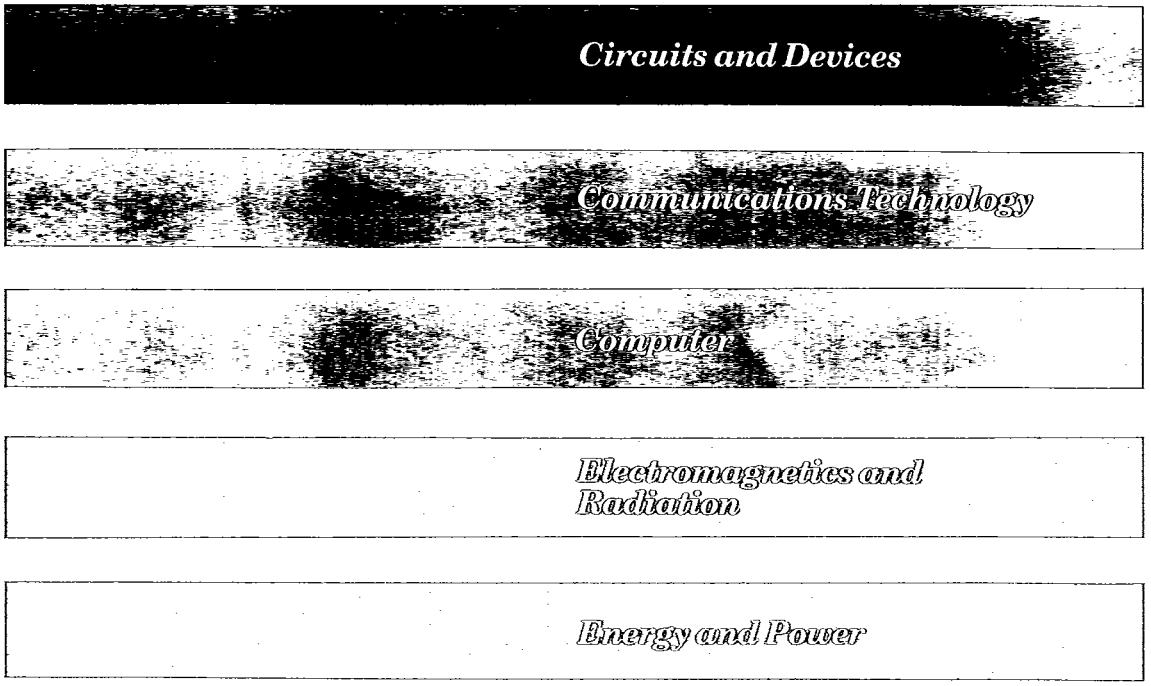
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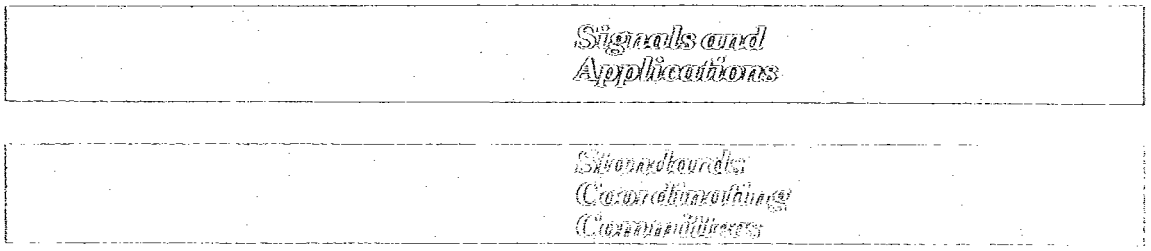
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(Revision of IEEE Std 393-1977)

IEEE Standard for Test Procedures for Magnetic Cores



IEEE Power Electronics Society

Sponsored by the
Electronics Transformer Technical Committee



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IEEE Standard for Test Procedures for Magnetic Cores

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Electronics Transformer Technical Committee
of the
IEEE Power Electronics Society

Approved June 27, 1991

IEEE Standards Board

Approved December 9, 1991

American National Standards Institute

Abstract: Test methods useful in the design, analysis, and operation of magnetic cores in many types of applications are presented. Tests for specifying and/or measuring permeability, core loss, apparent core loss, induction, hysteresis, thermal characteristics, and other properties are given. Most of the test methods described include specific parameter ranges, instrument accuracies, core sizes, etc., and may be used in the specification of magnetic cores for industrial and military applications. More generalized test procedures are included for the benefit of the R & D engineer and university student. Although the primary concern is with cores of the type used in electronics transformers, magnetic amplifiers, inductors, and related devices, many of the tests are adaptable to cores used in many other applications.
Keywords: electromagnetic measurements, magnetic cores

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Foreword

(This foreword is not a part of IEEE Std 393-1991, IEEE Standard for Test Procedures for Magnetic Cores.)

The purpose of this standard is to present test methods useful in the design, analysis, and operation of magnetic cores in many types of applications in electronics and related industries. Most of the test methods described include specific parameter ranges, instrument accuracies, core sizes, etc., which may be used in the specification of magnetic cores for industrial and military applications. Other sections of the standard describe more generalized test procedures, which are included more for the benefit of the R and D engineer and university student.

This standard has been updated to include core materials, test methods, and information on measuring instruments. Information from two discontinued standards is now included. The old standards were IEEE Std 106-1972, Standard Test Procedure for Toroidal Magnetic Amplifier Cores and IEEE Std 164-1962, Methods of Testing Bobbin Cores.

SI units are used throughout this standard; equivalent CGS and English units are included in some definitions. Whenever possible, all definitions and symbols are in accordance with those of the International Electrotechnical Commission (IEC).

The revision of this standard was prepared by the Working Group on Magnetic Cores—Test Codes Subcommittee of the Electronics Transformer Technical Committee of the IEEE Power Electronics Society.

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IEEE Standard for Test Procedures for Magnetic Cores

1. Scope

This standard specifies applicable tests to describe the significant properties of magnetic cores used in electronic applications. It is primarily concerned with magnetic cores of the type used in electronics transformers, magnetic amplifiers, inductors, and related devices. However, many of the tests specified herein are general in scope and adaptable to magnetic cores used in many other applications. Standards covered by this publication include tests for specifying or measuring, or both, permeability, core loss, apparent core loss, induction, hysteresis, thermal characteristics, and other properties of all commonly used types of magnetic cores.

1.1 Specific Types of Magnetic Cores to Which this Standard Applies

(1) Wound strip cores
(2) Die-stamped laminated cores
(3) Cores using laminations formed by chemical milling or photoetching techniques
(4) Pressed or molded cores

1.2 Specific Applications to Which this Standard Is Directed

1.2.1 Linear applications as in power supply transformers, audio transformers, control system transformers, many pulse transformers, capacitor reversing inductors, instrument transformers, etc.

1.2.2 Nonlinear or saturating applications, including magnetic amplifiers, saturable inductors, ferroresonant devices, current rise delay inductors, and saturating inductors.

1.2.3 Specific applications not covered by this publication: magnetic cores for power distribution industry; cores for microwave applications.

1.3 References and Related Standards

1.3.1 References. The following publications shall be used in conjunction with this standard:

[1] ANSI/ASTM A-343-82 (86), Test Method for Alternating Current Magnetic Properties of Materials at Power Frequencies Using the Wattmeter-Ammeter-Voltmeter Method and 250 cm Epstein Test Frame.[1]

[2] IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms—4th ed.[2]

[3] IEEE Std 390-1987, IEEE Standard for Pulse Transformers (ANSI).

[4] Hamburg, D. R. and L. E. Unnewehr, "An electronic wattmeter for nonsinusoidal low power factor power measurements," *IEEE Transactions on Magnetics,* vol. MAG-7, no. 3, pp. 438–442, Sept. 1971.

[5] Toppetto, A. A. and D. A. Henry, "Pulse Inductance-Problems and Peculiarities." Electronic Components Conference, 1972.

1.3.2 General Related Standards. The following standards may be consulted for additional guidance:

ANSI/ASTM A-34-83 (88)e1, Practice for Magnetic Materials.

[1]ASTM publications are available from the Customer Service Department, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103, USA.

[2]IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

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ANSI/ASTM A-340-90, Definition of Terms—Terms, Symbols, and Conversion Factors Relating to Magnetic Testing.

ANSI/ASTM A-346-74 (88), Test Method for Alternating-Current Magnetic Performance of Laminated Core Specimens Using the Modified Hay Bridge Method.

ANSI/ASTM A-347-85 (91), Test Method for Alternating-Current Magnetic Properties of Materials Using the Modified Hay Bridge Method with 25-cm Epstein Frame.

ANSI/ASTM A-348-84, Test Method for Alternating-Current Magnetic Properties of Materials Using the Wattmeter-Ammeter-Voltmeter Method, 100 to 10,000 Hz and 25-cm Epstein Frame.

ANSI/ASTM A-598-69 (1983), Test Method for Magnetic Properties of Magnetic Amplifier Cores.

ANSI/ASTM A-698-74 (85)e1, Test Method for Magnetic Shield Efficiency in Attenuating Alternating Magnetic Fields.

ANSI/ASTM A-712-75 (91), Test Method for Electrical Resistivity of Soft Magnetic Alloys.

ASTM A-717-81 (88)e1, Test Method for Surface Insulation Resistivity of Single-Strip Specimens.

ANSI/ASTM A-718-75 (91), Test Method for Surface Insulation Resisitivity of Multi-Strip Specimens.

ASTM A-772-89, Test Method for A-C Magnetic Permeability of Materials Using Sine Current.

ASTM A-811-90, Specification for Soft Magnetic Iron Fabricated by Powder Metallurgy Techniques.

IEC 367-1 (1982), Cores for inductors and transformers for telecommunications. Part 1: Measuring methods.[3]

IEC 367-2A (1976), Cores for inductors and transformers for telecommunications. Part 2: Guides for the drafting of performance specifications. First supplement.

IEC 723-1 (1982), Inductor and transformer cores for telecommunications. Part 1: Generic specification.

IEEE Std 111-1984, IEEE Standard for Wide-Band Transformers (ANSI).

IEEE Std 295-1969 (Reaff 1981), IEEE Standard for Electronics Power Transformers.

IEEE Std 306-1969 (Reaff 1981), Test Procedures for Charging Inductors.[4]

IEEE Std 390-1987, IEEE Standard for Pulse Transformers (ANSI).

2. Definitions

Electrical and magnetic terms used in this standard are in accordance with those given in IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms [2].[5] Certain parameters of particular significance in the application and evaluation of magnetic cores as well as certain terms not included in IEEE Std 100-1988 are further discussed in Section 5, Symbols and Terms, of this standard.

3. Configurations

3.1 Effect of the Configuration or Geometry of the Core Material on the Finished Product. The configuration or geometry of the core material has a decided effect on the magnetic properties of the finished product. For exam-

[3]IEC publications are available from IEC Sales Department, Case Postale 131, 3 rue de Varembé, CH 1211, Genève 20, Switzerland/Suisse. IEC publications are also available in the United States from the American National Standards Institute.

[4]IEEE Std 306-1969 has been withdrawn; however, copies can be obtained from the IEEE Standards Department, IEEE Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

[5]The numbers in brackets correspond to those of the references in 1.3.1; when preceded by B, they correspond to those of the bibliography in Section 7.

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ple, one finds distinct differences in core loss and permeability measurements, when a core specimen is tested as strips in an Epstein frame, as a toroidal wound core, or as an EI assembly of punched laminations. It is important, therefore, that a specified magnetic parameter refer to the specific configuration on which the test measurement is to be made.

3.2 Basic Core Shapes. For reference, the following are recognized as the basic core shapes in which tests are performed:

(1) *Toroid.* Stack of ring stampings (no effective gap); spiral wound strip (very small effective gap); pressed or molded (toroids, beads, tubes).
(2) *Cut Strip-Wound* (C and E cores).
(3) Cores assembled from die cut or chemically etched sheet materials (stamped laminations) such as DE, DU, EE, EI, FF, LL, UI, UT, W. These have varying effective air gaps depending upon size, shape, lamination-thickness, and assembly technique.
(4) Pressed and molded parts, such as cup, rod, bar, slug, sleeve, strip, or assemblies of parts such as pot cores, cross cores, half cross, H core, EE, EV, UI, RM.

3.3 Epstein Strip Core. Epstein strip core is used in a specified coil assembly for evaluation of sheet and strip materials.

4. Materials

The shapes in Section 3 are usually achievable using one or more of the following basic materials:

4.1 Ferromagnetic

(1) Flat-rolled sheet or strip, for example, silicon-iron, nickel-iron, cobalt-iron
(2) Powdered permalloy (powdered molybdenum-nickel-iron alloy)
(3) Powdered iron
(4) Flat cast strip, Amorphous metal alloys

4.2 Ferrites. For example: nickel-zinc, manganese-zinc, magnesium-manganese.

5. Symbols and Terms

Symbol	*Term and (Unit)*
a	Hysteresis loss coefficient in Legg's equation (tesla).
A_e	Effective cross-sectional area, see 5.1 (SI units: m^2; CGS unit: cm^2).
A_L	Induction factor (henry/turns^2)—often called inductance factor and permeance.
B	General symbol for induction, or magnetic flux density. Also the amplitude of change in induction. (SI unit: tesla; CGS unit: gauss. 1 T = 10^4 G.)
ΔB	The total cyclic change in induction, often in the presence of a static magnetic field.
$\vec{B}$	Vector representing induction.
B_m or $\hat{B}$	The peak value of induction.
B_r	The remanent value of induction.
B_s	Saturation induction.
c	Residual loss coefficient in Legg's equation (unitless).
D	Disaccommodation (percent).
D.F.	Disaccommodation factor.
dB	Differential notation for induction.
e	Eddy current loss coefficient in Legg's equation (second).
f	Frequency (hertz).
G	Reset gain in the Constant Current Flux Reset Test (has same units as permeability).
H	General symbol for magnetic field strength, also the amplitude of alternating field strength. (SI unit: amperes/meter; CGS unit: oersted. 1 Oe = 79.577 A/m).
ΔH	Total change in field strength, often in the presence of a static magnetic field.
dH	Differential notation for magnetic field strength.
$\vec{H}$	Vector representation of the magnetic field strength.
H_c	Coercive field (force).
H_{pk}	Peak value of magnetic field strength.
H_z	Equivalent peak field strength from rms current.

