magnetizing force, H, which is increased from zero to higher and higher values, the magnetic induction, B, also increases but not linearly with H. This is shown by a curve *oabcd*. This nonlinearity is another of the characteristics of ferromagnetic material.

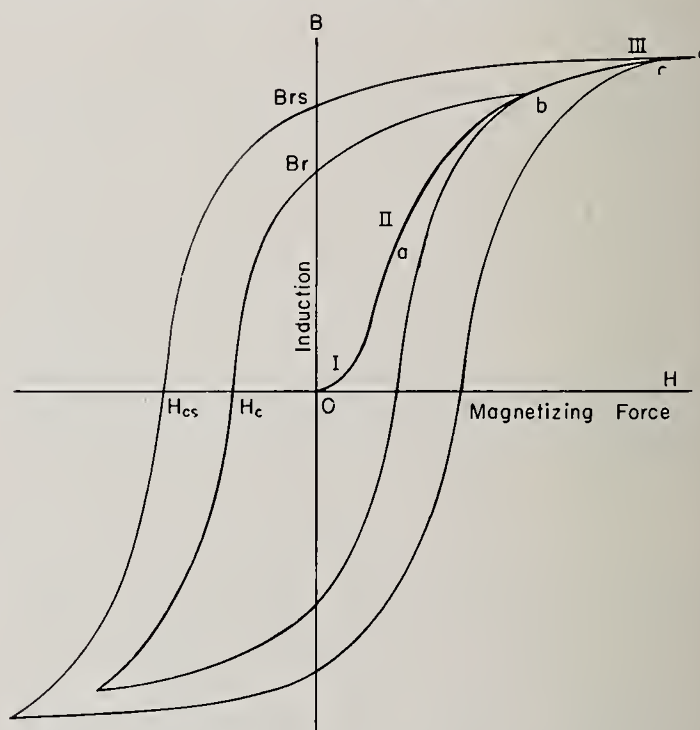

FIGURE 1. *Normal induction curve and hysteresis loops.*

If the increase in H is stopped at a point such as b and then decreased, the induction does not retrace the original curve in reverse order but lags behind it as indicated by the curve b, B_r, H_c, etc. This lag is called *magnetic hysteresis*. The point where the magnetizing force is zero is called the *residual induction*, B_r. The negative magnetizing force at which the induction becomes zero is called the *coercive force*, H_c. The closed curve starting from b through B_r, H_c, etc. back again to b is called a *hysteresis loop*. The loop does not always close at the first reversal of the magnetizing force but will close after enough reversals have been made.

[7] There is a technically important class of material called ferrites. The atomic interactions in these materials is mainly antiferromagnetic but there is a net magnetic moment which gives them ferromagnetic characteristics. The ferrites are ceramic bodies having extremely high electrical resistivity which makes them particularly valuable for use at high frequencies.

If the limits of H in each direction are equal, the limits of B in the two directions will also be equal and the material is said to be in a *symmetrically cyclic condition.* The induction at the tip of such a loop is called the normal induction. The ratio of B to H at this point is called the *normal permeability* $\mu = B/H$.

It is easy to see that the size of a hysteresis loop for a given material depends upon the value of induction at its tip. The *normal induction curve, oabcd,* is the locus of the tips of a family of cyclically symmetrical hysteresis loops.

The normal induction curve usually consists of three distinct stages. In stage I the rate of increase of B as H is increased is comparatively small. The steep part of the curve represents stage II of the magnetization. In this stage, a small increase in H produces a relatively large increase in B. In stage III the rate of increase of B is again small. In this stage the intrinsic induction, B_i, asymptotically approaches a limiting value which is called the *saturation induction,* B_s. For this reason, stage III is sometimes called the saturation range. Magnetic saturation is another of the distinguishing characteristics of ferromagnetic materials.

The magnetizing force and induction at the tip of a hysteresis loop are denoted by the symbols H_m and B_m, respectively. As B_m is carried higher and higher in the saturation range there comes a time when further increase does not produce any further increase in B_r and H_c. The maximum values of these quantities are called *retentivity,* B_{rs}, and *coercivity,* H_{cs}, respectively.

For permanent-magnet materials, the important part of the hysteresis loop is that portion in the second quadrant between the residual induction point, B_r, and the coercive force point, H_c. This is called the *demagnetization curve.* Points on this curve are designated by the coordinates B_d and H_d. The product of B_d and H_d for any point on the demagnetization curve represents the energy external to the magnet which could be maintained under ideal conditions. A curve obtained by plotting the products of the corresponding coordinates B_d and H_d as abscissas against the induction B_d as ordinates is called the *energy-product curve.* The maximum value of the energy-product, $(B_dH_d)_m$ is a good criterion of the relative quality of permanent magnet materials.

3.5. Core Loss

When materials are subjected to alternating magnetic fields, as in the cores of transformers, a certain amount of energy is expended which cannot be recovered but is dissipated in the form of heat. This loss of energy is called core loss. Core loss is made up of two major components, hysteresis and eddy currents.[8] The hysteresis loss depends upon the area of the hysteresis loop and the frequency of alternations. The eddy currents are induced in the core by the alternating magnetic flux and depend not only upon the frequency and maximum induction but also upon the electrical resistivity of the material, the thickness of the laminations, and the insulation between them.

4. Measurement of Static Magnetic Fields

4.1. General Principles

There are two aspects of a basic phenomenon by which magnetic fields can be measured. They are (1) the mechanical force experienced by a current-carrying conductor in a magnetic field or (2) the electromotive force induced in a conducting loop (test coil) when the magnetic induction encircled by or linked with the loop is changing, either because the induction is varying or because the loop is moving with respect to the induction. It is important to note that the quantity measured by either method is by definition magnetic induction, B. Magnetizing force, H, is calculated in terms of either electric current and its geometry or a measured value of B divided by the magnetic constant, Γ_m. In the cgs system, Γ_m is unity so there is no numerical difference between B and H. Consequently, it is general practice in certain cases to measure B and call it H. In the mksa system, Γ_m is not unity so it must be taken into account in determining the value of H in a magnetic field.

There are several additional methods by which magnetic fields can be measured. These are (1) change in electrical resistance due to a magnetic field, (2) the Hall effect, (3) behavior of saturable magnetic cores in a magnetic field, (4) optical effects, and (5) nuclear magnetic resonance.[9] The measurement of a magnetic field in terms of the mechanical force experienced by a current-carrying conductor is, of course, basic. However, accurate measurements by this method, although simple in principle, require somewhat elaborate apparatus and very careful experimental procedure. Such apparatus is not commonly available. A pivoted-coil arrangement is similar in principle and often used on account of its convenience if high accuracy is not required.

4.2. Pivoted Coil

A pivoted (or suspended) coil is essentially an inversion of the well-known d'Arsonval type of instrument. In the d'Arsonval instrument the coil is located in the constant field of a permanent magnet and its deflection against the restoring force of a spring or suspension is a measure of the current in the coil. The inversion consists

[8] A third component may be observed at high frequencies, but at lower frequencies it is usually negligible compared with the total loss.

[9] The methods commonly used in the field of terrestrial magnetism are not described in detail but only such methods as find application primarily in connection with the testing of materials are considered.

in substituting the field to be measured for the field of the permanent magnet. The coil, preferably without the usual iron cylinder within it, is mounted in a fixture so that it can be placed in proper position in the field to be measured. There are three different methods of making the measurements. The most convenient is employed in a commercially available instrument. By this method, the current necessary to produce a certain standard deflection is observed by means of a milliammeter connected in series with the coil and the adjusting resistors. Since the current is inversely proportional to the field, the milliammeter is calibrated in terms of the field strength in gausses. It would also be possible to observe the deflection of the coil due to a standard current or to measure the torque required to bring the deflection back to zero. The first mentioned method is most convenient. The presence of an iron core inside the moving coil is objectionable because it distorts the field being measured. One limitation of this type of instrument is that for accurate results the field must be uniform throughout the volume occupied by the coil so that fields of small extent cannot be accurately measured.

4.3. Pivoted Magnet

The pivoted coil has two disadvantages. It is too large to go into small spaces such as the gap in the magnetic circuit of a d'Arsonval instrument. Also it requires connections to a source of current. The development of permanent magnet materials having extremely high coercivity has made it possible to produce an instrument by which magnetic fields can be measured in terms of the torque on a very small magnet. This instrument, called a gaussmeter, consists of a light-weight shaft pivoted at each end and supported between jewels. A small cylindrical Silmanal magnet is mounted on the shaft near its lower end. At the other end is a hair spring for measuring the torque and a pointer which moves over a scale, calibrated in gausses. The magnet is about an eighth of an inch long in the direction of the shaft. It is magnetized in a direction perpendicular to the axis of the shaft. The moving system is enclosed in a thin-walled protective tube which extends perpendicularly from the back of a case which houses the scale and pointer. The pointer is mounted on the shaft in a direction parallel to the magnetic axis of the magnet so that when the pointer reads zero on the scale it also indicates the direction of the field in which the magnet is located. To measure the strength of the field, the instrument is rotated about the axis of the probe until the scale reading is a maximum. The axis of the magnet is then at right angles to the direction of the field and the scale reading shows its value in gausses. It is important to avoid exposing the magnet to a field greater than 5,000 gausses as the magnets cannot be stabilized for higher fields and therefore the calibration would be affected.

Alternating fields and fields greater than 5,000 gausses can be measured by a modified form of the instrument in which the Silmanal magnet is replaced by a cobalt-plated surface on soft iron. By this system, the general direction of the field can be determined, but not its polarity.

The gaussmeter is regularly furnished with probes either 1¼ in. or 5 in. long and diameters of 0.052 in. or 0.090 in.

4.4. Ballistic Methods

Ballistic methods are so called because they employ a ballistic galvanometer. In making a measurement, a test coil connected to a ballistic galvanometer is placed in the field with its axis in the direction of the field and the deflection of the galvanometer is noted when the test coil is either suddenly removed from the field or rotated 180° about its diameter.[10] This produces an impulsive current in the galvanometer circuit which is proportional to the total change in linkage between the field and the test coil.

a. Ballistic Galvanometer

The ballistic galvanometer commonly used for magnetic measurements is a moving-coil instrument of the d'Arsonval type.[11] It is an instrument for integrating electrical impulses of short duration. The coil is usually suspended but some pivoted-coil instruments are also in use. The moment of inertia of the coil is high and the restoring force due to the suspension or spring is low so that the natural period on open circuit is long, usually of the order of 20 sec or more. The behavior of the galvanometer is controlled mainly by the amount of resistance in its circuit. This determines the amount of electromagnetic damping due to the current induced in the coil as it moves in the field of the permanent magnet. The damping due to air friction is usually negligible compared to the electromagnetic damping.

If the external resistance has a certain critical value, the return of the coil to its zero position after a deflection occurs in a minimum of time without oscillation. This is called critical damping. The external resistance for critical damping is an important characteristic of a ballistic galvanometer.

If the external resistance is greater than the critical value, the return to zero after an impulse is by a series of oscillations of continually decreasing amplitude. The galvanometer is then said to be underdamped.

If the external resistance is less than the critical value, the galvanometer is overdamped. The maximum deflection for a sudden impulse comes sooner than when critically damped but

[10] If the field arises from an electromagnet the field may be reversed by reversing the current in the magnetizing coil.

[11] For an excellent detailed discussion of the theory and operation of the ballistic galvanometer see Harris, Electrical Measurements, pp. 301–341, Wiley, 1952.

the return to zero is slow. For magnetic measurements, the ballistic galvanometer is usually used in the overdamped condition. Some operators, however, like to have the galvanometer critically damped or very slightly underdamped. Under this condition it is necessary that the impulse be complete before the coil has moved appreciably from its zero position. Otherwise, if the impulse is prolonged, the integration will not be complete and the reading will be low.

For measurements of magnetic fields it is usually possible to produce sudden brief impulses but in the testing of ferromagnetic materials, the impulses are likely to be of such long duration that it is necessary to use a very heavily overdamped galvanometer if good accuracy is to be obtained. As a rule, the intrinsic sensitivity of a ballistic galvanometer is sufficiently high to permit an increase in damping by shunting the galvanometer as shown in figure 2. The figure shows alternative methods of connecting a ballistic galvanometer to a test coil. The choice of methods is a matter of taste. In both diagrams *TC* is the test coil, *RS* is a series resistor for adjusting the sensitivity, and *RP* is a resistor connected in parallel with the galvanometer when the key *K* is closed on the lower contact. In diagram *A* the galvanometer can be short-circuited by closing *K* on the upper contact. This will stop the motion of the coil almost instantly if it is swinging. In diagram *B* the resistor *RC* is permanently connected to the galvanometer and so adjusted that when key *K* is open the galvanometer is critically damped. This allows the galvanometer coil to return to its zero position after a deflection in minimum time without oscillation.[12] Some operators omit *RP* when this connection is used.

If the restoring force could be made zero, the only control of the galvanometer deflection would be the electromagnetic damping.[13] The motion of the galvanometer coil would then follow the change in flux linkage in the test coil exactly and the final deflection would not be influenced by the time taken by the change. An instrument whose torsional restraint is so small that this condition is closely approximated is called a fluxmeter. As a rule, however, it is more convenient to have a suspension or spring stiff enough to give a fairly stable zero. A galvanometer which is sufficiently overdamped to approach the performance of a true fluxmeter is said to have fluxmeter characteristics.

If the circuit of a galvanometer with a weak suspension or spring is not free of temperature gradients or contacts between dissimilar metals, thermal electromotive forces may be very troublesome by causing an unsteady zero and spurious deflections. Also, it is desirable to have a method for setting the galvanometer exactly on zero quickly and easily. Figure 3 is a diagram of a

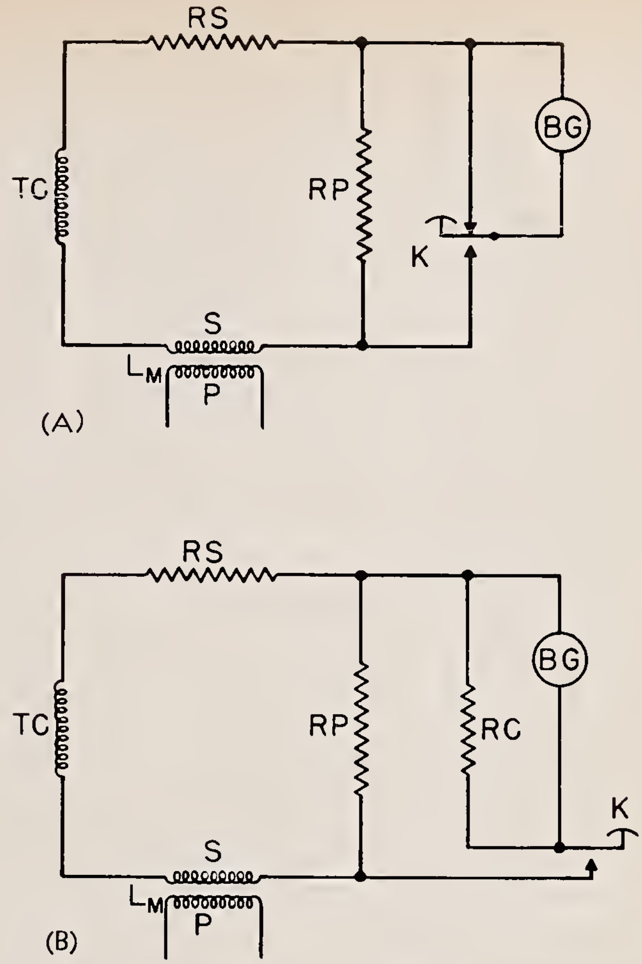

FIGURE 2. *Connections for ballistic galvanometer.*

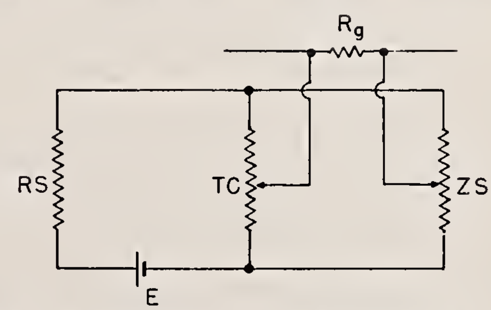

FIGURE 3. *Zero adjuster and thermal emf compensator.*

device which has been found to be very useful. Two slide-wire resistors are connected in parallel to a small dry cell through a high resistance. The two sliders are connected to opposite ends of a resistor of low value which is inserted in the galvanometer circuit. Contact *ZS* has a detent so that it can always be set at the same position. To compensate for thermal emfs, the slider *TC* is set so that the galvanometer does not drift when contact *ZS* is on the detent. To set the zero, contact *ZS* is moved one way or the other till the galvanometer reads zero. It is then quickly returned to its neutral position. The galvanometer is calibrated by means of a mutual inductor of known value whose secondary winding (in fig. 4) is connected permanently in series with the test coil.[14] It is often convenient to adjust the sensi-

[12] In practice the resistance is often adjusted so that the galvanometer is slightly underdamped and will pass beyond zero once before coming to rest. This makes it possible to be sure that the coil is swinging freely between the pole pieces without friction.
[13] Except for a slight amount of air damping which usually is negligible.

[14] If necessary, to avoid the possible effects of stray fields, a noninductive resistance equal to that of the secondary coil may be substituted for the coil after calibration.