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$\hat{i}$	Peak value of the current (amperes).
j	$\sqrt{-1}$
L_o	Self-inductance of a coil with a core of unity relative permeability with the same flux distribution as with a particular magnetic core (henry).
L_s	Series equivalent inductance.
L_p	Parallel equivalent inductance.
l	Magnetic flux path length (SI unit: meter; CGS unit: centimeter, cm).
l_e	Effective flux path length; see 5.1.
N	Number of turns on a coil.
R_p	Parallel equivalent resistance (ohm).
R_s	Series equivalent resistance.
Q	Quality factor.
ΔT	Change in temperature (°C).
T_c	Curie temperature (°C).
$\tan \delta_n$	Tangent of the loss angle.
V_e	Effective volume (cubic meters); see 5.1.
α	Turns factor.
δ_n	Loss angle.
μ	Permeability (henry/meter).
μ	Permeability vector.
μ_a	Relative amplitude permeability.[6]
$\overline{\mu}_i$	Relative initial permeability.[7]
μ_o	Magnetic constant, permeability of free space ($4\ \pi\ 10^{-7}$ henry/meter).
$\overline{\mu}$	Complex permeability.
μ_π	Pulse permeability.
$\mu_{\pi x}$	Pulse permeability at a specific condition, where the subscript x defines that condition (for example, i for initial permeability).
μ'_p and μ''_p	Real and imaginary components of the complex parallel equivalent relative permeability.
μ'_s and μ''_s	Real and imaginary components of the complex series equivalent permeability.
μ_z	Impedance permeability.
η_i	Hysteresis core constant.
ω	Angular frequency (radian second).

[6]In the case of qualified versions of permeability, such as pulse permeability, μ_π, the relative quantity is meant, unless otherwise stated.

[7]See footnote 6.

5.1 Effective Parameters. The effective magnetic parameters are defined as the parameters of a toroid with uniform cross section and permeability that, if wound with the same number of turns, would give the same electrical performance as the original core. The effective parameters are marked with the subscript *e*. Therefore, the effective core dimensions are as follows:

A_e = Effective cross-sectional area, the cross-sectional area of the equivalent toroid

l_e = Effective magnetic path length, the mean circumference of the equivalent toroid

V_e = Effective volume, the volume of the equivalent toroid

m_e = Effective mass, the mass of the equivalent toroid

5.2 Permeability. For general definition, see IEEE Std 100-1988 [2].

5.2.1 Initial Permeability. Under stated conditions, the limiting value of permeability of the core at the origin of the curve of first magnetization.

$$\mu_i = \frac{1}{\mu_o} \frac{\text{Lim}}{H \to 0} \frac{B}{H}.$$

When B and H are in CGS units, $\mu_o = 1$; μ_i = relative initial permeability.

5.2.2 Amplitude Permeability. The value of permeability at a stated value of field strength (or induction), the field strength varying periodically with time and with no static magnetic field being present.

$$\mu_a = \frac{1}{\mu_o} \frac{B}{H}$$

μ_a = Relative amplitude permeability

5.2.3 Maximum Permeability. The maximum value of the amplitude permeability as a function of the held strength (or of the induction). The values of the maximum permeability can be different for static and cyclic excitation.

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5.2.4 Incremental Permeability.* The permeability with stated alternating magnetic field conditions in the presence of a stated static magnetic field. See 6.2.2.1.

$$\mu_\Delta = \frac{1}{\mu_o}\frac{\Delta B}{\Delta H}$$

where

μ_Δ = Relative amplitude permeability
ΔB = Corresponding total cyclic change in induction
ΔH = Total cycle variation of the magnetic field strength

5.2.5 Pulse Permeability. The value of amplitude permeability when the rate of change of induction (for example, the exciting voltage) is held substantially constant over a period of time during each cycle. The frequency, amplitude, duration of the exciting voltage, and the time interval for which the permeability is measured must be stated.

$$\mu_\pi = \frac{1}{\mu_o}\frac{\Delta B}{\Delta H}$$

where

μ_π = Pulse permeability, relative
ΔB = Change in induction during the stated time interval
ΔH = Associated change in magnetic field strength

5.2.5.1 When pulse permeability is to be related to a specific circuit condition, a second subscript may be used, for example, $\mu_{\pi a}$ would represent the relative amplitude permeability determined under pulsed excitation.

5.2.6 Complex Permeability. Under stated conditions, the complex quotient of vectors representing induction and field strength inside the core material. One of the vectors is made to vary sinusoidally and the other referenced to it.

Series representation:

$$\overline{\mu} = \mu_s' - j\mu_s'' = \frac{1}{\mu_o}\frac{\overline{B}}{\overline{H}}$$

Parallel representation:

$$\frac{1}{\mu} = \frac{1}{\mu_p'} - \frac{1}{j\mu_p''} = \mu_o\frac{H}{B}$$

5.2.7 Differential Permeability. The rate of change of the induction with respect to the magnetic field strength.

$$\mu_{dif} = \frac{1}{\mu_o}\frac{dB}{dH}$$

where

μ_{dif} = Relative differential permeability
dH = Infinitely small change in field strength
dB = Corresponding change induction

5.2.8 Impedance Permeability.* A sinusoidal ac permeability related to the total rms exciting current, including harmonics. See 6.9.1.

$$\mu_z = \frac{B_i}{H_z\mu_o}$$

where

$H_z = \sqrt{2}\,NI/l_e$ = Equivalent peak field strength, amperes/meters
B_i = Maximum intrinsic flux density, tesla
I = RMS exciting current, amperes
N = Exciting coil turns
l_e = Effective magnetic path length

5.2.9 Peak Permeability

$$\mu_{pk} = \frac{B_i}{H_{pk}\mu_o};\quad H_{pk} = \frac{N\hat{i}}{l_e}$$

5.3 Core Loss. The power absorbed by the core under stated conditions of applied time varying magnetic field, and dissipated as heat. Unit: Watt.

5.3.1 Specific Core Loss. The power absorbed by a unit mass (or a unit volume) of core material, under stated conditions of applied time varying magnetic field and dissipated as heat. Unit: watts/unit mass or watts/unit volume.

5.4 Apparent Core Loss. The product of the rms exciting current with the rms value of induced voltage across the test winding containing the

* Definitions marked with an asterisk (*) refer to parameters for which alternate definitions are in common usage and are used in other sections of this standard.

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core, under stated conditions of excitation. Unit: volt ampere.

5.4.1 Specific Apparent Core Loss. The apparent core loss per unit mass of the ferromagnetic material making up the core.

5.5 Equivalent Series Circuit Elements. Under stated conditions of excitation and coil configuration, values of a reactance and a resistance connected in series so that they give representation to the real permeability of the core (μ'_s) and to the total losses in the core (μ''_s).

$$L_s = \mu'_s L_o$$
$$R_s = \omega \mu''_s L_o$$
$$Z = R_s + j\omega_s \, j\omega\bar{\mu} L_o$$

where

L_s = Self-inductance of coil with a core of $\bar{\mu}$ permeability; series equivalent inductance
R_s = Equivalent series resistance of coil in ohms with a core of $\bar{\mu}$ permeability
ω = Angular frequency in radians/second

5.6 Equivalent Parallel Circuit Elements. Under stated conditions of excitation and coil configuration, the values of inductance and resistance connected parallel so that they give representation to the real permeability of the core (μ'_p) and the total losses in the core (μ''_p).

$$L_p = \mu'_p L_o$$
$$R_p = \omega \mu''_p L_o$$
$$\frac{1}{Z} = \frac{1}{j\omega L_p} + \frac{1}{R_p} = \frac{1}{j\omega\bar{\mu} L_o}$$

where

$\bar{\mu}$ = Complex relative permeability
μ'_p = Real component of $\bar{\mu}$, parallel representation
μ''_p = Imaginary component of $\bar{\mu}$, parallel representation
L_o = Self-inductance of coil with a core of unity relative permeability, but with the same flux distribution as with a ferromagnetic core
L_p = Parallel equivalent self-inductance of the coil with a core of $\bar{\mu}$ permeability
R_p = Parallel equivalent loss resistance of the core
ω = Angular frequency in radians/second

5.7 Loss Angle (Dissipation Factor). The angle by which the fundamental component of the magnetizing current lags the fundamental component of the exciting current in a coil with a ferromagnetic core. The tangent of this angle is defined as the ratio of the in-phase and quadrature components of the impedance of the coil.

$$\tan\delta_n = \frac{R_s}{\omega L_s} = \frac{\omega L_p}{R_p} = \frac{\mu''_s}{\mu'_s} = \frac{\mu'_p}{\mu''_p}$$

where δ_n is the loss angle. All other symbols are defined in 5.2.6, 5.5, and 5.6.

5.7.1 Relative Dissipation Factor. The relative dissipation factor is defined as:

$$\frac{\tan\delta_n}{\mu_i} = \frac{\mu''_s}{(\mu'_s)^2} = \frac{R_s}{\mu_i \omega L_s} = \frac{\omega L_p}{\mu_i R_p} = \frac{\omega L_o}{R_p}$$

5.7.2 Quality Factor, *Q*. See IEEE Std 100-1988 [2] for general definition.

For inductive devices, the quality factor is defined as the inverse of the tangent of the loss angle:

$$Q = 1(\tan\delta_n)$$

where Q is the quality factor and δ_n is the loss angle.

5.8 Legg's Equation Parameters. Three coefficients of Legg's equation that, when included in the respective terms of that equation, give representation to the Hysteresis Loss, Eddy Current Loss, and Residual Loss of the core under stated conditions of excitation, at low flux densities.

Legg's equation is as follows:

$$\frac{R_s}{\mu f L_s} = aB + ef + c$$

where

a = Hysteresis loss coefficient,[8] (tesla)$^{-1}$
e = Eddy current coefficient, seconds

[8]When CGS units are used, coefficient a has the units of (gauss)$^{-1}$.

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c = Residual loss coefficient, unitless
R_s = Series equivalent loss resistance, ohms
L_s = Series equivalent inductance
μ = Relative permeability of core
f = Frequency, hertz

5.9 Saturation Induction, B_s. The maximum intrinsic value of induction possible in a material.

NOTE: This term is often used for the maximum value of induction at a stated high value of field strength where further increase in intrinsic magnetization with increasing field strength is negligible.

SI Unit: tesla CGS Unit: gauss (1 T = 10^4 G).

5.9.1 Peak Induction, B_m. The magnetic induction corresponding to the peak applied magnetizing force specified in a test.

5.10 Residual Induction, B_r. The value of induction corresponding to zero magnetizing force in a ferromagnetic material that is symmetrically and cyclically magnetized with a specific maximum magnetic field strength.

5.10.1 Remanent Induction. The induction in the ferromagnetic core when the magnetizing force around the complete magnetic circuit is zero.

NOTE: If there are no air gaps or other discontinuities in the magnetic circuit, the remanent induction is equal to the residual induction, otherwise the remanent induction will be less than the residual induction.

5.10.2 Squareness Ratio.* The ratio of remanent induction to peak induction with the magnetic material in a symmetrical cyclically magnetized condition. See 6.2.4.9 and 6.5.2.4.6.

5.11 Coercive Field or Force, H_c. The magnetic field strength at which the magnetic induction is zero, when the core material is in a symmetrically and cyclically magnetized condition, with a specified maximum value of field strength (for example, loci of points on the hysteresis curve when B = 0). See 5.2.1 for units.

5.12 H_1 and H_2 Reset Field Strengths. Two parameters measured in the Constant Current Flux Reset Test. H_1 and H_2 are the static field strengths required to cause specified changes of induction ΔB_1 and ΔB_2, respectively, in the core, after the core has been magnetized to the saturation region by a specified half-wave sinusoidal field strength change.

5.12.1 ΔH. The change in reset field strength required to increase the change in induction from the specified value of B_1 to the specified value of B_2 in the Constant Current Flux Reset Test.

5.12.2 Reset Gain, G. Defined by

$$G = \frac{\Delta B_2 - \Delta B_1}{\Delta H}.$$

5.13 Temperature Coefficient

(1) Between two given temperatures: (mean coefficient). The relative variation of the quantity considered, divided by the difference in temperature producing it.
(2) At a given temperature: The limiting value of the mean coefficient when the difference in temperature is very small.

5.14 Temperature Factor of Permeability. Defined as

$$\frac{\Delta\mu}{\mu T} \cdot \frac{1}{\mu^2}$$

where

$\Delta\mu$ = Change in permeability corresponding to ΔT
ΔT = Change in temperature, degrees Celsius
μ = Relative permeability at a specified temperature

5.15 Curie Temperature or Curie Point, T_c. The critical temperature above which a ferromagnetic body is paramagnetic. Unit: degrees Celsius.

5.16 Disaccommodation. The relative variation with time of the initial permeability after complete demagnetization and during storage free of magnetic, mechanical, and thermal disturbances at stated temperature. It is normally expressed as a percentage of the value measured at a short time after demagnetization.

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$$D = \frac{\mu_1 - \mu_2}{\mu_1} \cdot 100$$

where

D = Disaccommodation in percent
μ_1 = Initial permeability at a given short interval after complete demagnetization
μ_2 = Initial permeability measured at a given long interval after the first measurement.

5.16.1 Disaccommodation Factor. The factor given by

$$\text{D.F.} = \frac{\mu_1 - \mu_2}{\log_{10} \frac{t_1}{t_2}} \cdot \frac{1}{\mu^2}$$

where μ_1 is the initial permeability measured t_1 seconds after complete demagnetization; and μ_2 is the initial permeability measured t_2 seconds after demagnetization.

NOTE: The permeability varies almost linearly with the logarithm of time.

5.17 Magnetic Aging. The change in the magnetic properties of a material resulting from metallurgical changes with time. This term applies whether the change results from continued normal or a specified accelerated aging condition.

5.18 Turns Factor. Under stated conditions, the number of turns that a coil of specified shape and dimensions placed on the core in a given position should have to obtain a given unit of self-inductance. When measured with a measuring coil of the specified shape and dimensions and placed in the same position, it is defined as

$$\alpha = \frac{N}{\sqrt{L}}$$

where

α = Turns factor
N = Number of turns of the measuring coil
L = Self-inductance (in henrys) of the measuring coil placed on the core

5.19 Induction Factor, A_L.* Under stated conditions, the self-inductance that a coil of specified shape and dimensions placed on the core in a given position should have, if it consisted of one turn. See 6.2.2.8.

$$A_L = \frac{L}{N^2}$$

where

A_L = Induction factor, henrys/turns^2
L = Self-inductance of the coil on the core, in henrys
N = Number of turns of the coil

5.20 Volt—Second-Area. The area under the induced voltage versus time curve when the core is tested under stated pulse conditions and with a specified winding configuration.

5.21 Hysteresis Constant, η_b. Under stated conditions and at low induction (in the Rayleigh region), the quotient of the hysteresis loss per unit permeability and the peak value of the flux density.

$$\eta_b = \frac{\tan \delta_\eta}{\mu_c \hat{B}}$$

where

η_b = Hysteresis material constant (in [tesla]$^{-1}$)
δ_η = The loss angle due to hysteresis only
μ_c = Relative effective permeability
$\hat{B}$ = Peak value of induction (in teslas) in the core during measurement

5.21.1 Hysteresis Core Constant η_i. Under stated conditions and at low induction (in the Rayleigh region), the quotient of the tangent of the loss angle due to hysteresis and the product of current and square root of inductance of the measuring coil.

$$\eta_i = \frac{\tan \delta_\eta}{\hat{i}\sqrt{L}}$$

where

η_i = Hysteresis core constant (A^{-1} $H^{-1/2}$)
$\tan \delta_\eta$ = Tangent of loss angle due to hysteresis only

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I = Peak value of the current, in amperes, passed through the measuring coil

L = Self-inductance of coil on core, in henrys

6. Test Methods

6.1 Permeability Measurements. The permeability of magnetic cores is determined by indirect means, by measuring other quantities that have a known relationship to permeability.

A common method is to measure the inductance of a coil wound on the core under test and to determine the permeability from it. Bridge methods to determine the incremental and initial permeabilities are examples of this approach.

The measurement of voltage induced across a coil on the subject core by a test current is used to determine the pulse permeability and the impedance permeability. The induced voltage is used also to display the differential permeability versus the magnetic field strength in the Sine Current Test Method.

The following sections describe the various methods used for determining permeability. It must be noted that since the conditions to which the cores are subjected vary with each method, the resulting data are meaningful only in the context of these specific conditions.

6.2 Tests for Evaluating Cores With Pulsed Excitation

6.2.1 Reference Pulse Shape. For the testing of magnetic cores with pulsed excitation, it is often desirable to specify the shape or other properties of the pulse with a high degree of precision, as in the tests for computer-type cores of 6.2.4. This section defines many of the pulse parameters useful for the testing of transformer, computer, and other cores with pulsed excitation. The shape of the reference pulse, which may be either a current or voltage pulse, is given by the current- or voltage-time relationship shown in Fig 1 in accordance with the following definitions:

NOTE: (A) designates a general amplitude quantity that may be current (I) or voltage (V).

(1) *Pulse amplitude* (A_M). That quantity determined by the intersection of a line passing through the points on the leading edge where the instantaneous value reaches 10% and 90% of (A_M) and a straight line that is the best least squares fit to the pulse in the pulse-top region. (Usually this is fitted visually rather than numerically.) For pulses deviating greatly from the ideal trapezoidal pulse shape, a number of successive approximations may be necessary to determine A_M.

(2) *Rise time* (first transition duration) (T_r). The time interval of the leading edge between the instants at which the instantaneous value first reaches the specified lower and upper limits of 10% and 90% of A_M. Limits other than 10% and 90% may be specified in special cases.

(3) *Pulse duration* (90%) (T_d). The time interval between the instants at which the instantaneous value reaches 90% of A_M on the leading edge and 90% of A_T on the trailing edge.

NOTES: (1) Often the input pulse tilt (droop) is only a few percent, and in those cases pulse duration may be considered as the time interval between the first and last instants at which the instantaneous value reaches 90% of A_M.
(2) Pulse duration may be specified at a value other than 90% of A_M and A_T in special cases.

(4) *Fall time* (last transition duration) (T_f). The time interval of the pulse trailing edge between the instants at which the instantaneous value first reaches specified upper and lower limits of 90% and 10% of A_T.

(5) *Trailing edge* (last transition) *amplitude* (A_T). That quantity determined by the intersection of a line passing through the points on the trailing edge where the instantaneous value reaches 90% and 10% of A_T and the straight line segment fitted to the top of the pulse in determining A_M.

(6) *Tilt* (droop) (A_D). The difference between A_M and A_T. It is expressed in amplitude units or in percent of A_M.

(7) *Overshoot* (first transition overshoot) (A_{OS}). The amount by which the first maximum occurring in the pulse top region exceeds the straight line segment fitted to the top of the pulse in determining A_M. It is expressed in amplitude units or in percent of A_M.

(8) *Backswing* (last transition overshoot) (A_{BS}). The maximum amount by which the instantaneous pulse value is below the zero axis in the region following the fall time. It is expressed in amplitude units or in percent of A_M.

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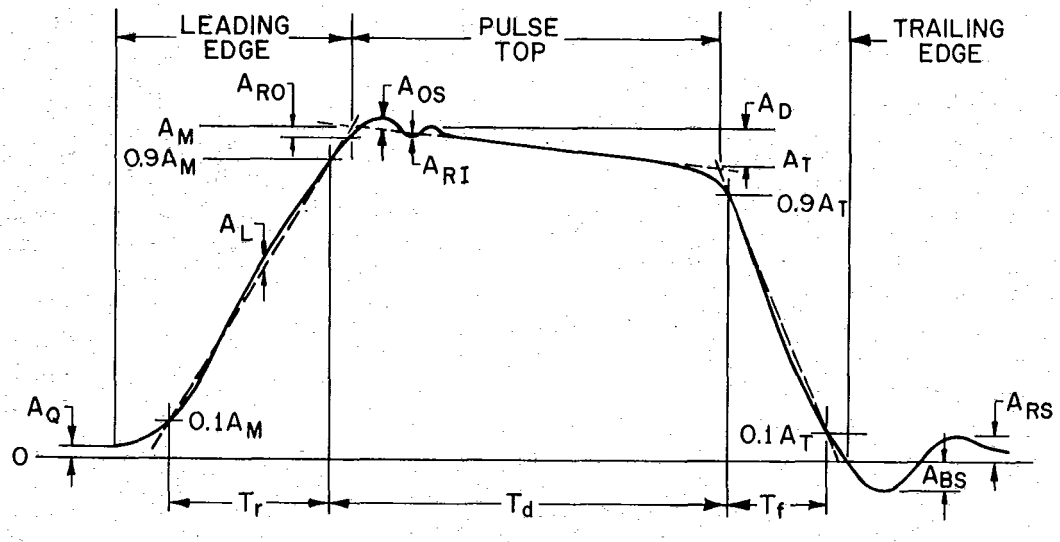


Fig 1
Reference Pulse Shape

(9) *Return swing* (last transition ringing) (A_{RS}). The maximum amount by which the instantaneous pulse value is above the zero axis in the region following the back swing. It is expressed in amplitude units or in percent of A_M.

(10) *Rolloff* (rounding after first transition) (A_{RO}). The amount by which the instantaneous pulse value is less than A_M at the point in time of the intersection of straight line segments used to determine A_M. It is expressed in amplitude units or in percent of A_M.

(11) *Ringing* (first transition ringing) (A_{RI}). The maximum amount by which the instantaneous pulse value deviates from the straight line segment fitted to the top of the pulse in determining A_M in the pulse top region following rolloff or overshoot or both. It is expressed in amplitude units or in percent of A_M.

(12) *Leading edge* (first transition) linearity (A_L). The maximum amount by which the instantaneous pulse value deviates during the rise-time interval from a straight line intersecting the 10% and 90% A_M amplitude points used in determining rise time. It is expressed in amplitude units or in percent of 0.8 A_M.

(13) *Quiescent value* (base magnitude) (A_q). The maximum value existing between pulses.

(14) *Leading edge* (first transition). That portion of the pulse occurring between the time the instantaneous value first becomes greater than A_q to the time of the intersection of straight line segments used to determine A_M.

(15) *Pulse top.* That portion of the pulse occurring between the time of intersection of straight line segments used to determine A_M and A_T.

(16) *Trailing edge* (last transition). That portion of the pulse occurring between the time of intersection of straight line segments used to determine A_T and the time at which the instantaneous value reduces to zero.

NOTE: Additional definitions applicable to computer-type cores are found in 6.2.4.

6.2.2 Pulse Magnetization Characteristics

6.2.2.1 General Considerations. The nonlinear variation of magnetizing current versus time for any given core can be described by graphical means. The objective of this test method is to obtain a family of normalized curves, as shown in Fig 2, from which useful core parameters in the design of pulse transformers can be readily derived.

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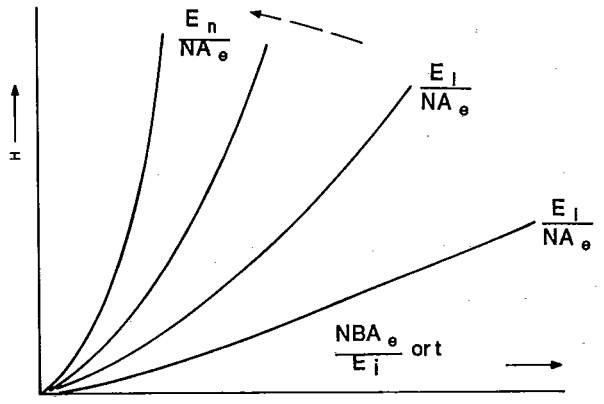


Fig 2
Pulse Magnetization Characteristic

Symbols in Fig 2 denote the following:

H = Magnetizing force, in amperes per meter
t = Time, in seconds, from application of excitation
E_i = Constant excitation voltage, in volts
N = Number of turns on excitation winding
B = Instantaneous flux density in core, in webers per square meter (tesla)
A_e = Effective core cross-sectional area, in square meters
T = Temperature, in degrees Celsius

The excitation voltages must be at equal increments and, as indicated on Fig 2, will be related as

$$E_1 < E_2 < \cdots E_i < \cdots E_n.$$

Assuming that all flux links all turns, Faraday's law states that

$$e = N\frac{d\Phi}{dt} \qquad \text{(Eq 1)}$$

where e is the instantaneous induced voltage in N turns; Φ is the instantaneous flux in core in webers; and t is the time in seconds.

If the effective cross-sectional area of the portion of the core linked by the turns is A_e, and if the flux density is B, Eq 1 becomes

$$e = N A_e \frac{dB}{dt}$$

$$dB = \frac{edt}{N A_e}. \qquad \text{(Eq 2)}$$

The incremental permeability, μ_Δ, is defined (see 5.2.4) as

$$\mu_\Delta = \frac{dB}{dH}$$

so that

$$dB = \mu_\Delta \cdot dH. \qquad \text{(Eq 3)}$$

Substituting Eq 3 in Eq 2:

$$\mu_\Delta\, dH = \frac{edt}{N A_e}$$

$$dH = \frac{1}{\mu_\Delta} \cdot \frac{edt}{N A_e}. \qquad \text{(Eq 4)}$$

For the practical purposes of this test, consider a constant applied voltage, E_i, and rewrite Eq 4 with $e = E_i$.

$$dH = \frac{1}{\mu_\Delta} \cdot \frac{E_i\, dt}{N A_e}. \qquad \text{(Eq 5)}$$

Equation 5 provides the relation for the curves in Fig 2. Because the incremental permeability is not a constant, this differential equation cannot be solved to yield H as a function of time. For this reason, the family of curves must be generated experimentally.

6.2.2.2 Unipolar Test Circuits. A typical test circuit, which can be adjusted as described below, to give a tilt not exceeding 1% during the necessary time interval is shown in Fig 3 [5]. A current transformer or noninductive shunt will yield a signal proportional to H, which is then displayed as a function of time. This probe must of itself introduce no appreciable tilt during the display time, and its pulse recovery time must be negligible compared to the test pulse repetition rate.