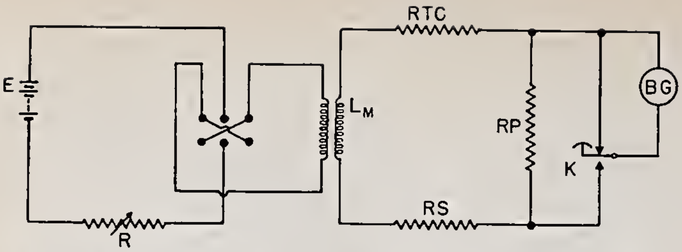

FIGURE 4. *Calibration circuit for ballistic galvanometer.*

tivity so that the scale is direct reading in terms of induction thus avoiding the necessity of multiplying the reading by an odd-valued scale constant to obtain the value of the field in specified units. The calibrating current which must be switched in the primary of the mutual inductor is calculated by the formula

$$I_c = \frac{KBaN}{L_m}$$

where

I_c=current

K=a constant dependent upon the system of units

B=induction

aN=area-turns of the test coil

L_m=mutual inductance.

In the cgs system I_c is in amperes, B is in gausses, aN is in cm²-turns, L_m is in henries, and K is 10^{-8}. In the mksa system I_c is in amperes, B is in teslas, aN is in m²-turns, L_m is in henries, and K is unity.

If the field is to be measured by withdrawing the test coil, the resistance in the galvanometer circuit is adjusted so that when I_c is suddenly reduced to zero the deflection is 10 cm. If the field is to be measured by flipping the coil through 180° or by reversing the field, the galvanometer is adjusted to read 10 cm when I_c is reversed. If the value of H is desired, it is only necessary to divide the observed value of B by Γ_m. In the cgs system Γ_m is unity so that H is numerically the same as B. In the mksa system Γ_m is $4\pi \times 10^{-7}$ so that it is not possible as it is in the cgs system simply to measure B and call it H.

b. Intercomparison of Mutual Inductors and Calibration of Test Coils

At the National Bureau of Standards the standard of mutual inductance is one built with considerable care for use in determining the unit of resistance. The value of mutual inductance has been computed in terms of the dimensions of the inductor and is known to a few parts in a million. Since ballistic magnetic measurements are carried out with direct currents, the working standards of mutual inductance are calibrated by comparison with the primary standard using a direct-current method somewhat similar to one proposed by Maxwell [1].[15] A diagram of connections is shown in figure 5. L_{m1} and L_{m2} are the mutual inductors to be compared. L_{m1} must have the greater value. The primary windings are connected in series to the battery, B, through the reversing switch, S, the rheostat, C, and the ammeter, A. The secondary windings are connected so as to oppose each other. R_1 and R_2 are adjustable precision resistors. It is important that the ballistic galvanometer, Ⓖ, be connected as indicated because if it is connected between points E and G leakage currents might give trouble unless the insulation between coils in the inductors is practically perfect. A measurement is carried out as follows. With switch S_b closed R_1 is set at some convenient value and the primary current is set at a value not exceeding the current-carrying capacity of the primary windings of the inductors. R_2 is then adjusted so that upon reversal of the primary current by switch S there is no residual deflection of the galvanometer. If the self-inductances of the secondary windings of the two inductors are not equal there may be a small double kick but this is generally not troublesome. When balance is obtained, the value of L_{m2} is

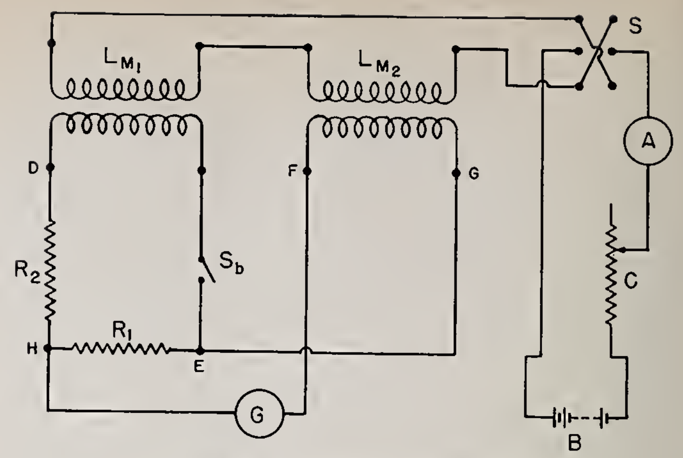

FIGURE 5. *Diagram of connections.*

$$L_{m2} = L_{m1} \frac{R_1}{\Sigma R}.$$

ΣR is the total resistance of the secondary circuit of L_{m1} including R_1, R_2, the secondary winding of L_{m1}, and all the leads. The excess over $R_1 + R_2$ is determined by setting R_1 and R_2 to zero, opening switch S_b, and measuring the resistance of the rest of the circuit by means of a Wheatstone bridge connected across S_b. Correction for the resistance of the leads to the bridge can be made by measuring their resistance with switch S_b closed. The usual precautions should be taken against the effect of stray fields. Leads should be twisted and the two inductors should be located at some distance from each other and so oriented that no interaction between the primary of one inductor and the secondary of

[15] Figures in brackets indicate the literature references on page 33.

the other can be observed. Some errors may result from capacitance between the primary and secondary circuits. This can be minimized by repeating the observations after reversing the connections of the primary of one inductor and the secondary of the other and averaging the results.

It is usually not feasible to calculate the value of area-turns of a test coil with a satisfactory degree of accuracy, especially if it has more than one layer. It is much better to determine the value experimentally. If a test coil is placed at the middle of a long slender solenoid whose pitch of winding is uniform and accurately known, its area-turns can be calculated from the mutual inductance between the solenoid and test coil and the induction per unit current in the solenoid. The mutual inductance can be determined by the method described above. It is important that the axis of the test coil be alined with that of the solenoid. The error due to lack of alinement is proportional to $1-\cos\theta$ where θ is the angle between the two axes. If the angle is less than 2.5°, the error from this source will not exceed 0.1 percent.

The value of area-turns is calculated from the equation

$$(aN)=KL_m/C$$

where

aN= area-turns

K= a constant depending on the system of units

L_m= the mutual inductance

C= the value of induction per ampere in the solenoid.

In the cgs system, K is 10^8, L_m is in henries, and C is in gausses per ampere. Area is then in square centimeters. In the mksa system K is unity, L_m is in henries, C is in teslas per ampere, and area is in square meters.

If a coil whose area-turns value is to be determined is too large to insert in an available solenoid or has a handle which cannot be detached, the calibration field may be obtained by means of a Helmholtz arrangement. This consists of two identical very short coaxial coils, the axial distance between them being equal to their radius. This produces a very uniform field along about the middle third of the axis between the coils. If a is the radius in centimeters, N is the number of turns in each coil, and i is the current in amperes, the magnetizing force at the midpoint between the two coils is

$$H=\frac{0.4\pi Na^2i}{\left(\frac{5a^2}{4}\right)^{3/2}} \text{ oersteds.}$$

This reduces to

$$H=\frac{0.8991Ni}{a} \text{ oersteds.}$$

To convert to ampere turns per meter (mksa units) multiply by $10^3/4\pi=79.58$. If coils having very small values of area-turns are to be tested this can be done in the field between the poles of an electromagnet. The field must be uniform over the area of the test coil and measured by a standard method. Since it is generally not feasible to reverse the current in the electromagnet, the reading must be made either upon suddenly removing the coil from the field or preferably by rotating it through 180° about an axis which is perpendicular to the direction of the field.

4.5. Rotating Test Coil

A continuously rotating test coil can be used to measure magnetic fields. The coil is rotated at constant speed about a diameter. It is connected through a commutator or cam-operated reversing switch to a d-c instrument which indicates the average voltage induced in the coil. If the reversal comes at the time when the a-c voltage induced in the coil is zero, the reading on the instrument will be a maximum and will be proportional to the magnetic field. Commercial instruments operating on this principle have the rotating coil at the end of a long shaft which has at its other end a synchronous motor. The shaft has to be long enough to avoid errors due to stray fields from the motor. The accuracy of the measurement depends directly upon the accuracy with which the frequency of the power source is controlled. The apparatus is generally calibrated by observations in known fields.

4.6. Bismuth Spiral [2]

One of the so-called secondary effects which is utilized to measure magnetic fields is the change in electrical resistance of a conductor when it is subjected to the influence of a transverse magnetic field. Most metals show this effect, but only in bismuth is it sufficiently large to be of practical value for the measurement of magnetic fields.

The bismuth spiral is made of small insulated bismuth wire wound bifilarly in a flat spiral, all the turns being in one plane. The ends are usually soldered to heavy copper leads. The spiral is held in place and protected from mechanical damage by thin discs of mica which are fastened to the copper leads. The diameters of the spirals range from 0.5 to 2.0 cm and they are ordinarily about a millimeter thick overall. It is essential that the bismuth be of very high purity. Otherwise, anomalous and uncertain results will be obtained. The major difficulty encountered in the use of a bismuth spiral is that it has two temperature coefficients; not only does bismuth have the ordinary temperature coefficient in the absence of a magnetic field but also the change in resistance due to a magnetic field depends upon the temperature. If proportional change in resistance is plotted against the value of magnetic field, the curve is not linear below about 5,000 gausses. Above this value the curve is practically linear but the projection of the linear part does not pass through zero.

Bismuth spirals are not much used at present but the principle might be useful for some applications.

4.7. Hall Effect

The Hall effect furnishes a very convenient means for the measurement of magnetic fields. Instruments are available which utilize this principle. It can be very simply stated as follows. If a thin strip or film of metal, usually bismuth, indium antimonide, or indium arsenide, has a current in it, two points can be found at opposite ends of a line approximately at right angles to the current which will be at the same electrical potential if no magnetic field is acting. If a magnetic field is applied at right angles to the plane of the strip a difference of potential appears between the two points. This difference of potential is proportional to the intensity of the magnetic field. In practical instruments a-c is used so that the emf produced by the action of a magnetic field can be amplified and thus provide increased sensitivity. Calibration is carried out in magnetic fields of known value.

4.8. Saturable Core

A saturable core[16] is one which reaches practical saturation under the influence of a relatively low magnetic field. Thus a very small change in the effective magnetizing force will produce a large change in the inductance of a coil containing a saturable core. This principle is used for the measurement of magnetic fields. This is done by energizing a coil containing a saturable core with alternating current. The frequency is usually a few kilocycles per second. If a steady magnetizing field such as that of the earth is also present, there will be induced in the circuit a second harmonic component. This second harmonic voltage is proportional to the intensity of the superposed steady field. The steady field is determined in either of two ways. The amplified second harmonic voltage may be filtered out and measured or the steady field may be neutralized by means of direct current in a coil surrounding the core. When this is done, the second harmonic voltage disappears. The value of the field is then calculated in terms of the direct current, and the turns and dimensions of the coil. This is the more precise method because variations in the amplifier only change the sensitivity with which the balance can be made. If the second harmonic voltage is measured directly, the apparatus must be calibrated in fields of known values.

4.9. Nuclear Magnetic Resonance

Nuclear magnetic resonance is another phenomenon by which it is possible to measure homogeneous magnetic fields with very high accuracy. The measurement is based on the equation

$$2\pi\nu=\gamma_p B$$

or transposing,

$$B=\frac{2\pi\nu}{\gamma_p}.$$

In this equation B is the field in gausses, ν is the resonance frequency in cycles per second and γ_p is a quantity called the gyromagnetic ratio. The gyromagnetic ratio γ_p is the ratio of the magnetic moment of a nucleus to its angular momentum.

The measurement is made by immersing a sample of material containing nuclei, whose gyromagnetic ratio is known, in the steady field to be measured. The sample is then subjected by means of a surrounding coil to an alternating magnetic field at right angles to the steady field. The frequency of the alternating field is adjusted to be equal to the resonance frequency of the nuclei in the sample. At this frequency which is directly proportional to the intensity of the steady field there is an absorption of energy from the exciting circuit. This is generally observed by means of a cathode ray oscilloscope. B is then calculated, using the equation

$$B=\frac{2\pi\nu}{\gamma_p}\text{ gausses}$$ [17]

where ν is the resonance frequency and γ_p is the gyromagnetic ratio.

5. Tests With Direct Currents

5.1. Testing of Materials

General Principles. The principal object of testing ferromagnetic materials by d-c methods is to obtain data from which normal induction curves and hysteresis loops can be plotted. This is done either by using suitably shaped specimens such as rings which constitute the entire metallic part of the magnetic circuit or by means of permeameters.

A permeameter is a magnetic circuit provided with magnetizing and test windings in which a test specimen can be inserted so as to compose a part of the circuit. Since there is no material which acts as an insulator with respect to magnetism, the magnetic circuit must be arranged so as to produce the greatest possible uniformity in the distribution of magnetic induction across the section and along the length of that part of the specimen directly involved in the test. Several permeameters have been developed which differ

[16] Several devices using this principle are described in the book, Saturating Core Devices, by L. R. Crow, The Scientific Publishing Company, Vincennes, Indiana.

[17] To convert from gausses (cgs) to teslas (mksa) multiply by 1×10^{-4}.

from each other in form of magnetic circuit and method of determining corresponding values of H and B. In the Koepsel [3] and Esterline [4] permeameters. the ends of the specimen are clamped between iron pole pieces resembling those of a d'Arsonval instrument but much larger. The magnetizing winding surrounds the specimen. Compensating coils in series with the main magnetizing winding are mounted on the pole pieces. Their function is to compensate for the magnetic reluctance of the pole pieces. In the Koepsel apparatus there is a regular d'Arsonval moving coil whose pointer gives an indication of the value and direction of B in the specimen when there is a current of fixed value in the coil. Values of H are estimated in terms of the current in the magnetizing winding. In the Esterline apparatus, the d'Arsonval coil is replaced by a rotating armature. When this armature is driven at a constant speed the induced voltage is taken to be a measure of B in the specimen. Neither of these permeameters is capable of very high accuracy and neither is at present in common use.

Other permeameters have been developed by DuBois [5], Hughes [6], Picou [7], Iliovici [8], Niwa [9], and Burrows [10]. The Burrows permeameter is based on the principle of so distributing the magnetomotive force around the magnetic circuit that there is negligible magnetic leakage, at least from the specimen under test. It was for many years accepted as the standard apparatus for d-c magnetic testing. However, the operation of this apparatus is tedious and time-consuming and is unduly sensitive to nonuniformity in magnetic properties along the length of the specimen. Also, it requires two similar specimens. The MH permeameter [11] was developed with the object of eliminating or minimizing these drawbacks and has been adopted by the Magnetic Measurements Section as the standard method for d–c magnetic testing in the range of magnetizing force up to 300 oersteds (approximately 24×10^3 amp-turns/m). The Fahy Simplex permeameter [12] has been in general use for many years for tests in the same range of magnetizing force and for this reason is used for testing when so requested. The advent of very hard magnetic materials requiring the use of very high magnetizing forces for testing led to the development and adoption of the High-H permeameter [13] for magnetizing forces up to 5,000 oersteds (approximately 40×10^4 amp-turns/m).

These three methods, the MH, High-H, and Fahy Simplex permeameters, are called ballistic methods because a ballistic galvanometer is employed in the measurements.

In ballistic tests, values of B are obtained in terms of the deflection of a ballistic galvanometer connected to a test coil (B-coil) surrounding the specimen. The deflection is proportional to the change in the induction linked with the test coil. If the change is simply a reversal in direction, then the induction is one half of the observed change. There are two ways in which values of H may be determined. One way is to calculate it in terms of the current-turns per unit length at a given section of the magnetic circuit. This is the method employed in the testing of ring specimens and in the Burrows permeameter. The other way is to determine B in the air at a suitable location and calculate the value of H from the equation

$$H=B/\Gamma_m.$$

Since $\Gamma_m=1$ in the cgsem system, it has become general practice to determine B[18] and call it H. This does not lead to a *numerical* error in the cgsem system. It has also become general practice to call the coils by which this determination is made H-coils. If H is calculated in terms of current the magnetic circuit and magnetizing windings must be so arranged that there is no magnetic leakage from the part of the specimen over which the B-coil extends and the magnetizing winding must be uniformly distributed over the same portion of the specimen. This is the principle involved in the Burrows permeameter and approximated in the ring test.

If H is determined ballistically, it is not necessary that the magnetizing winding surround the section of the specimen surrounded by the B-coil but the magnetic circuit must be so arranged that the field of induction in the region adjacent to the specimen occupied by the H-coil is uniform or if not it must be possible to extrapolate to the surface of the specimen. This is the underlying principle of the MH and High-H permeameters.[19]

In ballistic tests, as described earlier, the galvanometer is calibrated by means of a mutual inductor whose secondary winding is part of the galvanometer circuit. Excepting during calibration, the secondary winding may be replaced by a noninductive resistor having the same resistance. This is to avoid errors which might be caused by pickup from other parts of the circuit.

It is customary to adjust the sensitivity of the galvanometer so that the scale is direct-reading in terms of induction or magnetizing force. Thus, in the cgs system, the magnetic induction on reversal may be 1,000 gausses/cm of deflection or the magnetizing force may be 1, 10, or 100 oersteds/cm. By this procedure the necessity of multiplying the scale reading by an odd-valued factor is avoided. If H is measured in terms of current in the magnetizing winding, only the calibration for B needs to be made.

The calibrating current for a selected value of B is given by the equation

$$I_c=\frac{KBAN}{L_m}$$

[18] Any quantity determined in terms of an induced emf in a test coil is *by definition* B and not H.