Suitable element values in Fig 3 are as follows:

Q1 = 2N3253; R1 = 3300 Ω; R2 = 47 Ω;
C1 = 0.05 μF.

R1 and C1 are used only to filter the negative dc voltage from the pulse generator. The transistor must have a high current rating and a low capacitance. Suitable diodes, D2 and D3, which must have fast switching characteris-

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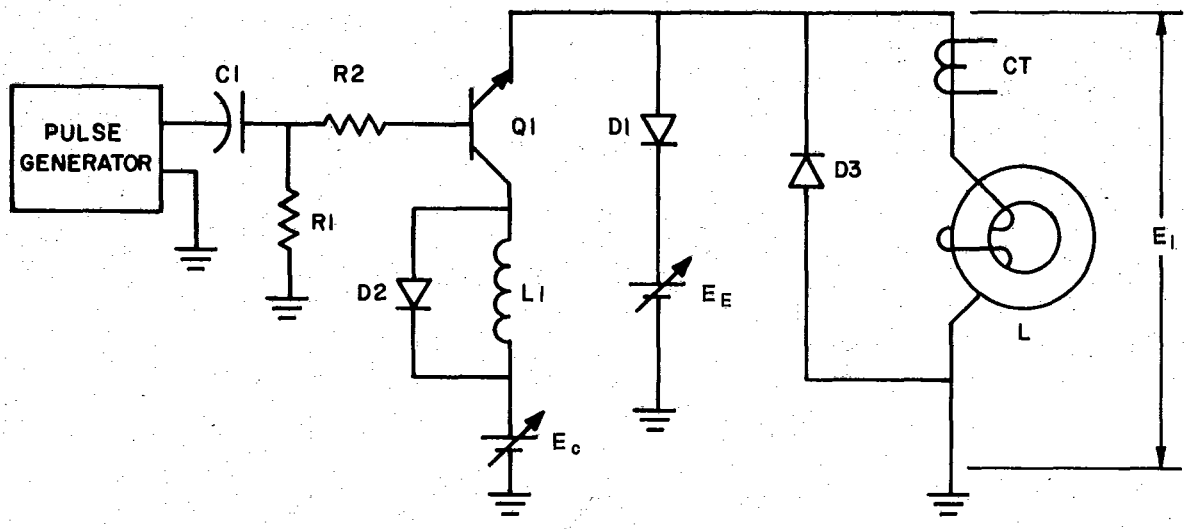


Fig 3
Test Circuit A

tics, are used across each inductor in order to clip the possibly excessive voltage kickback as each pulse is terminated.

The function of the current sink, D1 (which must have excellent forward-bias characteristics) and E_E, is to maintain the constant voltage, E_i, across the test sample, L, throughout the measurement interval. The voltage, E_i, is equal to the sum of E_E and the drop across the diode, D1. The inductor, L1, which should be similar to the test core both in material and turns, serves to prolong the conduction interval of the diode, D1, and thus to make the droop of E_i be negligible. The use of L1 is to be preferred to a current-limiting resistor because it effectively provides more current from the supply E_c, as the test sample demands it, and thus does prolong the conduction of the current sink with its constant voltage characteristic.

E_E is initially adjusted to the desired value of E_i less the value of the forward voltage drop of D1. E_c is adjusted to minimize the droop of E_i.

The circuit of Fig 4 is more convenient for the usual laboratory or production testing (IEEE Std 390-1987 [3]). It is a transistor switch that connects the constant voltage source, E_{ce}, across the test core winding. The tilt associated with this circuit is of the order of 1%. Isolation of the generator from the varying input impedance of the transistor is provided by R2. C1 decreases the transistor turn-on time. The resistor R4 reduces the backswing of the magnetizing current to a negligible level and may be replaced by a diode as D3 in Fig 3. Core-winding voltage is determined by $E_i = E_{cc} - E_{ce}$, the saturation voltage of the transistor being nearly zero. The resistor R3 merely reduces ringing due to the capacitance of the voltage monitoring cable.

Suitable element values in Fig 4 are R1 = 51 Ω; R2 = 300 Ω; R3 = 47 Ω; R4 = 100 Ω (all resistors are 1/2 W, noninductive); C1 = 500 pF; C2 = 50 μF, 25 V; Q1 = 2N2905A.

The pulse repetition rate must be slow enough to assure no distortion of the characteristics due to recovery phenomena and also to avoid internal core heating.

6.2.2.3 Major and Minor Loop Unipolar Characteristics. The unipolar pulse magnetization characteristics will differ depending on whether the core remains on a minor hysteresis loop or whether it is driven on a major hysteresis loop (saturation). Figures 5 and 6 show the differences to be expected.

When a minor loop characteristic, curve *a*, is obtained, the maximum flux density to which the core is driven should be stated with the data.

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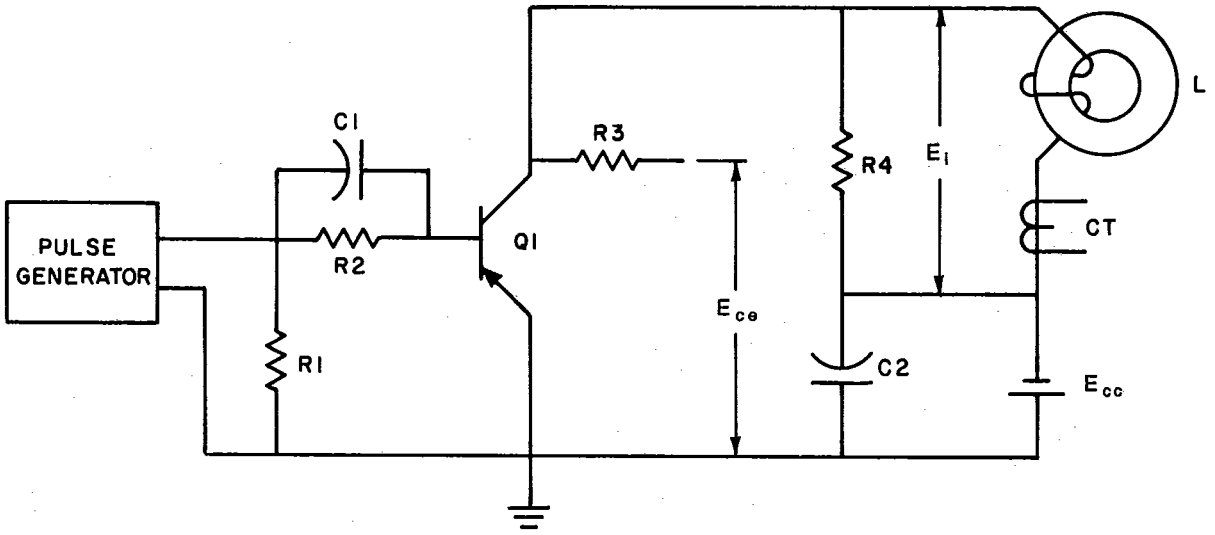


Fig 4
Test Circuit B

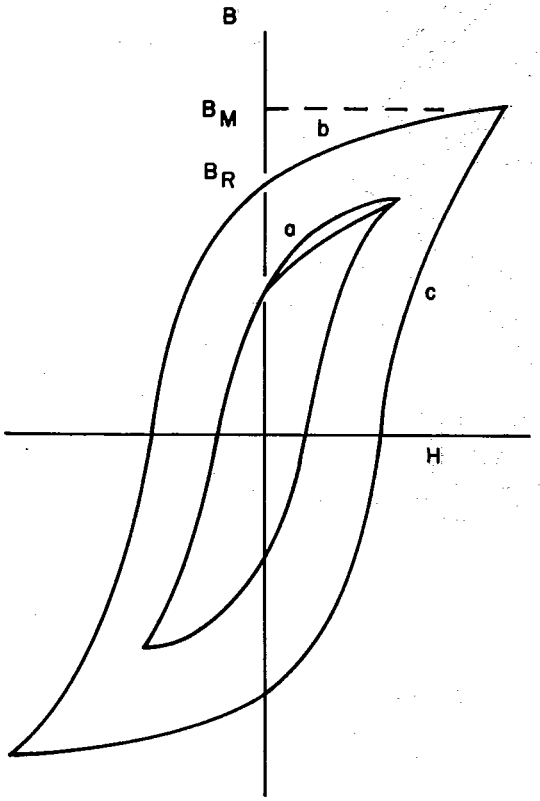


Fig 5
Pulse Magnetization Characteristics on Major and Minor Loops

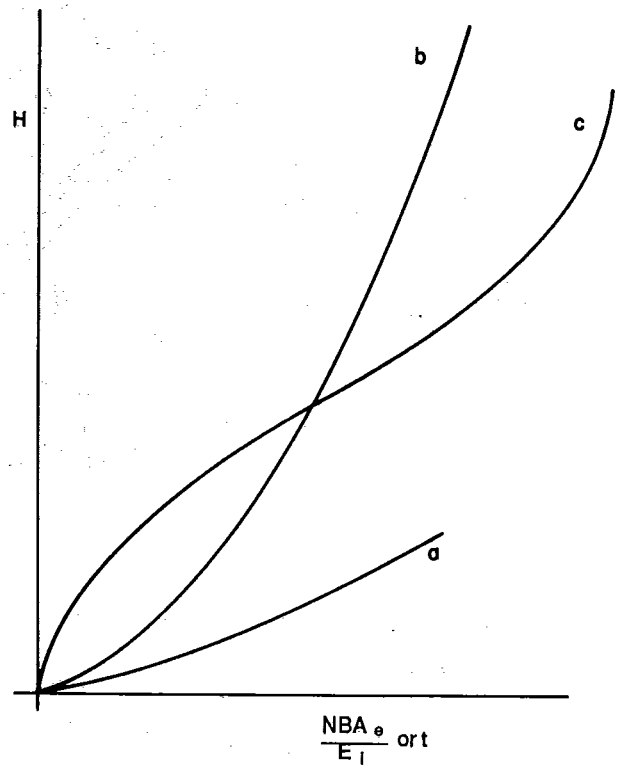


Fig 6
Pulse Magnetization Characteristics With Reset

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When a major loop characteristic, curve *b*, is obtained, the minimum flux density to which the core must be driven to ensure its entering saturation should be stated with the data.

NOTE: The pulse magnetization characteristic should be observed at 10 min and 100 min after magnetic preconditioning in order to observe any effects due to disaccommodation.

6.2.2.4 Bipolar Excitation (Reset). Duplicating the circuit of Fig 4 to excite a reset winding will provide pulse magnetization characteristics that reset as indicated in Figs 5 and 6, curve *c*. When working on a major loop, the reset circuit need not be as elaborate as long as all of the flux is reset by that pulse.

6.2.2.5 Test With Bias. In some circuit applications, a dc bias current is present. Curves for this condition may be generated with the circuit of Fig 4 and the addition of a suitable bias winding. The bias supply must have a high impedance so that it does not constitute a load on the core.

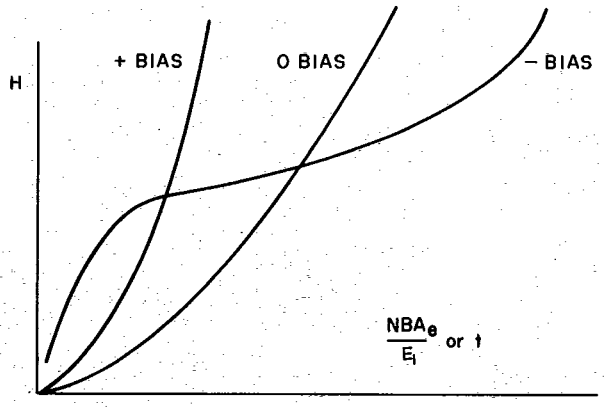
Figure 7 shows the nature of these curves for one member of the family.

It can be seen that aiding (positive) bias decreases the available flux, whereas opposing (negative) bias increases the available flux.

6.2.2.6 Measurement Conditions

(1) *Core Configuration.* The test sample will be any core having pulse transformer applications. In all cases, the dimensions of the sample will be reported because geometry as well as material determines the pulse magnetization characteristic.

Fig 7
Pulse Magnetization Characteristics With and Without Bias



(2) *Environment.* Because these measurements are not time-consuming and have an accuracy of graphical order, excessive care in maintaining constant temperature is not necessary. However, the temperature during the tests will be reported and will not vary by more than ± 2 °C throughout the measurements.

(3) *Time Interval.* If *e* is set equal to E_i in Eq 2, it is seen that, for a particular core at a specified voltage level, the time interval (pulse duration) to be used is limited by the magnetization characteristics of the material. Because the flux density is directly proportional to time, the magnetizing current would have to increase to prohibitive values as the material enters saturation.

For uniformity in reporting data, the time interval at each voltage will extend to a point where the incremental permeability has decreased to one-tenth the value of the initial permeability or to a flux density corresponding to a magnetizing force equal, at least, to ten times the coercive force of the material if the latter leads to a longer interval. The maximum value of flux density will be reported in all cases.

In certain cases, it may be desirable to expand the time scale toward zero time, measurement accuracy permitting.

(4) *Voltage Increments.* The curves will be generated for uniform increments of E_i/NA_e over a span suitable for the material such as $2 \cdot 10^4$, $4 \cdot 10^4$, $6 \cdot 10^4$, ..., $16 \cdot 10^4$, $18 \cdot 10^4$, $20 \cdot 10^4$.