[19] The Fahy Simplex permeameter operates on a somewhat different principle and is described later.

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where

I_c=calibrating current in amperes
K=a constant depending upon the system of units.
B=the selected value of induction
A=the cross sectional area of the specimen
N=number of turns in the test coil
L_m=mutual inductance in henries.

In the cgs system K is 10^{-8}, B is in gausses, and A is in square centimeters.

In the mksa system, K is unity, B is in teslas, and A is in square meters.

In calibrating for a selected value of H the equation becomes

$$I_c=\frac{K\Gamma_m HaN}{L_m}$$

where

I_c=calibrating current in amperes
K=a constant depending upon the system of units.
Γ_m=the magnetic constant
H=the selected value of magnetizing force
aN=area-turns of the test coil
L_m=mutual inductance in henries.

In the cgs system K is 10^{-8}, Γ_m is unity, H is the selected value of magnetizing force in oersteds, and aN is the area-turns of the test coil in cm²-turns.

In the mksa system, K is unity, Γ_m is $4\pi\times10^{-7}$, H is the selected value of magnetizing force in ampere-turns per meter, and aN is area-turns in m²-turns.

Since the calibration is usually made by reversal of the calibrating current, care must be taken when measuring changes in induction or magnetizing force as in the determination of points on the hysteresis loop to multiply the readings by 2.

Because the area of the B-coil is larger than that of the specimen, a correction must be made to the observed value of B to account for the "air" flux existing in the space between the coil and the specimen. Thus the induction, B, is

$$B=B_{\mathrm{obs}}-k\Gamma_m H$$

where

B_{obs}=observed value of B (for specimen of area A)
$k=\frac{a-A}{A}$
a=area of the test coil
A=area of the specimen
Γ_m=the magnetic constant
H=the magnetizing force.

In the cgs system, B is in gausses, Γ_m is unity and H is in oersteds. In the mksa system, B is in teslas, Γ_m is $4\pi\times10^{-7}$ and H is in ampere-turns per meter.

k is a numeric and has the same value in either system.

In making observations of normal induction, the specimen should first be demagnetized to eliminate latent polarization due to previous magnetization. This is done by subjecting it to the influence of reversals of magnetizing force of gradually decreasing magnitude starting from a peak value well into the third stage of magnetization. The frequency of reversal should be low enough so that induced eddy currents will not interfere with the demagnetizing process. About 1c/s has been found satisfactory for the average case. If the specimen does not compose the entire magnetic circuit and has a small cross section compared with the rest, it may be necessary to demagnetize the rest of the magnetic circuit using a larger specimen and then to repeat the process with the smaller specimen in place. After demagnetization, the magnetizing current is set at the value corresponding to the lowest point desired and reversed several times until successive readings of the induction are the same. The specimen is then in a symmetrically cyclic condition and the observed induction is the normal induction. The corresponding magnetizing force is then determined either by taking a ballistic deflection or by observing the magnetizing current according to the type of apparatus being used. Additional points on the normal induction curve are determined in the same way. Demagnetization need not be repeated if each point so determined is higher than any preceding one. It is the practice of some observers to start with the highest point and then to demagnetize from each point to the next lower one. This is sometimes preferable, especially if the specimen is likely to be heated unduly.

If points on a hysteresis loop are to be determined, cyclic condition is first obtained by several reversals of the magnetizing current corresponding to the tip of the loop and the resulting values of B and H observed. The current is then suddenly reduced in value by inserting additional resistance in the magnetizing circuit. For points on the negative side of the H-axis, the current is simultaneously reversed and reduced. The observed changes in B and H are subtracted from the values at the tip and the results thus obtained are taken to be the coordinates of the required point on the hysteresis loop.

The process is repeated for other points, care being taken to reestablish cyclic condition at the tip before each observation.

In setting up apparatus for ballistic testing, it is important to twist the conductors in both primary and secondary circuits and so to locate the mutual inductor with reference to the rest of the apparatus as to prevent errors due to stray fields.

5.2. Ring Method

Although a ring would appear to be the ideal form of specimen for magnetic testing, it has certain disadvantages which should always be taken into account. The principal advantage is the absence of airgaps and end effects.

In the cgs system, H is calculated using the equation

$$H=\frac{0.4\ N\ I}{D}$$

where

H=magnetizing force in oersteds
N=number of turns in winding
I=current in amperes
D=mean diameter of the ring in cm.

To convert to rationalized mksa units (ampere-turns per meter) multiply by $1000/4\pi=79.58$. This calculation is sufficiently accurate for most purposes provided that the mean diameter of the ring is large compared to its radial width. Since the outer circumference of the ring is greater than the inner circumference, the turns per unit length are less on the outside than on the inside and consequently the magnetizing force is not uniform across the section. Table 2 shows the ratio of the average value of H to that at the mean radius in rings of either circular or rectangular cross section. For difference no greater than 1 percent, a ratio of at least 10 of mean diameter to radial width is usually recommended.

Table 2. *Ratio of average value of* H *to value at mean radius in rings of rectangular and circular sections* [13]

Ratio of diameter to radial thickness	H_a/H_r	
	Rectangular	Circular
2	1.0986	1.0718
3	1.0397	1.0294
4	1.0216	1.0163
5	1.0137	1.0102
6	1.0094	1.0070
7	1.0069	1.0052
8	1.0052	1.0040
10	1.0033	1.0025
19	1.0009	1.0007

It is not safe to assume, however, that simply making the ratio 10 or more assures accurate results. Errors may also result from irregularity in winding or from nonuniform magnetic properties along the circumference of the ring. Irregularity in winding can be minimized by the exercise of extreme care in winding or by the use of a winding machine. However, errors due to nonuniformity in the specimen which can neither be calculated nor conveniently determined experimentally may be large and therefore, the use of ring specimens as reference standards for checking the accuracy of other methods is not recommended. The method is also limited to low magnetizing forces which can be applied without producing excessive heating.

In spite of the disadvantages of the ring specimen for measurements of high accuracy or for standardizing purposes, this form of specimen is widely used in production testing for quality control or the development of new materials, notably the ferrites. Its use has been greatly facilitated in recent years by the development of a machine by which extremely uniform windings can be rapidly applied. The secondary winding is applied first so as to minimize the effect of air-flux between coil and specimen.

A diagram of connections for the ring test is shown in figure 6. Current is derived from the battery, B, controlled by the resistors R and R', and measured by the ammeter A or some more precise method for measuring current. The current can be reversed by switch C or reduced by opening switch C', or reversed and reduced by operating both switches simultaneously. If switch D is closed upward the current is in the magnetizing coil M. If D is closed downwards, the current will be in the primary winding, P, of the calibrating inductor.

The secondary or test winding, T, is connected in series with the secondary winding of the inductor and the series resistor, RS, and the parallel resistor, RP, as shown. The ballistic galvanometer is connected through the key k across the resistor RP.

The procedure for making a test is described on p. 13 et seq.

5.3. Straight Bar and Solenoid

It is possible to make ballistic tests with a straight specimen of uniform cross section magnetized in a solenoid. In this case, the determination of the magnetic induction at the mid-section of the bar offers no particular difficulty. The principal problem lies in the determination of the magnetizing force. This arises from the fact that the magnetic circuit comprises not only the bar but also the air-space in which the lines of

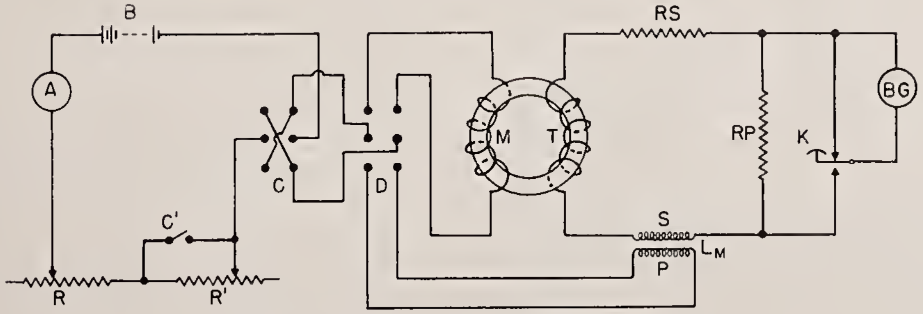


Figure 6. *Connections for the ring test.*

Table 3. *Demagnetizing coefficient and factor*

D=ratio of length to diameter	$H=H'-\frac{NI}{\Gamma_m}$			$H=H'-\frac{D_B B_i}{\Gamma_m}$				Equation [a]	
	Ellipsoid	Mann [14]		Du Bois [15]		Shuddemagen [16]			
	N	N	D_B	N	D_B	N	D_B	N	D_B
10	0.2549	0.2550	0.0203	0.2160	0.0172	0.2000	0.0159	0.2512	0.0200
15	.1350	.1400	.0111	.1206	.0096	.1040	.0083	.1235	.0098
20	.0848	.0898	.00714	.0775	.0062	.0655	.0052	.0747	.0059
30	.0432	.0460	.00366	.0393	.00313	.0335	.00267	.0367	.00292
40	.0266	.0274	.00218	.0238	.00189	.0206	.00164	.0222	.00176
50	.0181	.0183	.00146	.0162	.00129	.0139	.00110	.0150	.00119
60	.0132	.0131	.00104	.0118	.00094	.0101	.00080	.0109	.00087
70	.0101	.0099	.00080	.0089	.00071	.0077	.00061	.0083	.00066
80	.0080	.0078	.00062	.0069	.00055	.0061	.00049	.0066	.00052
100	.0054	.0052	.00041	.0045	.00036	.0041	.00033	.0045	.00035
150	.0026	.0025	.00020	.0020	.00016	.0020	.00016	.0022	.00017
200	.0016	.0015	.00012	.0011	.00009	.0012	.00009	.0013	.00011

[a] $\log_{10}N=1.15-1.75\log_{10}D$
$\log_{10}D_B=0.05-1.75\log_{10}D$

NOTE: The above values of N and D_B are calculated for cgsem system of units.

induction extend from one end of the bar to the other. Thus the total magnetomotive force is not confined to the space within the solenoid and consequently the magnetizing force available for the bar is less than would be calculated in terms of the ampere-turns per unit length in the solenoid. Classical theory attributes this diminution to the effect of fictitious poles near the ends of the specimen and therefore the effect has been called a "demagnetizing" effect. The effect is expressed by the equation

$$H=H'-\frac{D_B B_i}{\Gamma_m}$$

where

H=the effective magnetizing force

H'=the apparent magnetizing force

D_B=the demagnetizing coefficient

B_i=intrinsic induction

Γ_m=the magnetic constant.

In the cgs system, Γ_m is 1. In the rationalized mksa system, Γ_m is $4\pi\times10^{-7}$.

Except for ellipsoids of revolution, D_B cannot be calculated but must be determined experimentally. It has been found that the demagnetizing coefficient is practically constant up to about the top of the second stage of magnetization. Above this the value decreases with increased induction. Within the linear range, the value for bars of circular section is a function of the ratio of the length to diameter of the specimen [20] but published tables by different experimenters are not in perfect agreement.

According to Bozorth [32], the demagnetizing factor depends not only upon the dimensional ratio but also upon the permeability. He also gives graphs by which apparent permeability can be converted to true permeability or vice versa. Most of the tables available at the present writing are given in terms of "intensity of magnetization" rather than in terms of B_i. The equation commonly given is

$$H=H'-NI$$

where H and H' are the true and applied magnetizing force respectively, N is the demagnetizing factor, and I is the "intensity of magnetization." The intensity of magnetization as understood here is $B_i/4\pi$ so that

$$N=4\pi D_B.$$

Table 3 shows some published values of the demagnetizing factors together with equations which practically average the values given by Mann [14], DuBois [15], and Shuddemagen [16]. These equations provide a means for estimating the demagnetizing factor for intermediate values of the dimensional ratio.

The diagram of connections shown in figure 6 for the ring test is substantially right for the solenoid test. The only changes required are to take M to be the solenoid winding and T to represent the test coil at the middle of the test bar. In calculating the applied magnetizing force H', if the solenoid is very long compared to its mean diameter and if the cgs system of units is used, the equation is

$$H'=0.4\pi\ n\ I$$

where

H'=applied magnetizing force in oersteds

n=number of turns per cm

I=current in amperes.

If the solenoid is relatively short, a more nearly accurate value can be obtained by using the

[20] For sections other than circular, the diameter is taken to be the diameter of the circle which has the same area as that of the bar.

equation

$$H' = \frac{0.4\pi n I l}{\sqrt{l^2+d^2}}$$

where

l = length of the solenoid in cm

and

d = mean diameter of the winding in cm.

A more accurate value for multilayer coils can be obtained by calculating each layer separately and adding the results. To convert from oersteds to rationalized mksa units, multiply by $1000/4\pi = 79.58$.

Unless the test coil is wound directly upon the specimen its area should be determined and the standard air-flux correction should be applied to the observed value of B. (See p. 14.)

On account of the difficulty of obtaining accurate values of the demagnetizing factor this method is not capable of high accuracy but for some purposes it may be the most convenient for straight specimens if approximate results are good enough.

5.4. Permeameters

a. MH Permeameter

The MH [21] permeameter [11] was designed with the purpose of producing an instrument which would not have the disadvantages inherent in the Burrows permeameter but would have comparable accuracy. It should also be an absolute instrument in the sense that its constants can be determined from its own dimensions and therefore do not have to be calibrated by reference to any other permeameter. The MH permeameter fulfils these essential requirements. In addition, it has the advantages that it requires only a single specimen and is more simple and rapid to operate than the Burrows permeameter. Furthermore, it is much less sensitive to the effect of nonuniform magnetic properties along the length of the specimen. It is also used for ordinary magnetic testing within its proper range; that is, up to 300 oersteds or 24×10^3 amp-turns per meter. The permeameter is shown in figure 7. The magnetic circuit is made of laminated electrical sheet of armature grade. The laminated structure reduces the effect of eddy currents induced in the circuit by the changes in flux incident to the testing procedure. The specimen and the symmetrical U-shaped yokes which span it rest on two end pieces supported by Bakelite blocks. The yokes are recessed so as to make good contact with the end pieces and the ends of the specimen in such a way that no clamping is required. This eliminates mechanical strain in the specimen. The symmetrical yokes promote a uniform distribution of magnetic induction across the section of the specimen and along its length. The distribution is also improved by auxiliary windings around the ends of the yokes and the end pieces. These are connected in series with the main magnetizing coil which surrounds the specimen. The proper number of turns in these auxiliary coils depends upon the magnetic properties of the yokes and end pieces and is determined experimentally for each instrument. The preferred length of test specimen is 28 cm but specimens as short as 24 cm can be used if necessary.

[21] MH is a designation for "medium H."

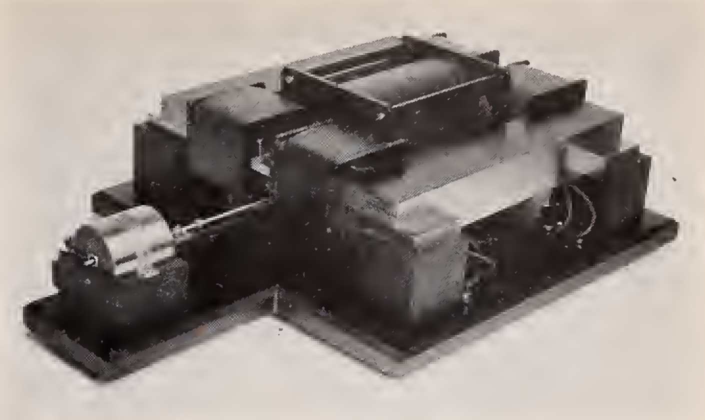


FIGURE 7. *MH permeameter.*

FIGURE 8. *Test coil assembly for MH permeameter.*

The test-coil assembly is shown in figure 8. This assembly is held in place within the magnetizing coil by two Bakelite rings. A platform extending between these rings serves to hold the B-coil in place and to support flexible specimens such as strips of electrical sheet so as to prevent errors due to mechanical strain.

A 100-turn B-coil extends over the middle 3 cm of the specimen. Just above it, but not surrounding the specimen, is a compensating coil adjusted to have the same value of area-turns as the B-coil. This coil is connected in series opposing the B-coil so that the reading of the galvanometer upon reversal of the magnetizing current is proportional to the intrinsic induction, B_i. Thus the usual air-flux correction is not required. If desired, the total induction, B, can be obtained simply by adding to the observed value of B_i the value of $\Gamma_m H$. In the cgs system $\Gamma_m = 1$. In the mksa system, $\Gamma_m = 4\pi\times10^{-7}$. The B-coil is able to accommodate specimens as large as 1×3 cm in cross section.

The H-coil system is also shown in the figure 8. It consists of two rectangular coils with nearly identical values of area-turns mounted on a turntable below the specimen. The upper coil extends into a recess in the supporting platform so as to

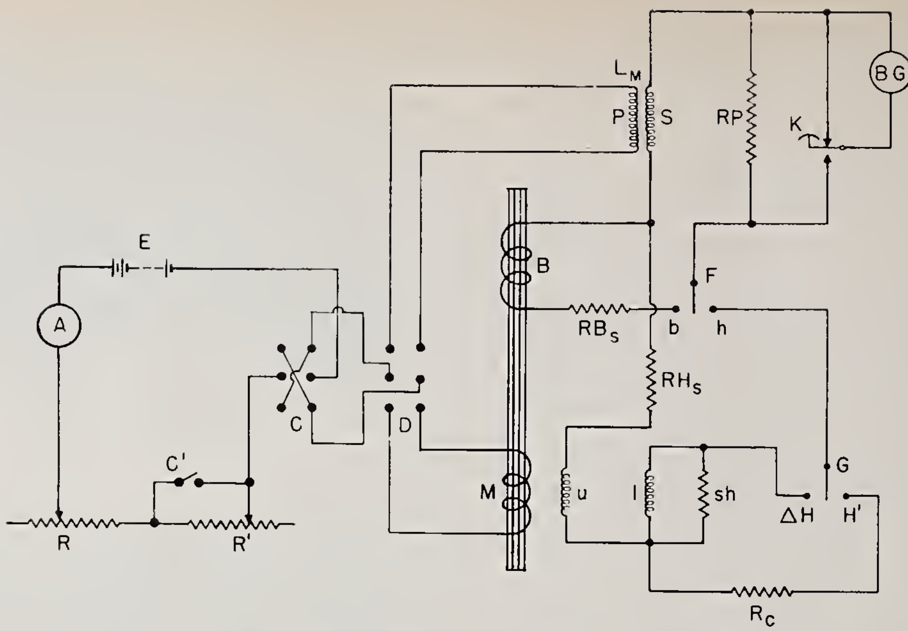


FIGURE 9. *Connections for the MH permeameter.*

come close to the surface of the specimen. The turntable can be rotated through 180° about a vertical axis by means of a rack and pinion arrangement operated by an iron-clad solenoid and plunger located far enough away from the magnetic circuit to avoid interference. The lower coil has the larger value of area-turns and is adjusted to equality of effective value of area-turns by means of a noninductive shunting resistor. If the two coils are connected in series opposing and rotated the reading of the galvanometer will be proportional to the gradient of the magnetic field. A reading taken by means of the upper coil alone together with the gradient permits extrapolation to the surface of the specimen and thus the determination of the magnetizing force acting on the specimen.

The use of rotating coils (flip coils) has some advantages over a fixed-coil system, especially when determining points on a hysteresis loop. With fixed *H*-coils, it is necessary to calculate values of H_d for a point on the loop in terms of the difference between two large quantities. With the flip coils the value of H_d is determined directly with suitable sensitivity and observations can be repeated without the necessity of reestablishing a symmetrically magnetized condition. The Burrows criterion for perfect demagnetization is that the induction for a given low magnetizing force shall be a maximum. This is not feasible to apply experimentally. With the flip coils, it is only necessary to observe whether or not the magnetizing force corresponding to a given low magnetizing current has the same absolute value regardless of the direction of the current. If there is a difference, the presence of residual magnetization is indicated. The demagnetizing procedure should then be repeated.

Taking into consideration all the possible sources of error inherent in the apparatus, it is estimated that by the exercise of great care in taking the readings and averaging several readings for each point, values of induction are accurate to within about 0.5 percent. Values of magnetizing force will come within the same accuracy or 0.05 oersted, whichever is larger. For routine tests, values of either induction or magnetizing force accurate to within 1 percent should be obtained without difficulty.

Figure 9 is a diagram of connections for the MH permeameter.

Battery *E* furnishes the magnetizing current which is controlled by resistors *R* and *R'* and measured by ammeter *A* or by a standard shunt and potentiometer. With switch *D* closed upward the current is in the primary winding *P* of the calibrating inductor L_m. If it is closed downward, the magnetizing winding is energized. With selector switch *F* closed on *b*, the *B*-coil *B* is connected to the galvanometer circuit through the calibrating resistor RB_s. If *F* is closed on *h*, the *H*-coils are in the galvanometer circuit through the calibrating resistor RH_s. The selector switch, *G*, determines whether the upper coil, *u*, alone is in the circuit or the coils *u* and *l* are connected in series opposing. Resistor *sh* is for adjusting the effective area turns of coil *l* to be equal to the area-turns of coil *u*. R_c, noninductive resistor, is to compensate for the resistance of coil *l* so that the resistance of the galvanometer circuit will be the same whether one or two coils are connected.

It should be noted that for a specimen which is magnetically nonuniform along its length, the values of *B* and *H* obtained by the MH permeameter relate only to the part of the specimen linked with the *B*-coil.

b. High-H Permeameter

The High-H permeameter [13] shown in figure 10 is used for testing "hard" magnetic materials at magnetizing forces up to 5,000 oersteds

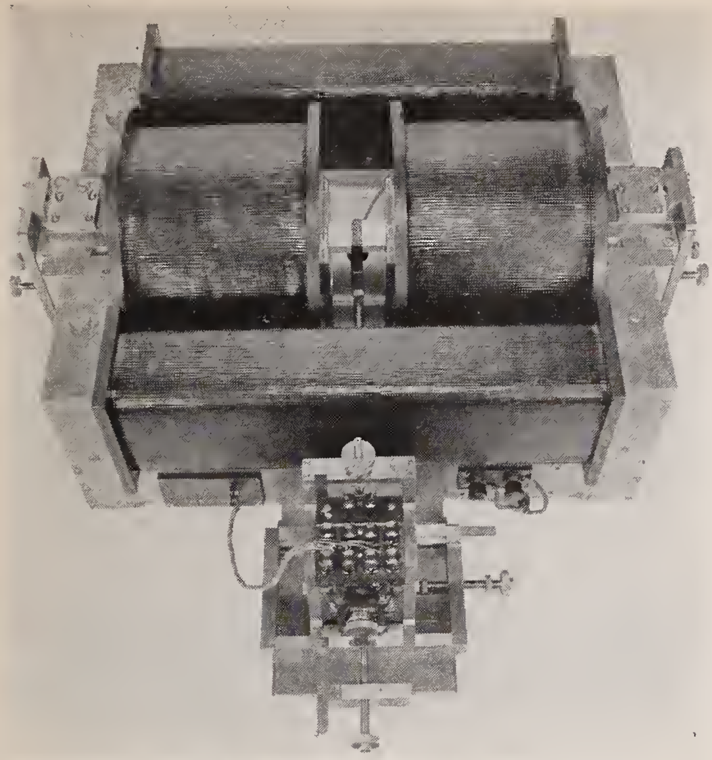


FIGURE 10. *High-H permeameter.*

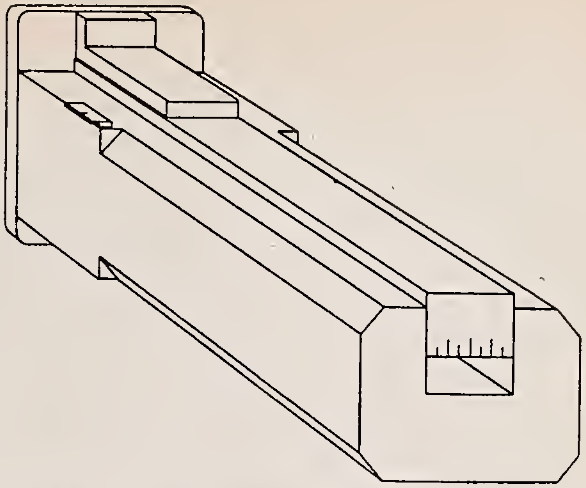


FIGURE 11. *Pole pieces of the high-H permeameter.*

(40×10^4 amp. turns/meter). Since only a short length of the specimen is included in the test, it is possible to apply the high magnetizing forces without appreciable heating. The magnetic circuit is made of laminated electrical sheet of armature grade. The specimen, of rectangular cross section, is held in pole pieces extending between two U-shaped yokes. The construction of the pole pieces is indicated in the sketch of figure 11. They have longitudinal channels into which filler pieces are fitted as shown. The specimen is located in the space between the bottom of the channel and the filler. The distance between pole pieces, or gap length, is adjustable; and scales are provided to indicate the gap length up to 10 cm, which is the maximum generally used. The filler pieces are fastened at their outer ends to heavy brass plates which are clamped to the ends of the pole pieces so as to keep the fillers parallel with the bottom of the channels. The main magnetizing coils surround the pole pieces and auxiliary coils are wound on the yokes.

Two similar *H*-coils are mounted one above the other on a vertical shaft below the specimen. They can be rotated 180° by means of a small motor through beveled gears and a long horizontal shaft. The lower coil has a slightly greater value of area-turns than the upper coil and is adjusted to have the same effective value by a noninductive shunt. If the two coils are connected to the galvanometer in series, opposing, and rotated through 180° from a position such that their axes are parallel to the direction of the field, the deflection is proportional to the radial gradient of the field. If the axis of the upper coil is set to be the same distance below the surface of the specimen as the distance between the axes of the coils this gradient can be used directly to extrapolate the value obtained by the upper coil alone to the surface of the specimen.

In order to keep the air correction small, individual *B*-coils are wound on thin brass forms to fit specimens of various sizes. The coils are 5 mm long and usually have 25 turns.

Relatively short specimens can be used but for specimens 5 cm or less in length, it is better to butt the ends against the pole pieces rather than to attempt to insert them in the regular way.

It is estimated that for magnetizing forces from 100 to 5,000 oersteds (8×10^3 to 40×10^4 amp-turns/meter) it is possible under favorable conditions to obtain values of either induction or magnetizing force which will be accurate within 0.5 percent. Under ordinary conditions of routine testing, the errors probably do not exceed 1 percent.

The wiring diagram shown in figure 9 applies also to the High-H permeameter if it is understood that the magnetizing coil, *M*, is on the pole pieces instead of over the specimen.

c. Fahy Simplex Permeameter

For several years, the Fahy Simplex permeameter [12] has been in use in many laboratories for routine magnetic testing. Since this permeameter tends to give average values of the properties of a nonuniform specimen, agreement with another permeameter which includes only a relatively short section in the test should be expected only for a uniform specimen. Unless a specimen has been checked for uniformity, it is safer to assume that it is nonuniform, and lack of agreement should not be interpreted as an error of either permeameter.

For checking other Fahy Simplex permeameters, the Magnetic Measurements Section has calibrated one by reference to a standard permeameter using uniform bars as standards. This instrument is used as a working standard and constitutes a practical means of making the check.

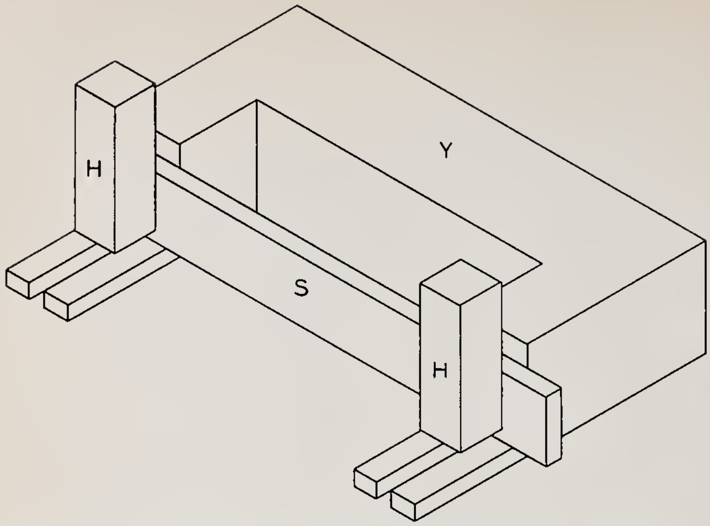


Figure 12. *Magnetic circuit of Fahy Simplex permeameter.*

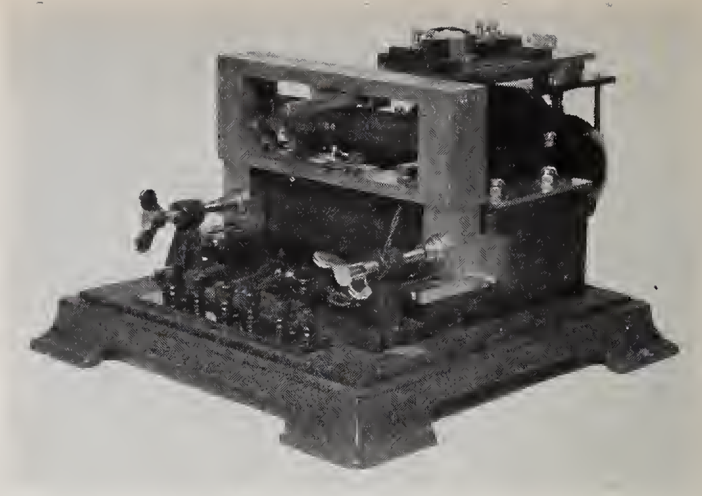


Figure 13. *Modified Fahy Simplex permeameter.*

The magnetic circuit of the Fahy Simplex permeameter is indicated in the sketch of figure 12. The yoke, Y, is made of laminated silicon sheet. Two soft iron blocks, H, make contact with the ends of the specimen. Clamps hold these blocks and the specimen in place against the pole pieces of the yoke as shown. The magnetizing winding is wound on the yoke. The B-coil for measuring the magnetic induction has 100 turns uniformly wound on a brass form which surrounds the specimen and extends over its whole length between the pole pieces. For determining the magnetizing force, a uniformly wound H-coil of many turns on a straight nonmagnetic form extends horizontally between the upper ends of the H-blocks.

In order to gain the advantages of "flip coils" for the determination of magnetizing force, especially for points on the hysteresis loop, the NBS instrument was modified by providing a means of rotating the H-coils through 180° about a vertical axis. The modified instrument is shown in figure 13. The H-blocks had to be lengthened slightly so that the H-coil could clear the magnetizing coil but experiment showed that this did not affect the accuracy of the results. As previously stated, the flip coil arrangement makes it possible to determine values of H_d on the hysteresis loop with adequate sensitivity and to repeat the observation without the necessity of repeating the process of producing a symmetrically cyclic condition for each repetition of the observation. It also provides a convenient and positive indication of proper demagnetization. Demagnetization has been complete if for a very small magnetizing force, the values of H are equal for reversals with the magnetizing current in either direction.

The Fahy Simplex permeameter is not an absolute instrument. It requires calibration by reference to an absolute instrument which is taken to be a standard; if it were not for the inevitable magnetic leakage, the theory of the instrument would be comparatively simple. The H-coil is assumed to indicate the difference of magnetic potential between the ends of the H-blocks. These blocks then in effect transfer the ends of the coil to the ends of the specimen. On account of leakage, however, the actual situation is not quite so simple. Experiment has shown that if the actual value of area-turns in the H-coil is used in calculating H, the value thus obtained is not correct.

The single-yoke arrangement leads to a nonuniform distribution of induction both along the length and across the section of the specimen. Also, since the magnetizing coil is on the yoke rather than on the specimen, some of the leakage flux is linked with the H-coil. The reluctance of the H-blocks should also be taken into consideration. In view of all of the potential sources of error inherent in the design, it was somewhat surprising to find that a simple correction proportional to the observed magnetizing force would bring the results practically in line with the results obtained with an absolute instrument if uniform specimens are used in the intercomparison. This correction is most conveniently applied by assigning to the H-coil a value of what might be called the "effective" area-turns which is somewhat different from the measured value. It has been found that if the specimen is laminated, the maximum number of strips for which reasonable accuracy can be obtained is ten. The error is apparently a function of the number of air gaps between the pole pieces and the H-blocks.

With so many factors involved, it is not feasible to give a precise estimate of the accuracy obtained but in general, under normal conditions, values of either B or H for normal induction may reasonably be expected to be accurate within 2 percent. For the determination of coercive force, another phenomenon must be taken into consideration. It has been found that when the average induction as indicated by the B-coil is zero, the B in the part of the specimen next to the pole pieces has already reached a negative value while the outer part next to the H-blocks is still positive. Since the H-blocks are in contact with this outer part, the value of H_c will be low. The error depends upon the slope of the hysteresis loop at the H_c point. If it were vertical, there would be no error. As a rule, the slope is less and consequently the error is greater the higher the value of H_c.

The Fahy Simplex permeameter has found favor primarily on account of its easy manipulation and the requirement of only a single specimen. Its accuracy is probably within the range of uniformity of most magnetic materials.

The wiring diagram is like that of figure 9 except that coil l and resistor sh are omitted and the magnetizing coil M is on the yoke instead of over the specimen.

5.5. Tests of Low-Permeability Materials

Materials having a permeability only slightly in excess of unity are generally tested in a straight solenoid. Since the intrinsic induction for such materials is very low, the correction for self-demagnetization is small and can be neglected without appreciable error in the value of magnetizing force calculated in terms of the current. In order to obtain a satisfactory degree of precision in the determination of the intrinsic induction it is necessary to balance out the direct effect of the magnetizing field. This can be done by connecting the secondary of a mutual inductor of variable value in series-opposition with the test coil which usually has several hundred turns The primary of the inductor is connected in series with the solenoid. The mutual inductor is adjusted so that, with no specimen in the test-coil, there is no deflection of the ballistic galvanometer upon reversal of the magnetizing current The galvanometer can then be used at its maximum sensitivity. When a specimen is inserted within the test coil and the magnetizing current is reversed, the galvanometer deflection is proportional to the intrinsic induction. The galvanometer is calibrated by means of a standard mutual inductor in the usual way.