(5) *Turns.* The number of turns used in these tests is very important for obtaining accurate characteristics. For cores having an initial permeability of 400 or less, 25 turns are recommended. For high permeability cores, 5 turns are recommended. The measurements should be repeated with two significantly different numbers of turns, one higher and one lower, in order to verify the results. The turns must be uniformly distributed around the test sample.

(6) *Temperature Dependence.* The pulse magnetization characteristics will normally be reported as in Fig 2 at temperatures of –25°, 0°, 25°, 50°, and 75 °C. Other temperatures, higher and lower, may be used if the core material has useful properties at these temperatures; however, equal temperature increments should be observed.

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6.2.2.7 Suggested Induction Levels and Pulsewidth for Pulse Testing Unbiased Gapped Magnetic Cores

Operating Flux Density		Pulse Duration	Material and Gage	
Gauss	Tesla	(μs)		
2500	0.25	0.25	80%Ni—20%Fe	1 mil
2500	0.25	2.0	80%Ni—20%Fe	2 mil
2500	0.25	5.0	80%Ni—20%Fe	4 mil
10 000	1.00	0.25	50 Ni—50% Fe	1 mil
10 000	1.00	2.0	50% Ni—50% Fe	2 mil
10 000	1.0	5.0	50% Ni—50% Fe	4 mil
2500	0.25	0.25	3% Si—Fe	1 mil
10 000	1.00	2.0	and	2 mil
10 000	1.0	6.0	Cobalt—Fe	4 mil

6.2.2.8 Derived Core Properties. The pulse magnetization characteristics for a particular core may be more conveniently shown as in Fig 8 in terms of Ni_m, the magnetomotive force, and time with volts per turn as the parameter.

Incremental Inductance Factor (Incremental A_L)

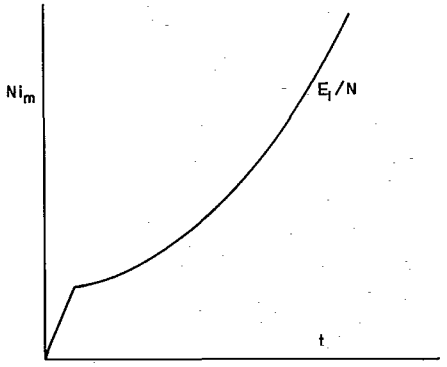
$$\text{Incremental } A_L = \frac{E_i / N}{d(Ni_m)/dt} \text{ henry / turns}^2$$

where $d(Ni_m)/dt$ is the slope of the curve, E_i/N, at the particular time of interest.

Average Inductance Factor (Average A_L) (cf 5.19)

$$\text{Average } A_L = \frac{E_i / N}{(Ni_m)/t} \text{ henry / turns}^2$$

Fig 8
Core Pulse Magnetization Characteristic



where $(Ni_m)/t$ is at the slope of the straight line joining the two points in question on the curve, E_i/N. It is common practice to use the origin ($t = 0$) as one point.

Core Linearity. Core linearity between any two specified times may be expressed as

$$\text{Linearity} = 1 - \frac{L_{max} - L_{min}}{1/2(L_{max} + L_{min})}$$

where L_{max} is the maximum incremental inductance during the time span and L_{min} is the minimum incremental inductance during the time span, or

$$\text{Linearity} = 1 - \frac{A_{L(max)} - A_{L(min)}}{1/2\left[A_{L(max)} + A_{L(min)}\right]}$$

where $A_{L(max)}$ is the maximum incremental A_L during the time span and $A_{L(min)}$ is the minimum incremental A_L during the time span.

6.2.2.9 Application of Data. For the design of pulse transformers, curves of output voltage or input current as a function of time may be predicted from the pulse magnetization characteristics of the core.

For this purpose, the normalized voltages, E_i/NA_e, are converted to actual values by multiplying the normalized values by the number of turns, N, and the effective area, A_e, of the core under consideration. Of course, if curves such as that of Fig 8 are used, the transformation is not necessary.

The H axis is converted to magnetizing current for the particular core by the following procedure:

Since

$$H = \frac{Ni_m}{l_e}$$

where I_m is the magnetizing current, in amperes; and l_e is the effective magnetic path length of core, in meters; it follows that

$$i_m = \frac{Hl_e}{N}.$$

In practice, the curves for a particular core size or geometry differing from the sample type used for developing the specification may deviate from the predicted curves.

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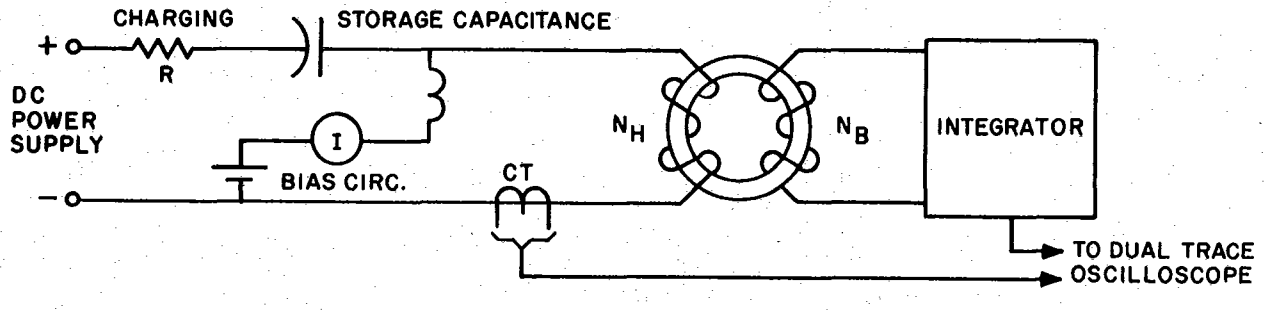


Fig 9
Pulse Permeability Test Circuit

6.2.3 Pulse Permeability. Pulse core permeability tests can be performed easily at any pulse duration and flux density by using the circuit of Fig 9. The equipment of obtaining the pulse source shown here can be replaced by many other types of circuits convenient to a specific laboratory.

The system may be run with a single pulse or at pulse rates as low as 10 pps for convenience in viewing, yet minimizing average power requirements. The value of the storage capacitance is chosen, along with N_H, so as to result in a resonant frequency low enough that the output waveform of the integrator is a linear ramp over the desired pulse duration. The power-supply voltage is raised until the integrator-output voltage is at the predetermined level E_B, measured at the desired pulse duration. This procedure applies the desired flux density B. Next, a pulse-current transformer or noninductive shunt is used to measure the exciting current at the pulse duration. Pulse-current transformer tilt must be taken into account if this type of current pickup is used. Pulse permeability can be obtained from the following equations (SI units are assumed):

Integrator Output (E_B):

$$B = \frac{E_B T}{N_B A};\ V_B = \frac{BN_B A}{T};\ T = RC\left[1 + \tau/(2RC)\right]$$

$$E_B = \frac{BN_B A}{RC\left[1 + \tau/(2RC)\right]}$$

Pulse-Current Transducer Output (E_{pct}):

$$H = \frac{N_H I}{l_e};\ B = \frac{\mu N_H I}{l_e};\ I = \frac{Bl_e}{\mu N_H}$$

$$E_{pct} = K_p I = \frac{Bl_e}{\frac{\mu}{\mu_o}\mu_o N_H}$$

or the pulse amplitude permeability:

$$\mu_{\pi a} = \frac{\mu}{\mu_o} = \frac{Bl_e K_p}{E_{pct}\,\mu_o N_H}$$

where

l_e = Mean effective magnetic path, in meters
E_{pct} = Pulse-current transducer voltage
B = Flux density, in webers/meter^2 (tesla)
K_p = Ratio of voltage output to current input for current transducer
N_H = Turns on core for excitation (H)
N_B = Turns on core for sensing flux change (B)
A = Effective core area, in square meters
RC = Time constant of integrator
I = Pulse duration

6.2.4 Tests for Computer-Type Cores Used in Switching and Memory Applications

NOTE: The tests described in this section are recommended for the specification and evaluation of small magnetic cores, usually of toroidal shape, which are used for switching, memory, counting, or similar functions in digital control circuits, computers, or similar applications. Such cores are usually pressed or molded ferrites or ferromagnetic tape-wound cores. The latter type has conventionally been referred to as a bobbin core, and this nomenclature will be used throughout this discussion for the computer-type core of any construction or configuration.

6.2.4.1 Definitions Applicable to Computer-Type Cores

6.2.4.1.1 "Write" input pulse (A_w) is an input current or source voltage pulse applied to a winding such that the resultant core magnetomotive force has an arbitrarily defined positive direction and an amplitude sufficient to

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drive the core flux from negative remanence[9] into the positive saturation region.

6.2.4.1.2 "Read" input pulse (A_r) is an input current or source voltage pulse applied to a winding such that the resultant core magnetomotive force has a negative polarity (with respect to the positive polarity defined for a write pulse) and an amplitude sufficient to drive the core flux from positive remanence[10] into the negative saturation region.

6.2.4.1.3 "Partial-write" input pulse (A_{pw}) is an input current or source voltage pulse applied to a winding such that the resultant core magnetomotive force has a positive polarity (with respect to the positive polarity defined for a write pulse) and an amplitude insufficient to drive the core flux from negative remanence[11] into the positive saturation region.

6.2.4.1.4 "Partial-read" input pulse (A_{pw}) is an input current or source voltage pulse applied to a winding such that the resultant core magnetomotive force has a negative polarity (with respect to the positive polarity defined for a write pulse) and an amplitude insufficient to drive the core flux from positive remanence[12] into the negative saturation region.

6.2.4.1.5 "Read response" is the response to application of a read input pulse. It is the voltage pulse developed across a test winding.

6.2.4.1.6 "Partial-read response" is the response of the transformer to application of a partial-read input pulse. It is the voltage pulse developed across a test winding.

6.2.4.1.7 "Write response" is the response to application of a write input pulse. It is the voltage pulse developed across a test winding.

6.2.4.1.8 "Partial-write response" is the response to application of a partial-write input pulse. It is the voltage pulse developed across a test winding.

6.2.4.1.9 Read response characteristics are the characteristics of the read response described by voltage time relationships and defined with the aid of Fig 10 in accordance with the following definitions:

(1) Read "one" response pulse is the read response during application of a repetitive pulse program of alternate read and write input pulses.

(a) Read "one" response pulse peak amplitude (E_1) is the peak value of the read "one" response pulse.

(b) Read "one" response switch time (t'_s) is the time interval between the first and last instants at which the instantaneous read "one" response value reaches 10% of E_1.

(c) Read "one" response peak time (t'_p) is the time interval between the instants at which the instantaneous read "one" response value reaches 10% E_1 (on the leading edge) and E_1.

(d) Read "one" response delay time (t_{DL}) is the time interval measured from the instant at which the instantaneous current input pulse value reaches 10% of I_M on the current input leading edge to the instant at which the instantaneous read "one" response pulse value reaches 10% of E_1 on the response leading edge.

(e) Read "one" response switch time (input referenced) (t_s) in the time interval measured from the instant at which the instantaneous current input pulse value reaches 10% of I_m on the current input leading edge to the instant at which the instantaneous read "one" response pulse value reaches 10% of E_1, on the response trailing edge

$$t_s = t_{DL} + t'_s.$$

(f) Read "one" response peak time (input referenced) (t_p) is the time interval measured from the instant at which the instantaneous current input pulse value reaches 10% of I_M on the current input leading edge to the instant at which the instantaneous read "one" response pulse value reaches $E_1 \cdot t_p = t_{DL} + t'_p$.

(g) The following pulse shape characteristics of the read "one" response pulse are defined similarly to the corresponding characteristics of the input pulse (6.2), with the exception of using 10% amplitude when defining t_d:

(i) Read "one" response pulse amplitude (E_{1M}),

(ii) Read "one" response rise time (t_r),

(iii) Read "one" response pulse duration (10%) (t_d),

[9]In the biased core case, positive or negative remanence should be changed to bias induction.

[10]See footnote 9.

[11]See footnote 9.

[12]See footnote 9.