In the Fahy Low-Mu permeameter [17] a somewhat different arrangement is employed. Two similar test coils are used. The specimen is inserted in one coil and the other constitutes a compensating coil to balance out the effect of the magnetizing force on the main test coil. The compensating coil has a value of area-turns somewhat greater than that of the other coil. In order to balance the system with no specimen present, the compensating coil is shunted with a resistor whose value is adjusted so that, with no specimen in the test coil, no deflection of the galvanometer results from a reversal of the magnetizing current. Then when a specimen is inserted in the test coil and the magnetizing current is reversed, the resulting deflection is proportional to the intrinsic induction. The galvanometer is calibrated in the usual way by means of a standard mutual inductor.

5.6. Magnetic Susceptibility

The measurement of magnetic susceptibility requires the use of much more sensitive apparatus than is needed for the measurement of ferromagnetic properties. Just as in the measurement of magnetic fields, there are only two basic methods for the determination of magnetic susceptibility. One is the measurement of the minute mechanical forces experienced by a body in a nonuniform magnetic field. The other is by means of induction methods. For precise measurements, the force methods are more commonly used.

The principal methods in use by the Magnetic Measurements Section are known as the Gouy method [18], the Faraday method [19], and the Thorpe and Senftle method [20].

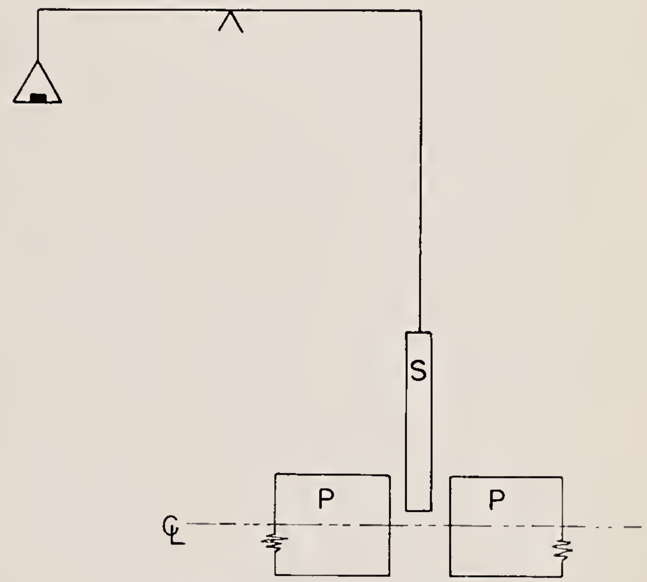


FIGURE 14. *Gouy apparatus.*

The Gouy apparatus is illustrated by the diagram of figure 14. A cylindrical specimen, s, of uniform cross section, A, is hung from a sensitive balance with its axis vertical. The lower end is located in the uniform part of the magnetic field between the poles, P, of a powerful electromagnet, and usually above the center line of the pole pieces. The specimen should be long enough to bring its upper end into a much weaker field. The force due to the application of the magnetic field is measured by the balance. The magnetic susceptibility is then calculated by using the equation

$$f=kA(B_1^2-B_2^2)/2\Gamma_m \text{ [22]}$$

Transposing,

$$k=\frac{2\Gamma_m f}{A(B_1^2-B_2^2)}$$

[22] Note: In the classical cgsem system of units, the equation is usually given as $f=kA(H_1^2-H_2^2)/2$. This equation is dimensionally inhomogeneous but gives the same numerical results as the other because in this system Γ_m is unity and there is no numerical distinction between B and H.

	cgsem	mksa (rationalized)
k=volume susceptibility	------	------
f=force	dynes	newtons
Γ_m=magnetic constant	1	$4\pi \times 10^{-7}$
A=area of specimen	cm^2	m^2
B_1=field at lower end	gausses	teslas
B_2=field at upper end	gausses	teslas.

The use of rationalized units yields values of magnetic susceptibility which are 4π times the values obtained by the use of unrationalized units. (See pp. 4–5). The Magnetic Measurements Section generally uses the nuclear magnetic resonance method (see pp. 12–13) for measuring B_1 and a pivoted magnet instrument for measuring B_2. (In the classical cgsem system, it is customary to measure B and call it H.) The Gouy apparatus at NBS is equipped for measurements at temperatures as low as that of liquid hydrogen.

The Faraday method is adapted to measurements of magnetic susceptibility of specimens too small for the Gouy method. A small sample of magnetically isotropic material experiences no mechanical force when placed in a uniform magnetic field. However, if there is a gradient in the field, a force will be experienced. In this case

$$f = \frac{m\chi B dB/dy}{\Gamma_m}.$$ [23]

Transposing,

$$\chi = \frac{\Gamma_m f}{mBdB/dy}$$

where

	cgsem	mksa (rationalized)
χ=mass susceptibility		(see pp. 5–6)
Γ_m=magnetic constant	1	$4\pi \times 10^{-7}$
f=mechanical force	dynes	newtons
m=mass	grams	kilograms
B=magnetic field	gausses	teslas
y=distance	cm	m.

Here as with the Gouy method, the values in a rationalized system are 4π times those in an unrationalized system.

Measurements with this method on an absolute basis are attended with some difficulty. The apparatus is generally calibrated by the use of standard samples of known susceptibility. The standard must be of the same size and shape as the specimen to be tested and located in the same position in the nonuniform field.

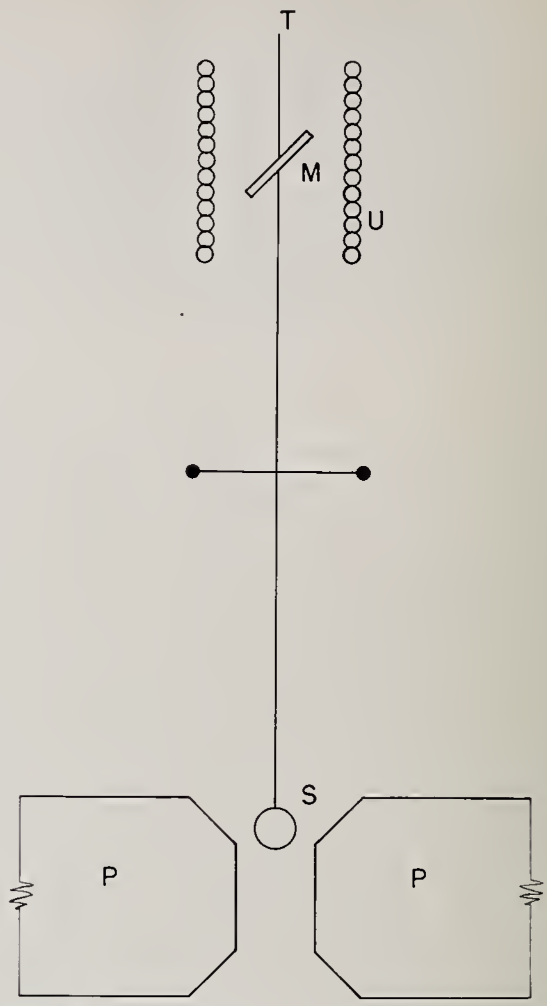


FIGURE 15. *Vertical beam Faraday apparatus.*

The apparatus is shown diagrammatically in figure 15. The specimen, S, is mounted at the lower end of a quartz beam, and a permanent magnet, M, is mounted near the upper end. The beam is supported by a horizontal beryllium-copper wire near the midpoint; the specimen is carefully positioned between the pole pieces in the region where the product of the field by the field gradient is constant over the volume of the specimen. Measurements are made by applying a field and then restoring the beam to its original position by means of a torque exerted on the permanent magnet by a current in the solenoid, u. The position of the beam is indicated by observing the tip, T, with a telescope and scale.

The Thorpe and Senftle method, described by Thorpe and Senftle [20], is generally used for measuring small samples of material. The method is illustrated in the diagram of figure 16. A quartz spring supports the specimen initially in a position between the poles of the magnet and slightly below the center of the pole faces. After the deflection of the spring, due to the application

[23] The force is given as $f=m\chi HdH/dy$ when the classical cgsem system of units is used. This equation is dimensionally inhomogeneous but gives rise to no numerical error because Γ_m is unity and no distinction is made between B and H in the classical cgsem system.

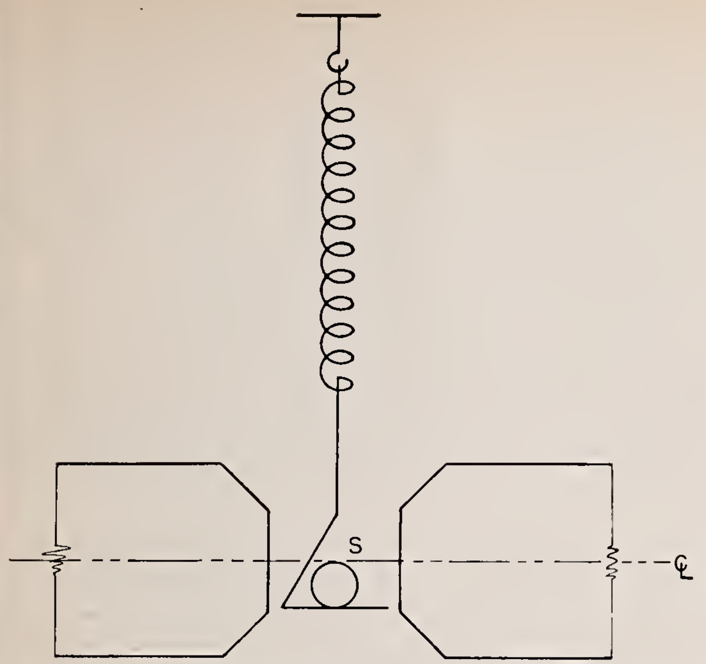


Figure 16. *Quartz Helix magnetic susceptibility balance.*

of the field, has been observed for this position, the magnet is lowered to a new position and another observation of the deflection is made. This procedure is repeated for several selected positions of the magnet until there is no observable change in deflection when the magnet is moved to a lower position. From the proper integration of the curve of displacement of the sample versus the distance of the magnet from the sample, the maximum value of the magnetic field between the poles of the magnet, the mass of the sample, and the elastic constant of the quartz spring, it is possible to calculate the magnetic mass susceptibility of the sample by the equation

$$\chi=\frac{2AK\Gamma_m}{mB^2_{\max}}$$

where

χ=mass susceptibility

A=area under the curve

K=elastic constant of the quartz spring

Γ_m=magnetic constant

m=mass of the sample

B=the maximum field of the magnet.

Since

$$m=\mathrm{Kh/g}$$

where

h=measured static deflection of the quartz spring

and

g =acceleration due to gravity,

$$\chi=\frac{2gA\Gamma_m}{hB^2_{\max}}.$$

The induction methods most generally used are a-c bridge or balance methods [24] and the vibration magnetometer.[25] These methods involve the inducing of voltage in a coil as a result of changing flux linkages due to the applied field or a position change of the coil or sample. These methods have the advantages that they use uniform magnetic fields and cover a larger range of susceptibilities than the force methods; however they usually require a standard material for calibration purposes.

5.7. Magnetic Standards

In view of the nature of the magnetic units, it is obviously not feasible to realize them in concrete form. The calibration of magnetic testing apparatus is carried out in terms of the electrical units by the use of standard shunts, potentiometers (or ammeters), and mutual inductors. The basic standards are (1) a mutual inductor so designed that its value can be calculated from its dimensions (2) a standard resistor, and (3) a standard cell. These basic standards are used to calibrate working standards and these working standards in turn are used for the calibration of the measuring circuits. For the intercomparison and standardization of permeameters it is necessary to make use of carefully selected and prepared test specimens whose magnetic properties are accurately determined by some standard method. It may perhaps be proper to refer to such test specimens as magnetic standards.

The preparation and maintenance of standards of magnetic susceptibility present some difficult problems. The material must be of high purity (ferromagnetic impurities are particularly troublesome) and means must be provided to prevent contamination during handling or storage. Questions of stability and temperature effects are also important. Standards of susceptibility are required for the calibration of apparatus with which it is difficult or impossible to obtain absolute results. The Magnetic Measurements Section has a continuing program for the investigation of standard materials such as water, benzene, nickel chloride, and hydrated ferrous ammonium sulfate (Mohr's salt) and the improvement of methods of preparations and measurement of standards specimens.

5.8. Limits of Accuracy

The problem of magnetic testing consists in determining simultaneous values of magnetic

[24] Magnetochemistry—P. W. Selwood Interscience Publishers.
[25] A Vibrating Sample Magnetometer by N. V. Frederick—IRE Transaction on Instrumentation **I–9**, No. 2 (Sept. 1960).

induction and magnetizing force. It is relatively easy to obtain fairly accurate values of induction, but the accurate determination of the corresponding magnetizing force is more difficult. It is only by the exercise of great care in the selection of test specimens and manipulation of the testing apparatus that an accuracy of 1 percent can be attained. The influence of the quality and condition of the test specimen is of great importance, especially in the standardization of permeameters because inaccuracies really arising from the condition of the specimen itself should not be charged to the testing apparatus.

5.9. Requirements of Standard Specimens for D-C Permeameters

Specimens to be used as standards for the calibration or intercomparison of permeameters should be chosen and prepared with the following points in view: (1) magnetic uniformity along the length, (2) metallurgical stability, and (3) uniformity of section.

If the specimen varies in permeability along its length, errors are introduced in the measurements which cannot be calculated or eliminated by compensation, and which may be of considerable magnitude. It is possible to have errors due to this cause alone which amount to 25 percent or more. Moreover, various methods are sensitive to this influence in varying degrees. It is obvious, therefore, that such specimens should not be used for the intercomparison or standardization of testing apparatus. Various methods for the determination of the degree of uniformity of magnetic-test specimens have been proposed [21], but probably the most satisfactory one is to prepare a specimen much longer than is required for the final form and to make measurements at suitable intervals along its length. If the results of these measurements are in agreement, then the specimen is, from this point of view, satisfactory to use as a standard.

It is well known that specimens of steel freshly heat-treated are not metallurgically stable; that is, changes in internal structure or condition may go on for some time. These changes are accompanied by corresponding changes in magnetic properties. It is necessary, therefore, to make sure that specimens to be used as magnetic standards are metallurgically stable. This can be accomplished by either natural or artificial aging.

It is quite obvious that irregularity in cross section along the length of a specimen would have an effect similar to that of a variation in magnetic permeability. For this reason, it is important that care should be used in preparing the specimen to maintain a uniform cross section.

5.10. General Precautions

In the calibration and use of magnetic standards, it is necessary to avoid (1) mechanical strain, (2) variations in temperature, and (3) mechanical vibration.

Mechanical strain influences the magnetic properties of materials to a marked degree. It is important, therefore, in the calibration and use of magnetic standards that they be clamped without bending. The effect of bending is particularly noticeable in materials of high permeability and in the steep part of the magnetization curve.

The effect of variations in temperature is not negligible [22], and care should be taken that standards be not heated during the course of a test. The temperature coefficient is not constant and varies for different materials or even for the same material with different heat treatments.

Mechanical vibration should be avoided in magnetic testing. It has a tendency to increase the apparent permeability and to decrease the hysteresis. This is generally not a serious factor, but for work of high accuracy, it should be considered and the specimens protected from excessive vibration.

6. Tests With Alternating Currents

6.1. Core Loss and A-C Permeability at Power Frequencies

Magnetic tests with alternating currents are extensively employed by producers and users of magnetic core materials in connection with quality control and for obtaining design data. These tests are generally made by methods specified by the American Society for Testing Materials. Since magnetic materials are continually being improved and new and better methods of testing are being developed, the specifications require frequent revision in which the Magnetic Measurements Section cooperates. For this reason, it is neither necessary nor desirable to give detailed descriptions of the current standard methods. The general principles are presented here but for specific details, the reader is referred to the latest Standards on Magnetic Materials issued by the ASTM [23].

The principal objects of testing with alternating currents are to determine core loss, a-c permeability, and incremental permeability of laminated magnetic core materials. The test specimens usually consist of strips of flat-rolled material assembled in the form of a square magnetic circuit inserted in four solenoids which are permanently mounted on a suitable base. Each of the solenoids has two uniformly distributed windings. The corresponding windings of the four coils are connected in series to form primary and second windings having an equal number of turns. The primary winding carries the magnetizing current. The secondary winding is used to energize voltmeters and the voltage coil of a wattmeter (if used). A third winding may be required in certain types of tests. The set of coils mounted on a base is generally called an Epstein frame.

Since flat-rolled core material has directional properties, half of the specimen strips are generally cut with their long dimension in the direction of rolling and half in a direction at right angles to the direction of rolling. Certain materials with oriented grain structure may have the strips all cut in the direction of rolling. When the strips are cut "half and half" they are so assembled that strips on opposite sides of the square are cut in the same direction.

There are two principal types of testing methods in which the Epstein frame is used, voltmeter-wattmeter methods, and bridge methods.

a. Voltmeter-Wattmeter Methods

The basic diagram of connections for these methods is shown in figure 17. The a–c source should deliver as nearly a sinusoidal voltage as possible with a minimum amount of distortion when fully loaded. The current is controlled preferably by means of a suitable autotransformer rather than by series reactance. Excessive resistance or inductance in the circuit causes an undesirable amount of distortion in the wave form. Connected in series with the primary winding, P, of the test frame are: an ammeter, A, of low internal impedance, the primary winding of a calibrated mutual inductor, L_m, the current coils of a wattmeter, W, designed specially for measurements at very low power factors and the primary winding of a compensating mutual inductor, L_{mc} (if used).