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A. "One" response

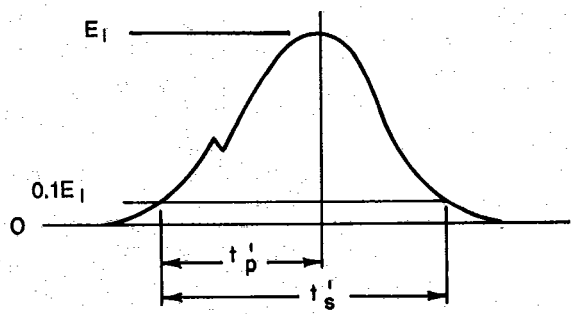


Fig 10(a)
For High NI_e Input Pulse

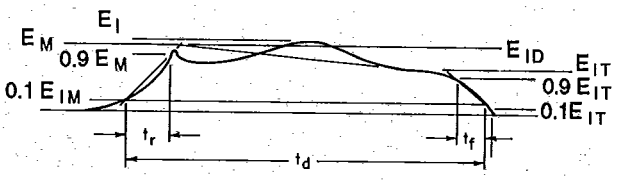


Fig 10(b)
For Low NI_e Input Pulse

B. "Zero" responses

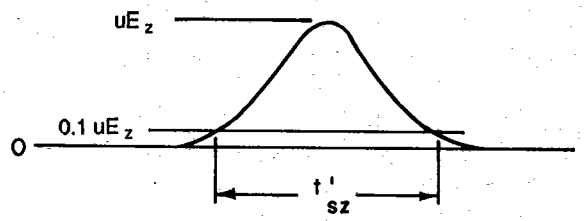


Fig 10(c)
"Undisturbed Zero" Response

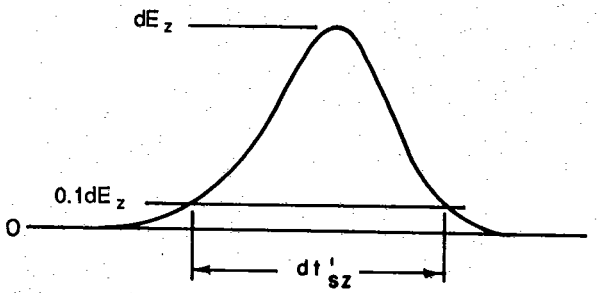


Fig 10(d)
"Disturbed Zero" Response

C. Integrated voltage

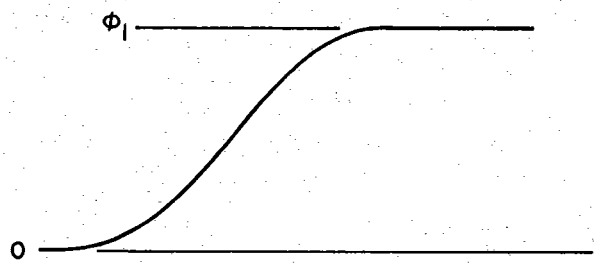


Fig 10(e)
"One" Integrated Voltage

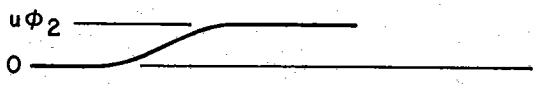


Fig 10(f)
"Undisturbed Zero" Integrated Voltage

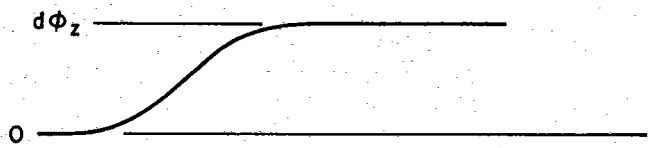


Fig 10g
"Disturbed Zero" Integrated Voltage

Fig 10
Read Response Pulses

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(iv) Read "one" response fall time (t_f),
(v) Read "one" response trailing edge amplitude (E_{1T}),
(vi) Read "one" response overshoot (E_{1OS})
(vii) Read "one" response tilt (droop) (E_{1D}).

(2) Read "undisturbed zero" response pulse is the read response observed when the second of two consecutive "read" input pulses is applied during the repetitive pulse program consisting of several sets of alternate write and read pulses followed by a single read pulse.

(a) Read "undisturbed zero" response pulse peak amplitude (uE_z) is the peak value of the undisturbed zero response pulse.

(b) Read "undisturbed zero" response pulse switch time (t'_{sz}) is the time interval between the first and last instants at which the instantaneous "undisturbed zero" response value reaches 10% of uE_Z.

(3) Read "disturbed zero" response pulse is the read response observed when the read input pulse is applied following eight successive "partial-write" pulses during a repetitive pulse program consisting of several sets of write and read pulses, followed by eight consecutive "partial-write" pulses and a single read pulse.

(a) Read "disturbed zero" response pulse peak amplitude (dE_z) is the peak value of the disturbed zero response pulse.

(b) Read "disturbed zero" response pulse switch time (dt'_{sz}) is the time interval between the first and last instants at which the instantaneous "disturbed zero" response value reaches 10% of dE_z.

(4) Read integrated-voltage pulse is an integrated read response voltage pulse. It is a measure of the flux associated with a read response voltage pulse.

(a) Read "one" integrated-voltage pulse amplitude (Φ_1) is the peak value of the integrated read "one" voltage pulse.

(b) Read "undisturbed-zero" integrated voltage pulse amplitude ($u\Phi_z$) is the peak value of the integrated read "undisturbed zero" voltage pulse.

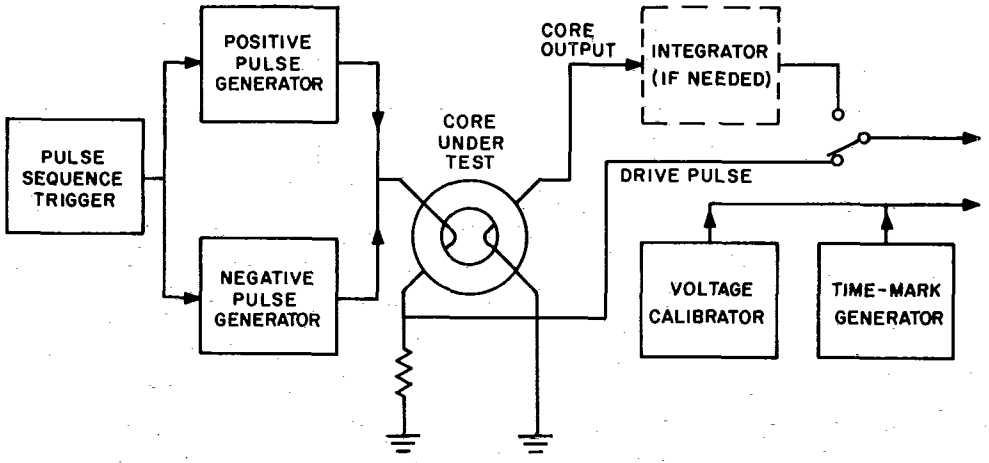
(c) Read "disturbed zero" integrated-voltage pulse amplitude ($d\Phi_z$) is the peak value of the integrated read "disturbed zero" voltage pulse.

6.2.4.2 Partial-Write Characteristics. The characteristics of the partial-write response are defined similarly to the read-response characteristics of 6.2.4.1.9.

Partial-write "one" integrated voltage pulse amplitude (Φ_{p1}) is the peak value of the integrated partial write "one" voltage pulse during application of a repetitive pulse program of alternate write and read input pulses followed by a partial-write input pulse.

6.2.4.3 Typical Test Circuit. A typical test circuit is shown in Fig 11.

Fig 11
Typical Test Circuit



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6.2.4.4 Test Conditions

(1) The following conditions should be specified for the characteristic tests:

(a) Input pulses

(i) Pulse repetition frequency (or pulse program time interval)

(ii) Write, read, disturb-write, and disturb-read input pulses should each have the following specified:

(1) Type of pulse: current pulse, or source voltage pulse applied through associated impedance

(2) Pulse parameters: amplitude, rise time, fall time, duration, tilt (droop), overshoot, rolloff, ringing, leading-edge linearity, and quiescent level

(3) Pulse source impedance

(4) Designation of test winding to which pulse is applied

(b) Load—Open-Circuit

(c) Response

(i) Designation of test winding(s) at which response is to be measured

(ii) Voltage integrator circuit configuration (when applicable)

(2) The characteristic test response should be measured using a wide-band direct-coupled oscilloscope with a high-impedance probe and an oscilloscope pulse calibrator.

6.2.4.5 Read Response. As applicable, one or more of the following read response pulse characteristics should be measured:

(1) Read "one" response pulse peak amplitude (E_1, I_1)

(2) Read "one" switch time (t'_s)

(3) Read "one" switch time (input referenced) (t_s)

(4) Read "undisturbed zero" response pulse peak amplitude (uE_z, uI_z)

(5) Read "undisturbed zero" switch time (t'_{sz})

(6) Read "disturbed zero" response pulse peak amplitude (dE_z, dI_z)

(7) Read "disturbed zero" switch time (dt'_{sz})

(8) Read "one" delay time (t_{DL})

(9) Read "one" peak time (t'_p)

(10) Read "one" peak time (input referenced) (t_p)

(11) Read "one" response pulse amplitude (V_{1M}, I_{1M})

(12) Read "one" response pulse duration (10%) (t_d)

(13) Read "one" response rise time (t_r)

(14) Read "one" response droop (E_{1D}, I_{1D})

(15) Read "one" response fall time (t_f)

(16) Read "one" response overshoot (E_{1OS}, I_{1OS})

(17) Read "one" integrated-voltage peak pulse amplitude (Φ_1)

(18) Read "undisturbed zero" integrated-voltage peak pulse amplitude ($u\Phi_z$)

(19) Read "disturbed zero" integrated-voltage peak pulse amplitude ($d\Phi_z$).

6.2.4.6 Partial-Write Response. Partial-write "one" integrated-voltage peak pulse amplitude (Φ_{p1}).

NOTE: Normally, at least the tests of 6.2.4.5 (1), (4), and (2) or (3) shall be performed.

If integrated-voltage measurements are required, normally the tests of 6.2.4.5 (17) and (18) and 6.2.4.6 shall be performed.

6.2.4.7 Test Equipment. Some of the basic equipment employed in bobbin core measurement is specialized to the extent that consideration must be given to its construction and design. If certain minimum standards are maintained, reproducible quantitative measurements can be realized. It is the purpose of this standard to outline the general equipment requirements that satisfy these minimum conditions.

(1) *Constant-Current Driver.* Any constant-current source possesses an internal impedance that is large compared to the load impedance. In the case of bobbin core measurements, the load consists of a core with a winding of one or more turns in series with a resistance only large enough to permit observation of the drive current waveform. The internal impedance of the read-current source should be such that the instantaneous deviation of the read-pulse waveform measured between the end of the pulse rise time and the start of the pulse fall time shall not change appreciably whether or not the core is included as a part of the load. In some types of measurements, the pulse rise time of the read-current source is important. For example, the peak-zero voltage is a function of the rate of change of current with respect to time. In other types of measurements, such as those of peak-one voltage and open circuit switching time, problems associated with the read-current rise-time characteristic can be minimized by specifying that the rise time of the read-current pulses should be equal to, or smaller than, one tenth of

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the shortest switching time to be measured. When the rise time is greater than one tenth of the open-circuit switching time, because of limitations of available test equipment, the exact form of the current rise as well as its magnitude must be specified. The pulse fall time of the current source should be controlled, particularly when the precise duration of the current pulse is important. Between current pulses, the maximum permissible residual current should be not more than 1% of the smallest pulse amplitude used.

When the above characteristics of the write current driver affect the response of the core to the read-current pulse, then these characteristics of the write-current driver must be specified.

NOTES: (1) In acceptable practice, the presence or the absence of the core should not change the instantaneous current more than 2% during the entire pulse period.
(2) In acceptable practice, this residual current should be not more than 1% of the smallest pulse amplitude used.

(1) *Core Test Jig (Core Holder).* The core test jig is a device for conveniently connecting one or more turns of wire through the bobbin core under test so that the driving current exerts a specified magnetomotive force on the core, and so that the response of the core may be observed. The windings are arranged to permit current pulses to switch and reset the core. The pickup or output windings should be arranged such that only flux changes occurring in the bobbin core are observed. In any practical arrangement of test-jig windings, there will be coupling between the drive winding and the output winding when there is no core in the test jig. The output signal resulting from this coupling is usually called air-flux signal. The air-flux signal can cause large errors in peak-zero voltage and should be canceled out by means of an opposing mutual linear inductance connected between the drive winding and the output winding.

NOTE: Since fast current rise times are employed in the measurement of bobbin cores, good practice must be observed in the interconnections between the constant-current driver, the core test jig, and the observing device or oscilloscope. In particular, impedance levels must be chosen to ensure that the observing device does not affect bobbin core switching characteristics.

(3) *Integrator.* See 6.8.1.2.6.

6.2.4.8 Oscilloscope Measurements. The two basic measurements involved are voltage and time. These measurements will be made on the face of a cathode-ray oscilloscope. The oscilloscope is calibrated in volts for vertical deflections and seconds for horizontal deflection.

(1) *Voltage.* The voltage appearing at the output winding of the bobbin core is measured by comparing it with a reference voltage that is injected into the same vertical deflection channel of the oscilloscope. It is common practice to use dc as the reference voltage waveform. The drive current may be measured by observing the voltage drop across a known resistance and comparing this voltage with the known reference voltage.

NOTE: To achieve the desired degree of accuracy in the measurement of bobbin core properties, it is common practice to select a voltage reference source and a current measuring resistance that are known to within 0.5%.

(2) *Time.* The time durations of the signals appearing at the output winding of the bobbin core are measured by comparison with a periodic voltage signal of known period. The periodic signals usually found convenient are pulses produced by a time-mark generator.

NOTE: It is common practice to select a source of voltage signals with time periods known to within 0.5%.

In addition to the measurements of voltage and time, which should be made in accordance with the description given earlier, a measurement of the integrator constant is necessary.

NOTE: In acceptable practice, the calibration signal should have a volt-second integral known to within 0.5%. This integrator constant may also be determined from frequency-response measurements.

6.2.4.9 Definitions of Calculated Ratios. The following ratios are computed functions of quantities measured in the integrated-output test.

(1) *Integrated One-to-Zero Ratio.* The ratio of the integrated one to the integrated zero; that is, $\Phi_1/u\Phi_z$. This is sometimes called signal-to-noise ratio (in bobbin cores).

(2) Squareness Ratio (B_r/B_m). The ratio of the difference between integrated one and the integrated zero, to the sum of the integrated one and integrated zero; that is, $(\phi_1 - u\Phi_z)/(\phi_1 + u\Phi_z)$.

NOTE: Signal-to-noise ratio (bobbin cores) and squareness ratio are functions of the pulse amplitude.

6.3 Bridge Measurements. As noted in 6.1, the permeability of a magnetic material cannot

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itself be measured but must be calculated from other values or parameters that can be directly measured. One of the most common techniques for determining the permeability, *B–H* characteristics, and magnetic losses—as well as many other magnetic and electrical circuit parameters—is the use of various types of ac bridge circuits. This section describes some general techniques associated with the common bridge circuits. When using a specific commercial bridge instrument, the manufacturer's operating instructions should always be consulted. Bridge circuits are shown in Fig 12 (see pp. 32–33).

Bridge methods are applicable to transformers or inductors using most of the core materials and core configurations described in this standard. However, the bridge circuit and the interpretation of measured values vary considerably as a function of the Q of the coil used to excite the magnetic material (5.7.2). Also, the method in which the initial measurement or zero balance is made has a significant effect upon the accuracy of the impedance measurement.

The following discussion relates to bridge measurements on electronics transformers. Most of it is applicable to singly excited magnetic circuits also. The measurements described result in the determination of inductance and resistance. These measured parameters may be related to permeabilities, core loss terms, and other magnetic parameters by various formulas found in this standard, principally in Section 5. See Fig 12 for typical bridge circuits.

6.3.1 Series Bridge, Low Impedance. In order to obtain highest accuracy, it is necessary to use rather heavy straps from the bridge terminals to the terminals of the apparatus.

A shorting strap comparable in length to the distance between terminals of the apparatus should be used and the straps to the bridge disturbed as little as possible. The impedance being measured may be determined from the formulas

$$L_x = L_1 - L_o + L_c$$
$$R_x = R_1 - R_o + R_c$$

where L_x and R_x are the values of the inductance and effective resistance of components being measured, L_1 and R_1 are the bridge readings (corrected in accordance with the bridge instruction where necessary) for the component in place, L_o and R_o are the zero-balance measurement when a shorting strap is used in place of the component. L_c and R_c are corrections for the inductance and effective resistance of the strap. The value of the strap inductance is given by

$$L_c = 0.005\ell\left[\log_e\left(\frac{4\ell}{d}+\frac{d}{2\ell}-0.75\right)\right] \text{ microhenrys}$$

where ℓ is the length of shorting wire, in inches, and d is the diameter of shorting wire, in inches.

Assuming the shorting wire is copper,

$$R_c = R_{dc}\left(1+28.5f^2d^4\cdot 10^6\right)$$

where R_{dc} is the direct-current resistance of the shorting wire and f is the frequency of test, in megahertz.

NOTE: The above method may also be used for high impedance, in which case the correction terms may be negligible.

6.3.2 Series Bridge (Low Q). This type of measurement is applicable for measurement of terminated measurements for the determination of reflection coefficient when the impedance to be measured is essentially resistive. In place of the shorting strap used in method 1 of 6.2.4.8, select a noninductive low-capacitance resistor of value as close as possible to the ideal nominal value looking into the terminals of the apparatus. If the resistor has low parasitic inductance and capacitance, the impedance being measured may be determined from the formulas

$$R_x = R_2 - R_a + R_R$$
$$L_x = L_2 - L_a + L_R$$

where R_x and L_x are the values of effective resistance and inductance of the component being measured, R_2 and L_2 are the bridge readings (corrected in accordance with the bridge instructions when necessary) for the component in place, R_a and L_a are the initial measurement with the standard resistor in place of the apparatus, R_R is the dc resistance of the resistor, and L_R its inductance.

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6.3.3 Parallel Bridge (High Q). To avoid errors in connecting to the apparatus under test, fairly rigid leads should be used. The grounded terminal of the bridge should be connected to the ground terminal of the apparatus to be measured, and the high terminal lead should be near to but not touching the terminal or terminals of the apparatus. The value of impedance is then merely the difference between the zero (open) measurement and the value measured with the terminals of the apparatus connected to the bridge (corrected in accordance with the bridge instruction where necessary). If a balanced to ground or direct capacitance measurement is to be made, only the grounded terminal of the apparatus should be connected to the grounded terminal of the bridge for the zero or open-circuit measurement with both "high" terminals of the apparatus.

6.3.4 Parallel Bridge (Low Q). A parallel bridge may also be used for terminated impedance measurements as in method 2 of 6.2.4.8. As before, a low-capacitance low-inductance resistor should be used for the zero measurement. For this case, the admittance being measured may be determined from the formulas

$$R_p = R_3 - R_B + R_R$$
$$C_p = C_3 - C_B + C_R$$

where R_3 and C_3 are the measured values of parallel resistance and capacitance of the component being measured, R_B and C_B are the initial measurements with the resistor in place of the component, and R_R the dc resistance and C_R the capacitance of the standard resistor.

6.4 Core Loss and Apparent Core Loss. See 5.3 and 5.4 for definitions of core loss and apparent core loss.

6.4.1 Core-Loss Measurements With Sinusoidal/Voltage Excitation. The power source should have low internal impedance to ensure low waveform distortion under actual test conditions. The operating flux density of the core under test will be established based on the rms value of induced voltage across a test winding on the core. An electronic or dynamometer wattmeter may be used to measure the core loss in watts. The specific core loss is obtained by dividing the measured core loss in watts by the core mass or core volume to obtain watts per unit mass or watts per unit volume.

6.4.1.1 Apparent Core-Loss (Exciting Volt-Amperes) Measurement With Sinusoidal Excitation. The power source should have low impedance to ensure low waveform distortion under actual test conditions. The operating flux density of the core under test will be established based on the rms value of induced voltage across a test winding on the core. The exciting current is measured using a true rms ammeter in the primary winding. The apparent core loss is $(N_p / N_T)\, V_T I_p$, where

N_p = Primary winding turns
N_T = Test winding turns
I_p = RMS primary current
V_T = Induced rms voltage across felt winding

The specific apparent core loss is found by dividing the measured volt–amperes by the core weight or core volume to obtain VA per unit weight or VA per unit volume.

6.4.1.2 Suggested Standard Test Conditions for Core Loss and Apparent Core-Loss Measurements

Operating Flux Density (Gauss)	(Tesla)	Material
2500	0.25	Ferrites
4500	0.45	80% Co Amorphous
5000	0.50	80%Ni–20% Fe
10 000	1.0	50%Ni–50% Ni
14 000	1.4	92% Fe Amorphous
15 000	1.5	Si–Fe
15 500	1.55	75%Fe–20%Co Amorphous
20 000	2.0	Cobalt-Iron

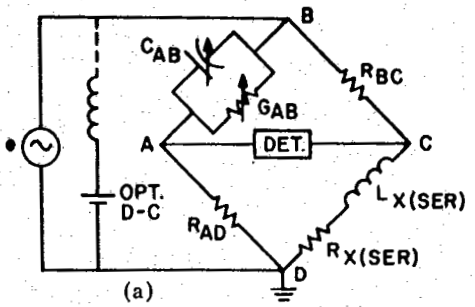
Operating Frequency (Hertz)	Material Thickness
60	0.007–0.025
400	0.004–0.006
1000	0.002–0.003
5000	0.0001–0.001
10 000 (and above)	Ferrites, 80% Co Amorphous

6.4.2 Core-Loss Measurements in Core Excited by Nonsinusoidal Signals

6.4.2.1 General Considerations. Magnetic cores are finding increasing applications in circuits in which the voltages and currents have wave shapes that cannot be classified by any of the standard waveforms, such as sine waves, steady dc, square waves, etc. In many such circuits, power levels are relatively large

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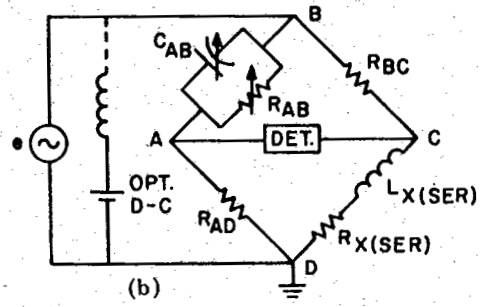
(a)

Maxwell L—R Bridge Using Conductance Standard

$L_X = (R_{AD}R_{BC})C_{AB}$
$R_X = (R_{AD}R_{BC})G_{AB}$

Reads series components directly requires a conductance standard.

NOTE: Will balance on dc like a wheatstone bridge and will read accurately over a wide frequency range. Best accuracy at low and medium-high Q values. For superimposed dc and high power measurements, R_{AD} is made large and R_{BC} small.



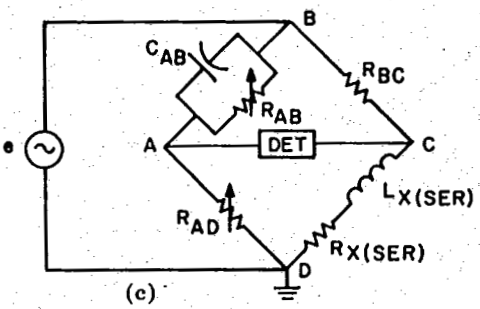
(b)

Maxwell L—R Bridge Using Resistance Standard

$L_X = (R_{AD}R_{BC})C_{AB}$
$R_X = (R_{AD}R_{BC})/R_{AB}$

Does not require a conductance standard but R_X must be computed.

(Same NOTE as under (a).)



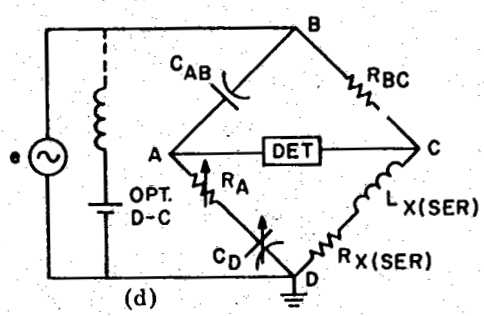
(c)

Maxwell L—Q Bridge

$Q_X = \omega L_X/R_X$
$L_X = (R_{BC}C_{AB})R_{AD}$
$Q_X = (\omega C_{AB})R_{AB}$

Can be made to read Q directly at a single frequency.

NOTE: Balances for L_X and Q_X are dependent. Balance is slow and difficult when Q_X is less than 3.



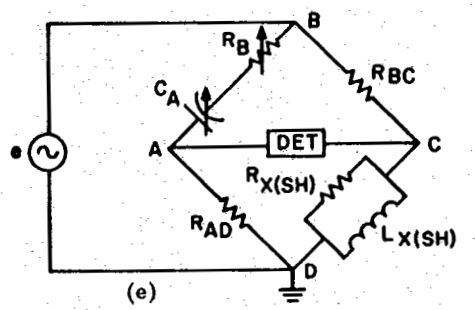
(d)

Owen L—R Bridge

$L_X = (C_{AB}R_{BC})R_A$
$R_X = (C_{AB}R_{BC})/C_D$

Will not balance on dc but will read accurately over a limited low and audio frequency range.

NOTE: Good for superimposed dc measurements because C_{AB} blocks dc from standard.



(e)

Hay L—R Bridge

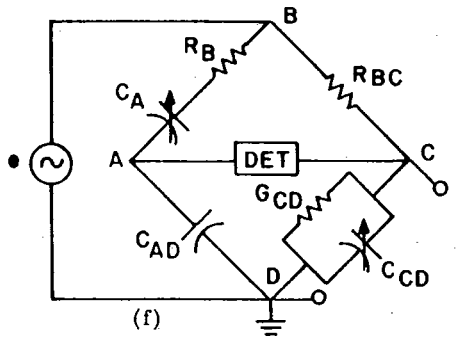
$L_{X(SH)} = (R_{AD}R_{BC})C_A$
$R_{X(SH)} = (R_{AD}R_{BC})/R_B$

Particularly accurate for high Q measurements. (R_B approaches zero.)

NOTE: If series inductance is desired it must be computed. The L—Q version of this bridge is difficult to balance for low Q values.

Fig 12
Bridge Circuits

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(f)

Schering Bridge Using Two-Capacitance Standards

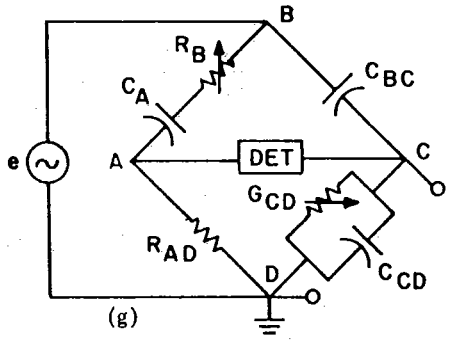
$$C_X = \Delta C_{CD}$$

$$G_X = \frac{C_{AD}}{R_{BC}}\left(\frac{1}{C_1} - \frac{1}{C_2}\right)$$

C_1 = value of C_A for initial balance

C_2 = value of C_A for final balance

Good for fairly high frequencies.
Capacitance standards may be accurately calibrated.
Not direct reading in G_X.
Limited range of C_X.
L_X determined by resonance method.



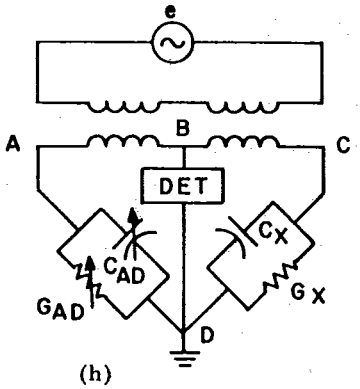
(g)

Schering Bridge Using Two-Resistance Standards

$$C_X = \frac{C_{BC}}{R_{AD}} \quad (\Delta R_B)$$

$$G_X = \Delta G_{CD}$$

Limited to moderate frequencies.
Not direct reading in C_X.
L_X determined by resonance method.