The secondary winding of the compensating inductor, L_{mc} (when used) is connected in series—opposition to the secondary winding, S, of the test frame. When the selector switch Sw is closed downward, the rms-reading voltmeter, rms Vm, the average-reading voltmeter,[26] Av Vm, and the potential coil of the wattmeter, W, are connected in parallel to the secondary winding S of the test frame through the secondary winding of the compensating inductor, L_{mc}. The 50-cm Epstein test requires a specimen consisting of 10 kg (22 lb) of material cut into strips 50 cm (19¹¹⁄₁₆ in) long and 3 cm (1³⁄₁₆ in.) wide. This relatively large sample previously was required in order to obtain a fair average result for material which was not very uniform even throughout a single sheet. The strips are assembled in the test frame with butt joints at the corners, which are clamped to maintain a low magnetic reluctance at the joints. Improved manufacturing techniques now permit the use of much smaller samples and the 25-cm Epstein test[27] requiring only 2 kg (4.4 lb) is now standard.

[26] This is an instrument whose moving system responds to the average value of the rectified alternating current.

[27] Tests are often made on smaller specimens but the 2 kg sample is standard at present.

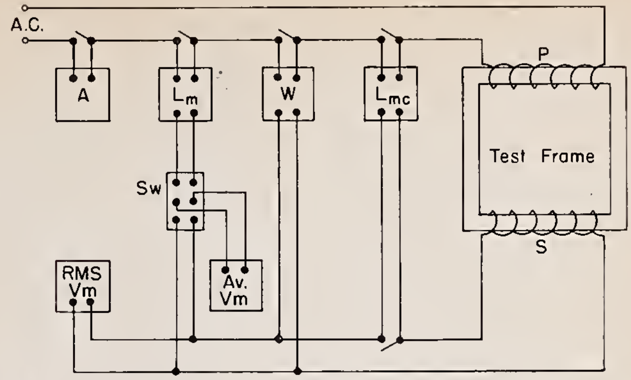


FIGURE 17. *Diagram of connections for Epstein tests by the voltmeter-wattmeter methods at power frequencies.*

In carrying out tests using the 25-cm Epstein frame, a better joint at the corners than the butt joint used in the 50-cm apparatus is required on account of the shorter magnetic circuit. A double-lap joint has been adopted. This requires strips at least 28 cm (11⅜₂ in.) long. Strips up to 50 cm (19¹¹⁄₁₆ in.) long can be used if necessary. The width of the strips is the same as in the 50-cm test, i.e., 3 cm (1³⁄₁₆ in.).

The sample is first weighed and then inserted in the test frame in four equal groups in such a way that at each corner the strips of adjacent groups successively overlap and groups at opposite sides of the square are cut in the same direction. No insulation other than the natural oxide is used between strips except in the case of oxide-free material. The corners may be clamped to reduce the magnetic reluctance but it must be done carefully so as not to introduce excessive mechanical strain in the strips.

The apparatus is then connected to the a–c source and the current is adjusted so that the voltage of the secondary coil of the test frame as indicated by the average-reading voltmeter corresponds to the desired maximum induction in the specimen. This voltage is given by the equation

$$E_{\text{ave}}=\frac{4B_mANf}{10^8}$$

where

E_{ave} = average voltage
B_m = maximum induction in gausses
A = cross-sectional area of the specimen, cm^2
N = number of turns in secondary coil
f = frequency in cycles per second

(If B is in teslas and a is in m^2, the factor 10^8 is not needed.)

The cross-sectional area of the specimen is determined from the mass, density, and length of the strips

$$A=\frac{m}{4l\delta}$$

where

A = area in cm^2
m = the mass in grams
l = length of a strip in cm
δ = density in g/cm^3.

The density for most of the conventional materials is assumed from their chemical composition. For other materials, the density must be determined experimentally. For silicon-iron alloys the values range from 7.55 to 7.85 depending upon the silicon content. (See table 4.) Densities of nickel-iron alloys vary from 7.85 to 8.90. (See table 5.)

Table 4. *Silicon-iron alloys*

Silicon content range	Assumed density
Percent	*g/cm³*
0 to 0.5	7.85
0.5 to 2.0	7.75
2.0 to 3.5	7.65
3.5 to 5.0	7.55

Table 5. *Iron-nickel alloys*

Density determined from straight lines joining points given below.

Nickel	Density
Percent	*g/cm³*
0	7.85
30	8.00
50	8.26
80	8.64
100	8.90

After the frequency and voltage have been properly adjusted, the wattmeter is read. The value obtained includes not only the total loss in the core but also the losses in the instruments connected to the secondary winding of the test frame. The loss in each instrument is E^2/R where E is the rms voltage and R is the ohmic resistance of the instrument.

If the wave-form distortion as indicated by the form factor, ff, differs from 1.111 (form factor of a sine wave) by more than 1 percent, it is necessary to make a correction to the observed value of the core loss to account for the fact that whereas the hysteresis component of the total loss is a function of the average voltage, the eddy-current component is a function of the rms voltage [24].

If the cross-sectional area of the specimen is much less than that of the secondary coil of the test frame, a correction must be made for the extra induced voltage due to the air flux. This correction can be calculated from the equation

$$E_a = \frac{4Nf\Gamma_m H_p(a-A)}{10^8}$$

where

E_a = average voltage due to air flux
N = number of turns in secondary coil
f = frequency in cycles per second
Γ_m = magnetic constant = 1
a = area of secondary coil in cm^2
A = area of specimen in cm^2
H_p = peak magnetizing force in oersteds.

If the mksa system of units is employed, the equation becomes

$$E_a = 4Nf\Gamma_m H_p(a-A)$$

in which

E_a = average voltage due to air flux
$\Gamma_m = 4\pi\times 10^{-7}$
H_p = peak magnetizing force in amp-turns/m and areas are in m^2.

In the cgs system, the peak magnetizing force is calculated by using the equation

$$H_p = \frac{0.4\pi N I_p}{l_a}$$

where

H_p = peak value of magnetizing force in oersteds
N = number of turns in primary winding
I_p = peak current, amperes
l_a = assumed length of the magnetic circuit = 94 cm.

In the mksa system, H_p is in ampere-turns/meter and l_a is in meters (0.94 meter) and the equation is

$$H_p = \frac{N I_p}{l_a}.$$

The peak value of the magnetizing force, H_p, is determined in terms of the peak current and the number of turns per unit length in the magnetizing winding, P. The peak current is proportional to the average voltage induced in the secondary winding of the mutual inductor, L_m

$$I_p = KE_{ave}.$$

The factor K is determined by observing the average voltage induced by a sinusoidal current of known value.

The a-c permeability is taken to be the ratio of the maximum induction to the peak value of magnetizing force.

It is convenient to compensate for the extra voltage due to air flux by means of the compensating mutual inductor (L_{mc} in the diagram). The mutual inductance is adjusted to be equal to that between the primary and secondary windings of the test frame (no specimen inserted). If this is done, the indicated induction is the intrinsic induction, B_i, in the specimen.

The specific core loss is calculated by dividing the corrected value of total watts by the "active weight" of the specimen. The active weight is

$$m_1 = \frac{ml_1}{4l}$$

where

m_1 = active weight in kg
m = weight in kg
l_1 = assumed length of magnetic circuit = 94 cm
l = length of strips.

b. **Bridge Methods**

Generally, core loss and a-c permeability are determined by the voltmeter-wattmeter method. In many cases, however, there are certain advantages, such as increased sensitivity and greater frequency range, in making these measurements by a bridge method. For measurements at low inductions (not over 1,000 gausses or 0.10 tesla) and at high frequencies, the bridge methods have been used successfully for several years. More recently, however, bridge circuits have been developed by which measurements may be made at higher inductions. The ASTM [23] has approved as standard a modified Hay bridge for use in measurements at inductions up to 10 or 12 kilogausses in nonoriented steels or 16 to 18 kilogausses in oriented silicon steels. For measurement at higher inductions, the distortion in the wave form of the exciting currents is considerable and it has been found necessary to use special techniques [25] in order to obtain accurate results with bridge methods.

Figure 18 is a diagram of a modified Hay bridge currently approved as standard by the ASTM [23]. The assumed equivalent impedance of the coil containing the test specimen is shown in the diagram at the right. The inductance of the coil alone without the specimen, L_w, and its resistance, R_w, are considered to be in series as shown. They are balanced by the capacitance C'_w and the resistance R'_w respectively. Ordinarily the inductance of the coil alone is so small that it is negligible and C'_w need not be used.

The apparent additional resistance, R_1, due to the core loss and the inductance, L_1, due to the permeability of the test material are considered to be in parallel. They are balanced by the resistance, R_b, and the capacitance C_b. R_a and R_c are fixed resistors whose product is equal to the product of the impedances of the other two arms of the bridge. Since R_c carries the total exciting current it must have such current-carrying capacity that it will not be heated excessively.

D is a detector, tuned to the fundamental frequency of the voltage supply. This detector should have a high impedance and high sensitivity to the fundamental frequency. Previously, vibration galvanometers have been employed for this purpose, but they have been almost entirely replaced by electronic devices of various kinds.

The a-c source is connected to the bridge through an isolating transformer. In the arrangement recommended by the ASTM, this transformer has a tapped secondary for convenience in selecting the proper range of voltage to be applied. The primary is fed from an autotransformer connected to the generator. This provides the fine control of the applied voltage. Other arrangements may be employed provided that there is isolation between the source and the bridge and the series resistance is not used to control the current. Resistance tends to distort the wave form of the induced voltage and may lead to excessive errors. [25]

For incremental values, the d-c magnetizing current may be supplied to the secondary winding, N_2. The average a-c voltage is then read across the primary winding, N_1. The IR drop in this winding causes a slight error but this is usually negligible. The d-c source must furnish a steady current. A storage battery is ordinarily the best

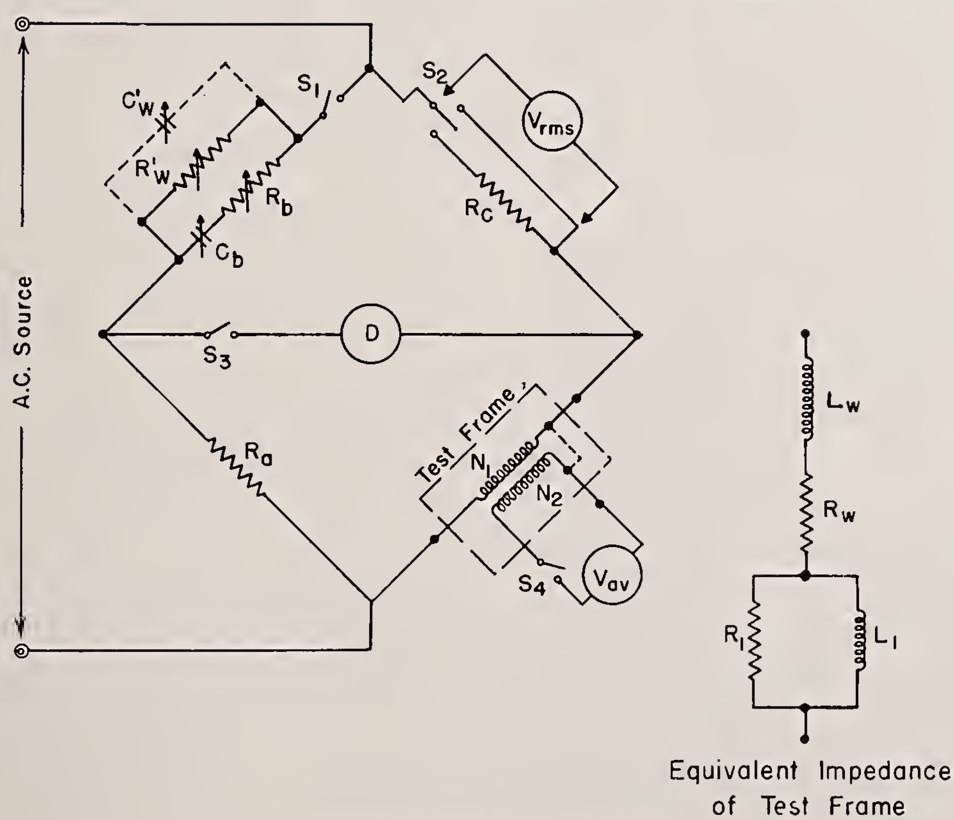


Figure 18. *Modified Hay Bridge.*

source as rectified a-c requires a great deal of filtering. The d-c circuit contains a series inductor of at least 10 h when carrying maximum current. This is to limit the a-c current in the d-c circuit to a negligible value.

The maximum induction in the specimen is indicated by a voltmeter connected to the secondary winding N_2 of the test frame. The voltmeter, V_{ave}, indicates the average voltage.[28] The maximum induction in terms of average voltage in cgs units is

$$E_{ave}=4\ BANf\times 10^{-8}$$

where

E_{ave}=average volts

B=maximum induction, gausses (if the air-flux compensating inductor is used, B is the intrinsic induction, B_i)

A=area of specimen, cm^2

N=number of turns in winding

f=frequency, cycles per second.

In mksa units,

B=induction in teslas

A=area in m^2

and the factor 10^{-8} is omitted. The other factors remain the same.

The rms value of the exciting current can be determined by connecting the rms-reading voltmeter across the resistor R_c as indicated.

As in d-c testing, the first step, especially if measurements are to be made at low values of induction, is to demagnetize the specimen. This is accomplished by first setting switch S_2 so as to take R_c out of the circuit and opening switch S_3 and then with switch S_4 closed, setting the a-c source to zero and connecting it to the bridge. The voltage is then raised until the average voltmeter indicates that a maximum induction of the order of 14 kilogausses has been reached. The current is then gradually and steadily decreased until the indicated induction is somewhat lower than the lowest at which a measurement is to be made. If this point is below about 1,000 gausses (0.100 teslas) it will be necessary to take into account the drift in values which takes place immediately after demagnetization. This drift is rapid during the first few seconds but the rate of change decreases as time goes on. For this reason, if reproducible results are to be obtained, a standard procedure must be followed. For the best reproducibility, it is necessary to wait several hours after demagnetization before making the test. This would be very inconvenient in most cases. Fortunately, it has been found that a satisfactory degree of agreement can be obtained if balance is reached about 3 min after demagnetization. If the test induction is higher than 1,000 gausses (0.100 teslas) the drift is not observed.

R'_W and C'_W (if used) are preset according to the equations

$$R'_W=\frac{R_aR_c}{R_W}$$

and

$$C'_W=\frac{L_W}{R_aR_c}\quad (C \text{ in farads}).$$

These balance the resistance, R_W, and the inductance, L_W, of the test winding, N (specimen not inserted), thus avoiding the necessity of calculating the effect of R_W and L_W.

Since R_c must carry the total exciting current and the voltage drop across it must be less than 10 percent of that across the test winding to avoid excessive distortion of the wave form, its proper value will depend upon the range of inductions at which measurements are to be made. Ordinarily, 1,000 ohms is used for the lowest range (10 to 50 gausses), 100 ohms is used for the medium range (50 to 500 gausses) and 10 ohms for the higher range (500 to 10,000 gausses). The resistor R_a may be set so as to make permeability direct-reading in terms of C_b or core loss may be direct-reading in terms of R_b. Directions for setting may be found in the ASTM specifications.

Readings are made as follows. With switch S_2 set to connect R_c into the circuit and switches S_1, S_3, and S_4 closed, the applied voltage is raised to the point at which the desired induction as indicated by the average-reading voltmeter is reached. Balance is then obtained by successively adjusting R_b and C_b until the detector shows a minimum reading. The balance equations are as follows

$$L_1=R_aR_cC_b$$

and

$$R_1=\frac{R_aR_c}{R_b}$$

where

L_1=inductance due to the permeability of the test material, henries;

and

R_1=increased apparent resistance due to core loss in the test material, ohms.

In the cgs system

$$L_1=\frac{0.4\pi N_1{}^2A}{10^8 l_1}\times\mu_L$$

and since

$$L_1=R_aR_cC_b$$

[28] According to ASTM specifications, the scale of this instrument is calibrated in terms of average volts multiplied by 1.111, the form factor of a pure sine wave. This may be confusing in some instances, especially when an rms-reading voltmeter and average-reading voltmeter are used together to determine the form factor.

it follows that

$$\mu_L=\frac{R_aR_cC_bl_1\times 10^8}{0.4\pi N_1^2A}.$$

In these equations

μ_L=effective a-c permeability of the test material

l_1=assumed effective length of the magnetic circuit=94 cm

N_1=number of turns in the primary winding.

In the mksa system, the equation is

$$\mu_L=\frac{R_aR_cC_bl_1}{N_1^2A}$$

where

l_1=assumed effective length in meters=0.94

and

A=area in square meters.

Areas are determined from the length, mass, and density of the strips.

Core loss, P_c, is calculated from the observed values of R_1 and E_1

$$P_c=\frac{E_1^2}{R_1}=\frac{E_1^2R_b}{R_aR_c}$$

The specific core loss $P_{B:f}$ is

$$P_{B:f}=\frac{P_c}{m_1}$$

where m_1 is the active mass as indicated above.

Reactive or quadrature power is

$$P_q=\frac{E_1^2}{\omega L_1}=\frac{E_1^2}{\omega C_bR_aR_c}$$

the unit is called the var. The specific value is P_q/m_1 where m_1 is the effective mass, determined as shown above.

Incremental values of permeability and core loss are determined in the order of increasing values of biasing magnetizing force. Direct current is supplied to the secondary winding and adjusted to the required value and reversed several times to establish a cyclic condition in the specimen. The a-c is then applied and the bridge is adjusted and readings taken as described above.

The d-c magnetizing force is calculated as follows:

In the cgs system, the biasing or d-c magnetizing force is

$$H_b=\frac{0.4\pi N_2I_{d\text{-}c}}{l_1}$$

where

H_b=biasing magnetizing force, oersteds

$I_{d\text{-}c}$ =d-c current, amperes

l_1=assumed length of the magnetic circuit, cm.

In the mksa system

$$H_b=\frac{N_2I_{d\text{-}c}}{l_1}$$

where

$I_{d\text{-}c}$=d-c current, amperes

and

l_1 is in meters

H_b is then ampere-turns per meter.

For incremental tests, the average-reading voltmeter is connected to the primary winding N_1. For this test values of incremental induction, B_Δ are limited to not more than 1,000 gausses (0.1000 tesla).

6.2. A-C Measurements at Higher Than Power Frequencies

Magnetic materials have been developed which are particularly useful at high frequencies on account of their extremely high electrical resistance. They are ceramic materials called ferrites. Magnetic tests of these materials are usually made on specimens in the form of small rings. Although the Hay bridge can be adapted to make measurements at the higher frequencies, it has the disadvantage that each ring must be wound individually. In order to obviate this difficulty, Haas [26] has developed a radiofrequency permeameter similar in principle to an instrument developed earlier for power frequencies by Kelsall [27]. It is shown diagrammatically in figure 19.

The radiofrequency permeameter consists essentially of a transformer. The primary is wound on a powdered ring core. The secondary consists of a central conducting tube over which the ring specimen can be placed. The one-turn secondary is completed by a coaxial outside cylinder and end plates which form a single short-circuited turn which is linked with both the primary core and the specimen as shown in the equivalent circuit. The top plate is removable for insertion of the test specimen. Measurements are made of the input

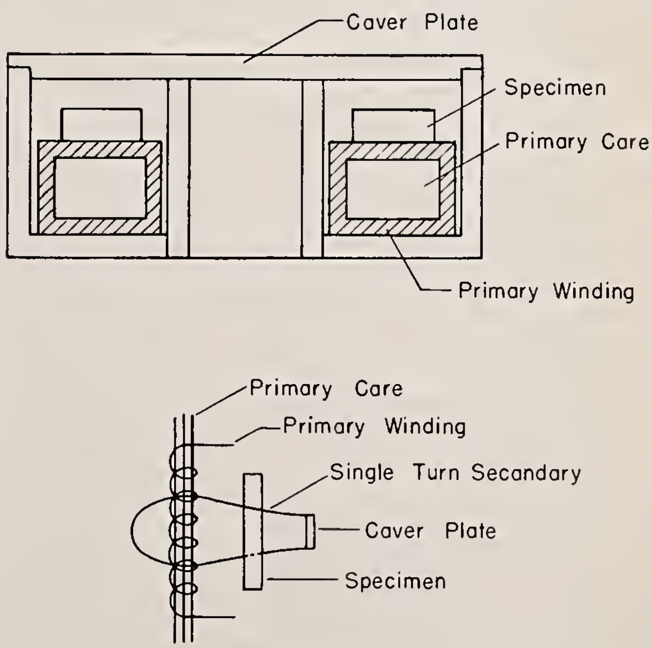


Figure 19. *Radio frequency permeameter.*

impedance of the primary winding with no specimen and the secondary open-circuited, with the secondary circuit closed but no specimen, and with the secondary circuit closed and a specimen in place. These measurements can be made with a Q-meter or an impedance bridge. From the values thus obtained, initial values of complex permeability and losses can be computed. Details of the measurements and computations can be obtained from the original paper [26].

7. Typical Magnetic Properties of Materials

Magnetic materials are used under a great variety of conditions both for cores and for permanent magnets. In order to meet many of these special requirements, it is frequently necessary to "tailor make" the material. This may require "special" alloying elements, heat-treating temperatures and procedure, and special mechanical working. In general, however, the metallic magnetic materials employed in practice are alloys mainly composed of one or more of the ferromagnetic metals, iron, nickel, and cobalt. Other elements are always present, either as undesired impurities or as alloying elements added for the purpose of producing certain desired characteristics. In figure 20 are shown typical normal induction curves of annealed samples of iron, nickel, and cobalt of comparatively high purity. These curves are given only for the purpose of general comparison and should not be considered as representing critical values. Small variations in the degree of purity or in the annealing procedure lead to substantial differences in normal induction.

Magnetic materials employed in commercial practice may be considered under the following six classifications: (1) solid core materials; (2) electrical sheet or strip; (3) special alloys; (4) ferrites; (5) permanent-magnet materials; and (6) feebly magnetic materials. In view of the rapid and continued progress in the development of magnetic materials, it is only feasible to give data characteristic of several of the materials commercially available at present. These data indicate merely the range of properties obtainable in the various classes of material and should not be considered as critical, since considerable variation from these values will be found in practice.

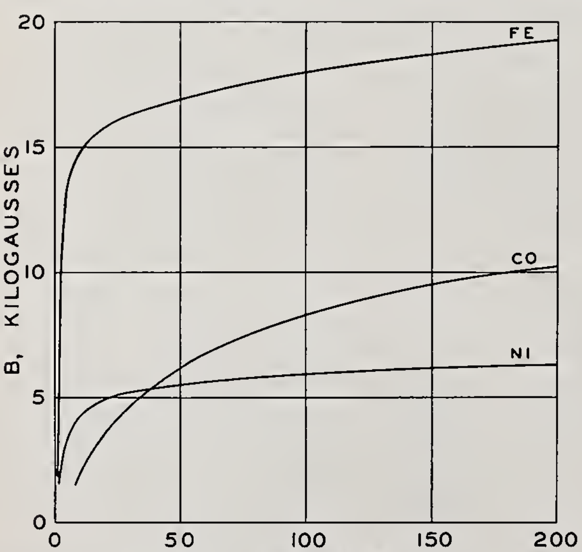


Figure 20. *Typical norml induction curves of annealed samples of iron, nickel and cobalt.*

7.1. Solid Core Materials

These materials are used for the cores of direct-current electromagnets, relays, field frames of d-c machines, etc. The principal requirement is high permeability particularly at relatively high inductions. For the majority of uses, it is desirable that the coercive force and hysteresis be low. The principal materials employed are soft iron, low-carbon steel, cast iron, and an alloy of approximately 49 percent of cobalt, 49 percent of iron, and 2 percent of vanadium known as Permendur or Supermendur. Permendur is characterized by very high permeability in the upper part of the normal induction curve and a saturation induction approximately 10 percent greater than that of pure iron. Its cost is relatively high, however, and its use is limited in general to pole tips in which a very high induction is required. Several varieties of soft iron are available, such as Armco iron, Norway iron, and Swedish charcoal iron. These irons are especially refined to reduce impurities and to make as pure iron as is commercially feasible. A typical composition is 99.91 percent of iron, 0.02 percent of carbon, with small percentages of manganese, phosphorous, and sulfur. Low-carbon steel should not have more than 0.0 to 0.2 percent carbon and should contain only the usual small amounts of the ordinary impurities. Cast iron has a relatively low permeability and is used principally in field frames when cost is of primary importance and extra weight is not objectionable. Cast iron is high in carbon (about 3%) and also contains about 3 percent of silicon and varying percentages of phosphorous, manganese, and sulfur.

The best magnetic properties for these materials are obtained by a suitable annealing treatment after machining and fabrication processes have been completed. The properties of cast iron can be greatly improved by malleabilizing, a process that converts a large part of the carbon to the amorphous form.

Typical normal induction curves for solid core materials are given in figure 21.

7.2. Electrical Sheet and Strip

The term electrical sheet (or strip) is commercially used to designate iron-silicon alloys produced in sheet or strip form and used as core

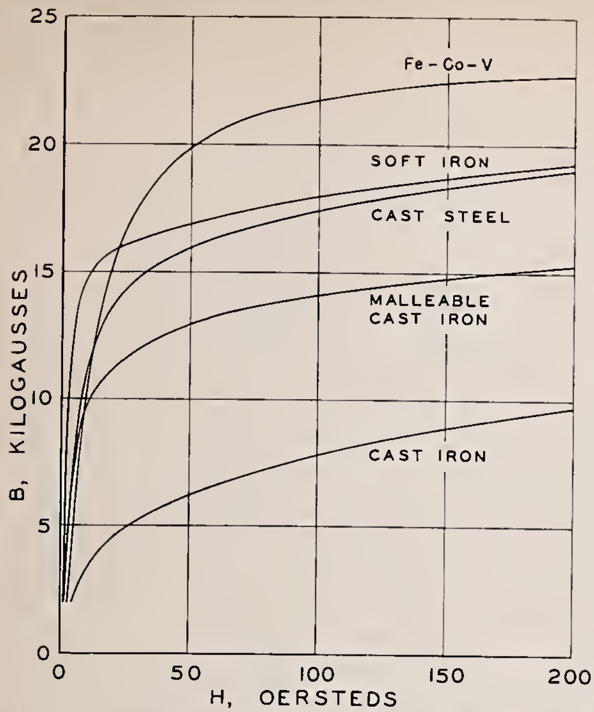


Figure 21. *Typical normal induction curves for solid core materials.*

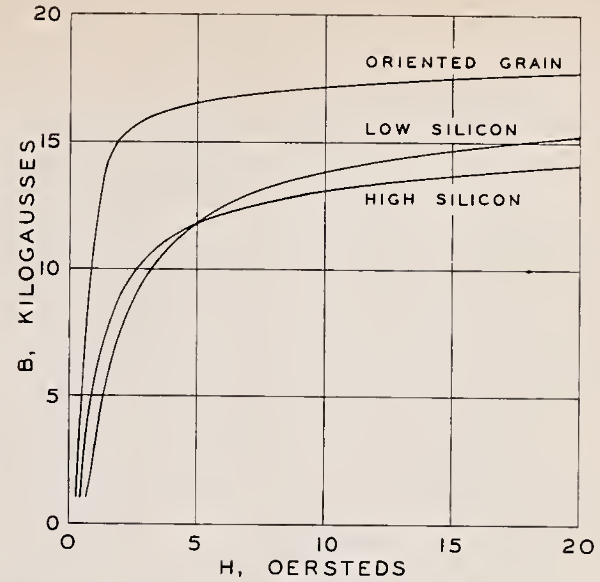


Figure 22. *Typical normal induction curves for electrical sheet.*

materials in alternating-current apparatus such as transformers, motors, electromagnets, or relays. The principal requirements are high permeability, low hysteresis, and high electrical resistivity. The several grades differ mainly with respect to their silicon content, which ranges from 0.5 percent to approximately 5 percent. Alloys containing the higher percentages of silicon are practically non-aging; that is, the permeability and losses do not change appreciably with time. The required magnetic properties are produced by annealing.

By a suitable combination of cold-rolling and heat treatment, electrical sheet may be produced in which the majority of the crystals are given a favorable orientation. Such material has considerably better magnetic properties in the preferred direction than ordinary grades. their maximum permeability is approximately twice as high and they have much lower core losses combined with higher permeability at high induction than ordinary grades. Figure 22 shows typical normal induction curves for two grades of electrical sheet and oriented-grain material. The improvement in the oriented-grain material is particularly conspicuous in the upper part of the normal induction curve.

The different grades of electrical sheet and strip are usually sold on the basis of guaranteed maximum values of total core loss, as determined in accordance with the specifications of the American Society for Testing Materials [23]. The common designations of the various grades are armature, electrical, motor, dynamo, and transformer. The transformer grades are further subdivided into classes denoted by numerals corresponding to the core loss under standard conditions. Armature, electrical, and motor grades are used principally in small motors, a-c magnets and starting transformers. The dynamo grade is used in high-efficiency rotating machines and small transformers. The transformer grades are used in power and radio transformers.

7.3. Special-Purpose Materials

For certain applications, special alloys and other materials have been developed which, after proper fabrication and heat treatment, have superior properties in certain ranges of magnetization. For instance, alloys of nickel and iron with possible small percentages of molybdenum or chromium have very high values of initial and maximum permeability. Alloys of this class which may have from 70 to 80 percent of nickel are called Permalloys. Special attention to the purity of the constituents, the manufacture, fabrication, and heat treatment has resulted in an alloy of nickel, iron, molybdenum, and manganese that has a maximum permeability greater than one million. This alloy when commercially prepared and rolled into thin tapes (0.001 to 0.004 in. thick) has a maximum d-c permeability between 300,000 and 900,000. An alloy of 50 percent nickel and 50 percent iron is called Hipernik. Another alloy having a small percentage of copper in its composition is called Mumetal. The characteristics of these alloys differ in detail but in general they have high initial and maximum permeability, low hysteresis, and low saturation values. The alloy, Supermendur, of 49 percent of iron, 49 percent of cobalt and 2 percent of vanadium has high permeability which persists at higher values of induction than the nickel-iron alloys.

Typical permeability curves for several special-purpose alloys are given in figure 23 and figure 24.

A certain alloy of nickel, cobalt, and iron after suitable heat treatment has very nearly constant permeability for inductions below 1,000 gausses and is called Perminvar. The 50–50- nickel- iron

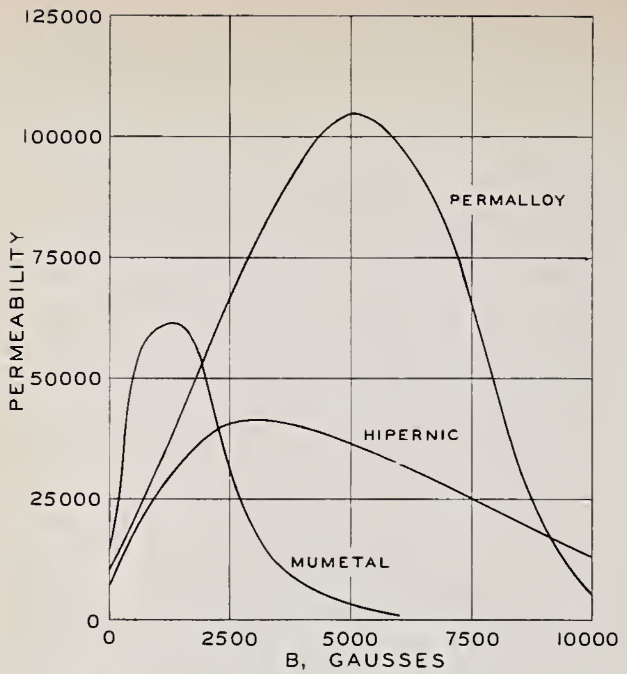


FIGURE 23. *Typical permeability curves for special purpose alloys I.*

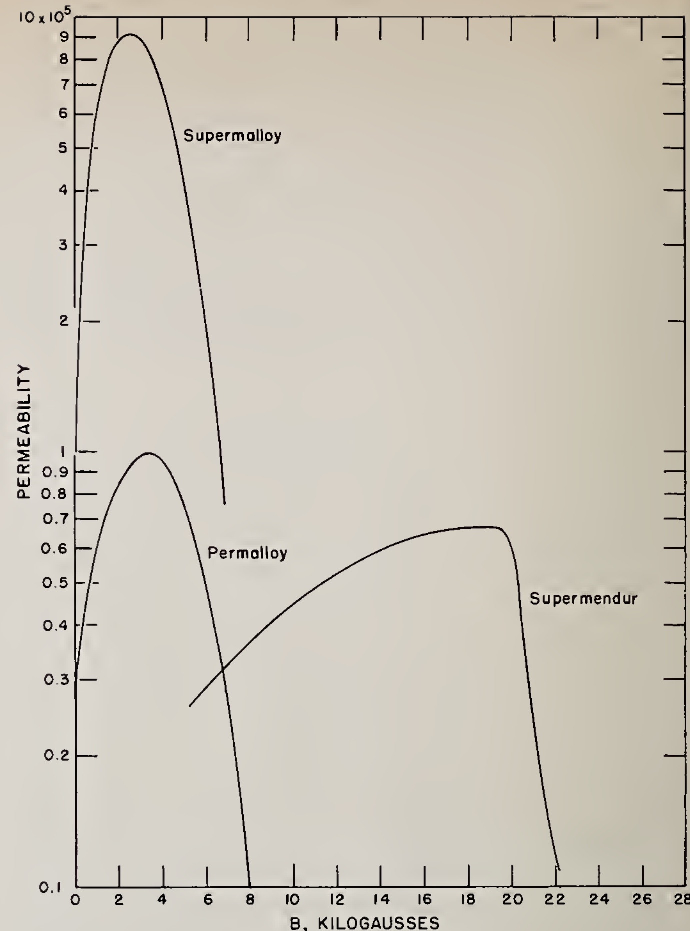


FIGURE 24. *Typical permeability curves for special purpose alloys II.*

alloy can also be heat-treated so as to have similar characteristics.

Many of the above described alloys are rolled into thin tape (as thin as 0.0001 in.) and spirally wound cores are prepared from the tape. This permits the designer to make use of their directional properties as well as to use them at much higher frequencies by decreasing eddy-current effects.

Another series of magnetic alloys of copper, nickel, and iron is temperature-sensitive having an approximately linear relation between permeability and temperature. These are called Thermalloys. The principal use is in the compensation of watt-hour meters for temperature variations. They are also used in certain types of thermal relays.

Although chemical composition and impurities are very important in the preparation of a magnetic alloy, experience has shown that with the same chemical composition a wide variety of magnetic properties can be obtained by varying the mechanical working and type of heat treatment. This is very striking in the nickel-iron and iron-silicon alloys and has led to the development of materials having a practically rectangular hysteresis loop. These are of great importance in the field of electronics.

7.4. Ferrites

Ferrites are nonmetallic ceramic materials whose extraordinarily high electrical resistivity is especially useful for high-frequency applications. They are finding increasing use in applications such as electronic computers, antenna rods, isolators, and magneto-strictive devices. They are made of iron oxide combined with certain bivalent oxides, hydroxides, or carbonates of metals such as manganese, cobalt, nickel, copper, zinc, or magnesium. The process of manufacture is similar to that of other high-grade ceramic materials. The powdered materials, which must be of high purity and proper particle size, are mixed in suitable proportions, pressed or extruded to the desired shapes, and fired. This procedure produces chemical compounds of the metallic oxides.

These materials are often called "soft" ferrites to distinguish them from certain ceramic materials used for the manufacture of permanent magnets. In common with other ceramics, they are mechanically hard and brittle and require special tools for cutting or grinding. Also, since they require no critical materials, they are relatively low in cost.

Although the saturation induction of the soft ferrites is not high, this is not important because they are generally used at low inductions. Their relative initial permeabilities (100 to 1,500) are very good for the high frequencies involved. The principal disadvantage of the ferrites is their low Curie points which range from 100 to 500 °C. This is important if they are to operate at temperatures much higher than room temperature. Typical magnetic properties of some ferrites at room temperature are shown in figure 25. In figure 26 is shown the temperature dependence of magnesium-manganese ferrite.

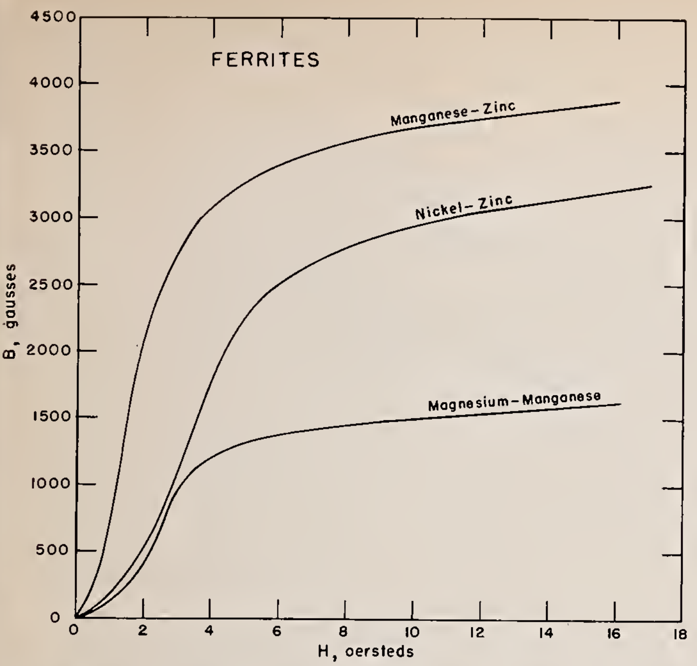


FIGURE 25. *Typical normal induction curves for "soft" ferrites.*

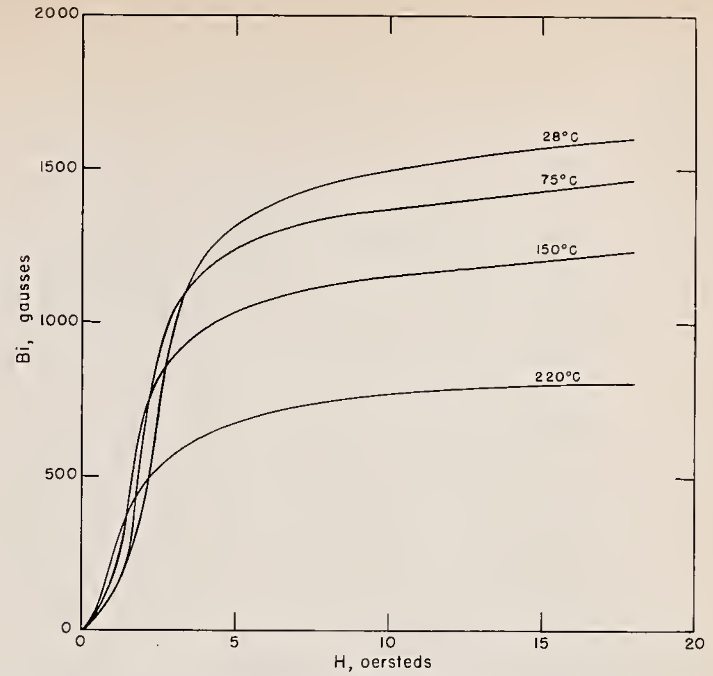


FIGURE 26. *Temperature dependence of a magnesium-manganese ferrite.*

7.5. Permanent-Magnet Materials

Although it is possible to make permanent magnets of almost any kind of steel that is capable of being hardened by heat treatment, it is best to use materials especially produced for the purpose. Magnets made from other types of material are likely to be inferior in quality or unnecessarily expensive. Before the development of the special magnet steels, magnets were generally made of plain high-carbon tool steel. This type of steel is relatively inexpensive, but its magnetic properties are so greatly inferior to those of the special steels that now it is practically never used for making permanent magnets.

Permanent-magnet materials may be grouped in five classes as follows: (a) Quench-hardened alloys; (b) precipitation-hardened alloys; (c) work-hardened materials; (d) ceramics; and (e) iron-powder compacts. Figure 27 shows typical demagnetization curves for several permanent-magnet materials.

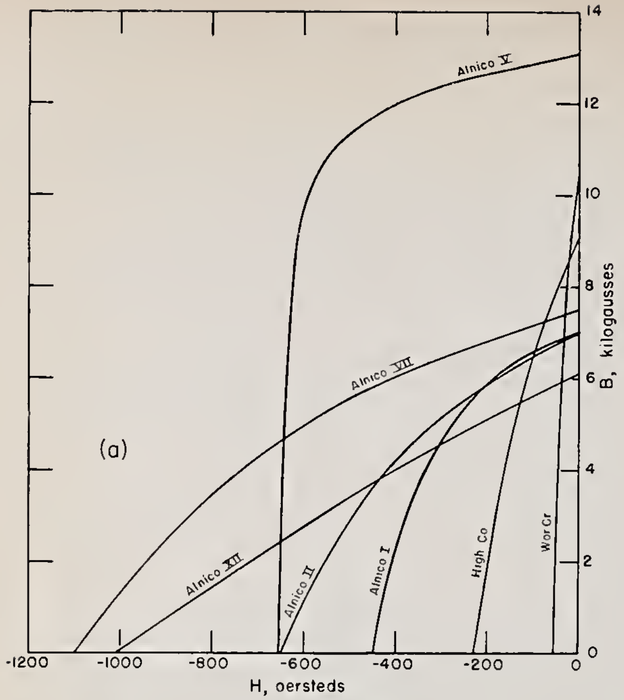
a. Quench-Hardened Alloys

Tungsten, chromium, and cobalt magnet steels have been in use for many years. Prior to the first world war, tungsten steel was the standard high-grade permanent-magnet material. The optimum tungsten content is between 5 and 6 percent, with about 0.6 percent of carbon. During World War I, when tungsten was scarce, chromium magnet steel was developed and extensively used in this country. There are two principal grades, one containing about 1 percent of chromium and 0.6 percent of carbon, and the other containing about 3.5 percent of chromium and 0.9 percent of carbon. The 3.5-percent chromium steel is used in many applications. Shortly after World War I, the Japanese metallurgist Honda announced the development of a new permanent-magnet steel having cobalt as the principal alloying element, which he named KS magnet steel. This steel also contained substantial percentages of tungsten, chromium, and molybdenum. The coercive force of this material is about four times as great as that of the tungsten or chromium magnet steels. This development stimulated further investigations which led to the commercial production of several types of cobalt magnet steel having various percentages of cobalt. High-cobalt magnet steels have from 35 to 41 percent of cobalt, and low-cobalt steels have from 8 to 9 percent. These steels also have tungsten and chromium in addition to the cobalt. An intermediate cobalt steel has 17 percent of cobalt and about 9 percent of chromium. Tungsten is sometimes substituted for part of the chromium.

The quench-hardened alloys can be forged and machined from the ingot.

b. Precipitation-Hardening Alloys

The most important permanent-magnet materials are of the precipitation-hardening variety. This group includes the Alnico, Cunife, Cunico, and Vicalloy. The process of hardening in these alloys is related to the change from a single phase at high temperature into two new phases when the temperature is lowered beyond a certain value. The fact that high values of coercive force can be obtained with alloys containing no carbon was anounced in 1932 by Seljesater and Rogers [28] in the United States, Köster [29] in Germany, and Mishima [30] in Japan. These precipitation-hardening permanent-magnet alloys contained aluminum, nickel, and iron. Although the residual induction was relatively low, the coercive force



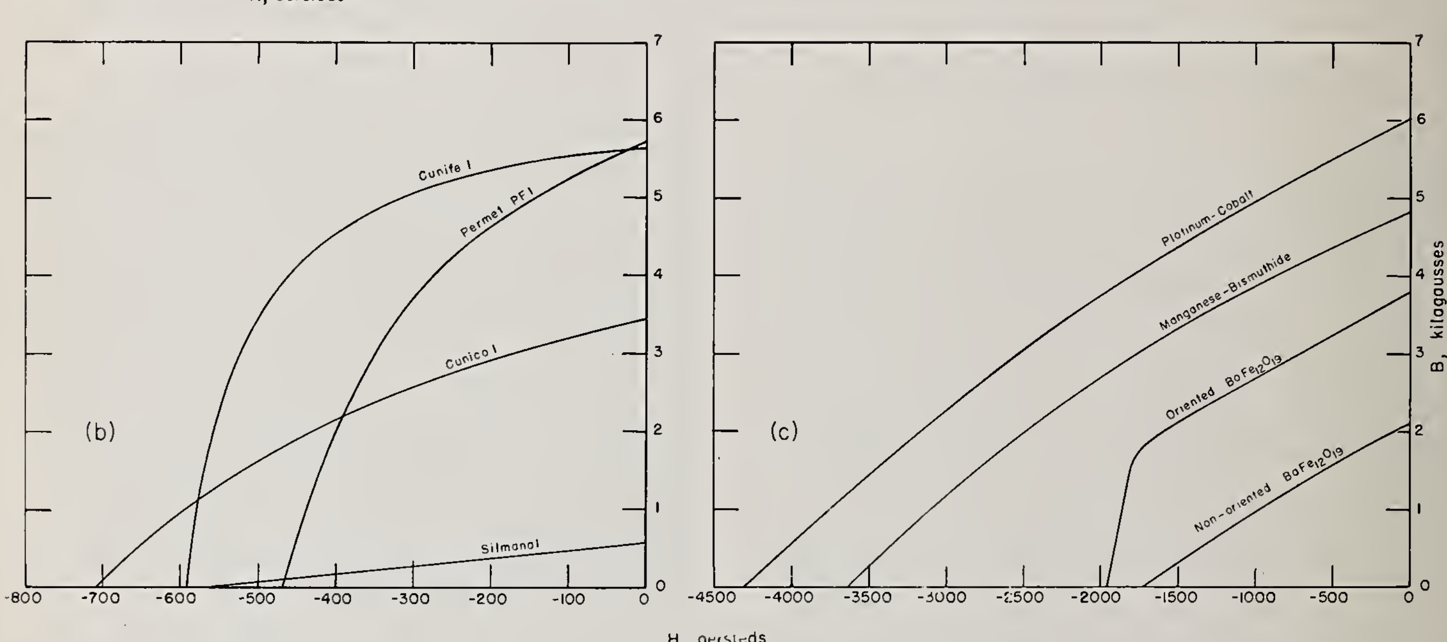


FIGURE 27. a) b) c) *Typical demagnetization curves for permanent magnet materials.*

was so high, about 475 oersteds, that new applications of permanent magnets were made possible. Further investigation showed that the addition of cobalt to the aluminum, nickel, and iron could increase both the residual induction and coercive force. There are more than twenty different commercial varieties called Alnico having coercive force values ranging from 400 to 1,100 oersteds and maximum energy products from 1.2×10^6 to approximately 7×10^6 gauss-oersteds. The Al-Ni-Co-Fe alloys are very hard and brittle, so that they cannot be formed by the usual methods of forging and machining but must be either cast or molded in powder form and then sintered. Final finishing is done by grinding.

Other alloys that belong to the precipitation-hardening group, however, are unusual for high coercive force permanent-magnet material in that they are so ductile that they can be formed readily by rolling or drawing and can be drawn to fine wires before the final heat treatment [31]. Cunife, Cunico, Silmanal, and Vicalloy are alloys of this type.

The platinum alloys have very high values of coercive force but their low residual induction and high cost limit their usefulness.

c. Work-Hardened Alloys

Several ordinarily "nonmagnetic" alloys of iron may become ferromagnetic after cold working due to a phase change in the material. Stainless steel (18% chromium, 8% nickel) is "nonmagnetic" at room temperature after being rapidly cooled from 1,200 °C in the usual process of manufacture. However, if it is hardened by cold working such as drawing through a reducing die it may develop properties such that it makes an acceptable permanent-magnet material at room temperature. If this work-hardened alloy is then reheated to a high temperature and cooled slowly it regains its original nonmagnetic condition at room temperature. Another alloy that shows this property contains 45 percent iron, 15 percent Ni, and 40 percent Cu. Nesbitt [32] has measured a coercive force of 240 oersteds and a residual induction of 4,400 gausses in wire of this composition which after quenching from 1,000 °C, was then cold drawn from 0.026 to 0.006 in. Increasing the percentage of iron to 60 percent, decreasing the percentage of copper to 25 percent, with 15 percent nickel produced an alloy that after similar treatment as above resulted in a coercive force of 170 oersteds and residual induction of 11,000 gausses.

d. Ceramic Magnet Materials

A commercial development in permanent-magnet materials which is increasing in importance each year is the barium ferrite or ceramic permanent-magnet material. This is a chemical compound and has mechanical characteristics similar to other ceramics. They are hard, brittle, have a lower density than metals, and extremely high electrical resistivity. The basic ingredients are barium carbonate and iron oxide. These materials in powdered form are compressed in dies under high pressure to the required shape. This compacted material is then sintered at a high temperature. This process produces a material which has an H_c of approximately 2,000 oersteds, a B_r of approximately 2,000 gausses, and a demagnetization curve which is practically a straight line. Further improvements in ceramic materials have resulted in a highly-oriented barium-iron oxide whose magnetic properties, on a weight basis, are almost equal to those of Alnico V. The coercive force is approximately 2,000 oersteds, the residual induction 4,000 gausses, and the energy product is 3.5 times that of the unoriented variety. At right angles to the direction of grain orientation, however, this material exhibits negligible permanent-magnet properties and has a permeability of only approximately 1.0.

e. Powder Magnets

Although pure iron is usually regarded as a high-permeability or "magnetically soft" material yet theory has predicted and experiments have proved that compacts of pure iron powders may produce very good permanent magnets. Powder magnets have been produced of iron and iron alloys (such as 70% iron and 30% cobalt) (Permet) with particle size of about 10^{-5} cm diameter with H_c up to 500 oersteds and energy product of 1.5×10^6 gauss-oersteds. The permanent-magnet properties result from the discrete small particles of a single phase instead of from the presence of two or more phases as in most other metallic permanent-magnet material. Further experimental work with particle size and shape and processes of manufacture have produced, in the laboratory, magnets with energy products comparable to those of Alnico V and theoretical considerations predict even higher values.

Manganese-bismuth permanent magnets also belong to this group. This material is an anisotropic aggregate of crystals of the intermetallic compound manganese bismuthide (Mn Bi) and is a product of powder metallurgy. Manganese bismuthide is prepared from the chemical action between molten bismuth and powdered manganese when heated to approximately 700 °C in an inert atmosphere of argon or helium. Cooling is accomplished in such a manner as to produce crystallization of the compound. Laboratory-produced material may have a residual induction of approximately 4,800 gausses and a coercive force of 3,600 oersteds with energy product values as high as 5×10^6 gauss-oersteds.

Powder metallurgy has also produced sintered Alnico magnets. These magnets have greater mechanical strength and more uniform magnetic properties than the cast variety at the expense of a slight decrease in the magnetic properties.

Magnet materials prepared from metal oxides such as cobalt ferrites and Vectolite have been made and used for many years; however, they have been practically superseded by the barium ferrites.

7.6. Feebly Magnetic Materials

It is occasionally desirable to use metallic materials for tools or parts of equipment which require practically nonmagnetic materials. Oxygen-free, high-conductivity copper, copper-beryllium alloy, and pure aluminum are often used where mechanical strength is not required. Aluminum-bronze, nickel-copper, stainless steels, and manganese steels can be used if a permeability not exceeding 1.10 is permissible. In using such a material, it should be kept in mind that even when the bulk material is sufficiently nonmagnetic, mechanical working, surface contamination or temperature effects may make it unsatisfactory.

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Upper Atmosphere and Space Physics. Upper Atmosphere and Plasma Physics Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.

Radio Physics.

Circuit Standards.