(h)

High-Frequency Admittance Bridge

$$C_X = \Delta C_{AD}$$

$$G_X = \Delta G_{AD}$$

Uses grounded standards.
Direct reading.
Useful over wide frequency range.
L_X determined by resonance method.

Fig 12 *(Continued)*
Bridge Circuits

and, therefore, the measurement of power, losses, and efficiency is a significant factor in their design and application. The source of these nonstandard waveforms is frequently the switching action of power semiconductors in systems that include inverters, cycloconverters, controlled rectifiers, and choppers. These waveforms are periodic but are often composed of discrete pulses that may vary in pulse shape from sinusoidal to square with pulse repetition rates up to 500 pulses/s. Pulses may have very steep rising or decaying wavefronts, especially in certain thyristor switching operations such as commutation. Current waveforms may contain large dc components.

In general, functions of this class can be expressed as a series of sinusoidal functions by means of Fourier series techniques. Many manufacturers of magnetic cores and magnetic materials supply measured core-loss data over a wide range of frequencies of sinusoidal excitation. However, due to saturation

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and other nonlinear characteristics of most magnetic materials, the total core loss of a given core cannot in general be related to the sum of its losses measured during excitation of the individual sinusoidal components of a complex wave function. Therefore, measurement of core losses in the presence of the true operating exciting function is most desirable.

6.4.2.2 Wattmeter Configurations. There are four basic types of wattmeters that may be used to measure core loss in cores with nonsinusoidal excitation: dynamometer; Hall-effect; thermal; and electronic multiplier. The use of dynamometer meters is limited to systems containing low-frequency components, and is generally not recommended for inverter or chopper-excited systems.

6.4.2.3 Frequency Response. The frequency response of the wattmeter needed to give accurate measurements depends upon the frequency components existing in the voltage and current waves applied to the core. If possible, it is desirable to know this frequency range in selecting a wattmeter. In general, a frequency response of at least 100 kHz has been found necessary for core-loss measurements for power inverter and chopper applications.

6.4.2.4 Phase-Angle Error. Since core-loss measurements are generally performed under a condition of very low power factor,

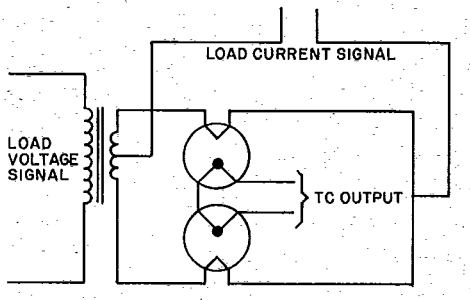
$$F_p = \frac{\text{active power}}{\text{apparent power}}$$

phase-angle errors within the wattmeter must be minimized. This is a greater problem for wattmeters designed to measure power in circuits containing functions with nonsinusoidal or discontinuous waveforms due to the high frequency components in such functions. Stray capacitance, lead inductance, and eddy currents induced in metallic structural members or transformer cases and cores can introduce large errors. These errors may vary not only with base frequency but also with waveform. The effects of these stray impedances can be most easily minimized or compensated in the electronic multiplier wattmeters. Input impedance as a function of frequency and of the wattmeter scale factors should always be specified in this type of wattmeter.

6.4.2.5 Calibration. Most commercial Hall-effect and electronic multiplier wattmeters are calibrated with only sinusoidal or steady dc signals, or both. Also, wattmeter accuracy is expressed only on the basis of sinusoidal measurements at various frequencies. In general, this method of calibration may not be adequate for measurement in systems with discontinuous waveforms. A thermal or calorimetric standard (see, for example, [4]) should be used to calibrate the device where measurements of signals with highly irregular waveforms are required. At the present time, there are no National Institute of Standards and Technology (NIST) calibration techniques nor instrumentation for measurement of nonsinusoidal power.

6.4.2.6 Hall-Effect Wattmeter. The Hall-effect semiconductor has been used in several circuit configurations to measure sinusoidal power over a wide range of frequency and, in some cases, nonsinusoidal power. In a Hall wattmeter, the magnetic field input to the Hall element is derived from the current flowing through the load whose power is being measured; the voltage input to the Hall element is derived from the load voltage. One or both of these input signals are often transformer-coupled to the external load circuit in commercial wattmeters, which introduces a large error into the power reading when the external signals contain significant dc components. Frequency response is generally below 10 000 Hz, although some manufacturers claim 50 000 Hz with sinusoidal signals. Thermal drift specifications should be examined thoroughly. Generally only average power is indicated. Further discussions on Hall wattmeters are given in [B25] and [B35].

6.4.2.7 Thermal Wattmeter. A device known as the thermal converter or thermal wattmeter has long been used in 60 Hz power systems to measure true power independent of wave shape. This device uses thermocouples in a bridge arrangement (see [B18] for details) as shown below.



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It is seen that the resultant current in the one heater is proportional to the sum of the two input signals while that in the other heater is proportional to the difference, depending upon the relative polarity of the two inputs. Assume that these currents are proportional to these two signals as shown. Also assume that the thermocouple output voltages are proportional to the square of the currents in the heaters (or rms currents). The difference of the two thermocouple output voltages is, therefore,

$$e_{out} = k(e_L + i_L)^2 - k(e_L - i_L)^2$$
$$= k(4e_L\, i_L)$$

where

e_L Instantaneous load voltage
i_L Instantaneous load current
e_{out} Sum of two thermocouple voltages
k Constant of proportionality, or calibration constant

It is seen that the resultant thermocouple output voltage can be related to instantaneous load power. Due to the long time constant of thermocouple, it can be shown that this output is actually *average* load power.

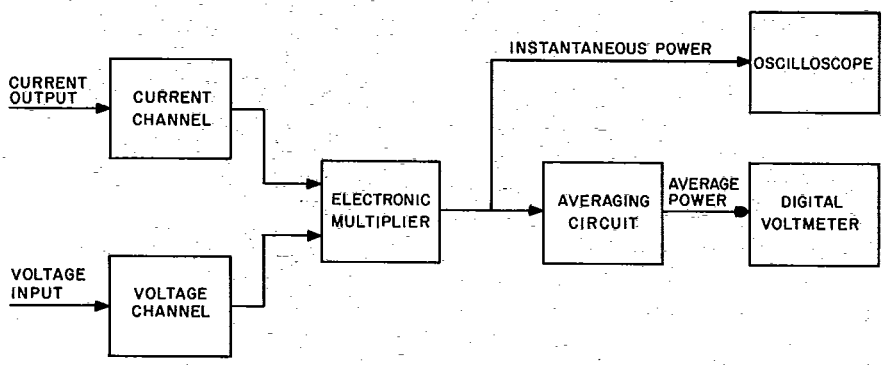
The frequency response of the thermal wattmeter is relatively low due to the transformer coupling between input signals and the thermocouple heaters. Also, dc power components cannot be measured in this configuration. By resistively coupling the input signals to the thermocouple heaters, power can be measured in systems containing dc and higher frequency components. At this writing, no commercial wattmeters using this thermocouple circuit and adaptable to inverter and chopper waveforms are known.

6.4.2.8 Electronic Multiplier Wattmeters. The potentially most versatile type of wattmeter for measurement of power in systems containing discontinuous or highly nonsinusoided waveforms is the electronic multiplier circuit.

The block diagram of the typical electronic Multiplier wattmeter is shown in Fig 13, which originally appeared in [4]. This type of wattmeter can, in general, give signals for viewing instantaneous power on an oscilloscope as well as indicating average power. Frequency response and phase-angle error are determined mainly by the frequency response of the quarter square multiplier and by the stray impedances of the input channels. The current signal is generally derived from a noninductive shunt that also permits coupling of dc components. Attenuation circuits in the voltage channel generally allow for a very wide range of input voltages, the upper limit being determined by the insulation characteristics of the voltage channel. Thus this type of wattmeter permits a wider range of voltage, current, and power levels than any other class of wattmeter. Proper compensation of the input channels permits measurements in systems of power factors as low as 0.01 with 2% accuracy.

Frequency response is in the 50 000–100 000 Hz range. Further discussion of electronic wattmeters can be found in [4] and [B6], [B15], and [B38].

Fig 13
Block Diagram of Wattmeter



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6.5 Saturing Core Tests

6.5.1 Constant-Current Flux-Reset (CCFR) Core Test Method

6.5.1.1 General Description. The constant current flux-reset core test method provides a means for measurement of core magnetic properties under operative conditions that approximate conditions in several different types of self-saturating magnetic amplifier circuits. The test employs an exciting current consisting of half-wave sine-current pulses of sufficient magnitude to drive the core flux into positive saturation. A direct-current demagnetizing force of adjustable magnitude is applied to the core so as to reset flux away from positive saturation during the intervals between pulses of excitation current. The resultant cyclic flux change is measured by means of a sensitive flux voltmeter connected to a separate pickup winding on the core. A low number of excitation, control, and pickup turns are used to facilitate rapid jigging of cores.

Test data are obtained by measuring values of induced pickup voltage as a function of the applied demagnetizing control ampere-turns under conditions of half-wave sinusoidal excitation current of constant magnitude. For some purposes, these data may best be presented in the form of a curve. For general production, core grading, and matching data are obtained only at particular standardized test points. These standard test points are selected as shown in Fig 14 to determine the bias point (H_o) and the gain (G) in the linear region of the curve. Also, the difference between peak induction and residual induction ($B_m - B_r$) is measured using zero-control ampere-turns.

The measurement of peak flux density is made by employing full-wave sine-current excitation. This measurement can best be made by switching to a full-wave sine-current supply instead of a half-wave supply, and using zero-control ampere-turns.

6.5.1.2 Test Circuit. A simplified schematic diagram of the test circuit is shown in Fig 15. The circuit consists of five major blocks. These are (1) full-wave sine-current supply; (2) half-wave sine-current supply; (3) dc control current supply; (4) test jig; and (5) flux voltmeter. The requirements on these various units are given in the following paragraphs.

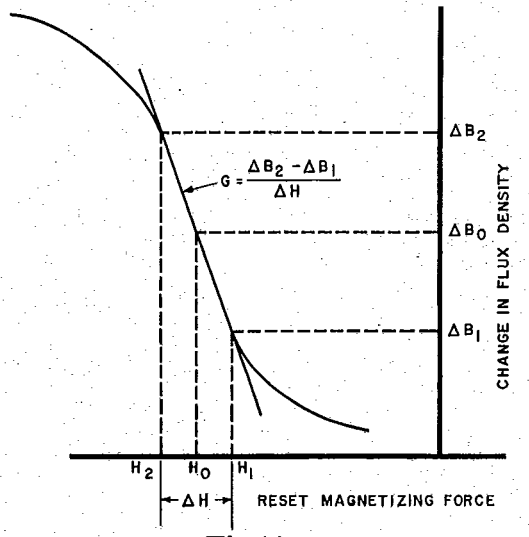


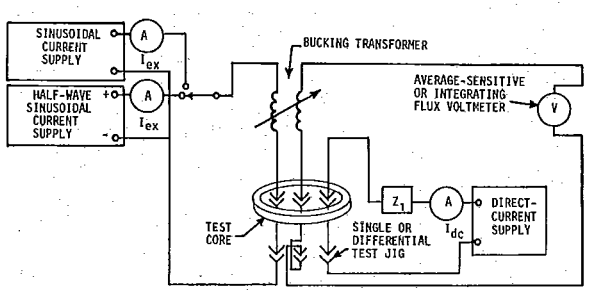
Fig 14
Test Points for the Constant-Current Flux-Reset Core Test Method

A sinusoidal and half-wave sinusoidal current supply shall be provided. These may be separate current supplies or may be obtained from a common source by suitable switching and rectifying means.

6.5.1.3 Plug-in Type Test Jig. A single or double (differential) plug-in type of test jig shall be used. A single test jig shall have a plug-in connector having an excitation winding, a pickup winding, and a control winding.

If a double or differential type of test jig is employed, the excitation windings of the two plug-in connectors shall have equal numbers of turns and shall be connected in series. The pickup windings of the two plug-in connectors shall have equal numbers of turns, and shall be connected in series opposition. Also, the control windings shall have equal turns and shall be connected in series with the same polarity connections as the excitation windings.

Fig 15
Circuit for the Constant-Current Flux-Reset Core Test Method



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Provision for cancellation of voltage pickup due to air induction linking the excitation winding with the pickup winding shall be made, if necessary.

6.5.1.3.1 Flux Voltmeter. Either an averaging instrument sensitive to total flux change or an integrating flux voltmeter shall be used to measure the core output voltage.

6.5.1.4 Excitation and Control Requirements

6.5.1.4.1 Voltage Source. The voltage of the excitation source shall be sinusoidal, with a harmonic content of less than 10% and shall have an rms amplitude greater than 100 times the half cycle average value of voltage induced in the excitation winding.

The frequency of the voltage source shall be known within 1%, and if not known within these limits it shall be measured to an accuracy of 1%.

Standard test frequencies of 60 400 or 1600 Hz may be used within the frequency limitations of the test circuitry and instrumentation. The tolerance on any standard test frequency used shall be ± 5%.

6.5.1.4.2 Excitation Windings. The excitation winding on the test jig shall consist of a single turn, wherever possible, but shall not exceed six turns.

All excitation windings shall be kept in a fixed position in relation to the pickup windings, and to nearby circuits and equipment, during testing. When differential core matching is desired, two identical excitation windings shall be used, connected in series. Geometric symmetry of the excitation windings in relation to each other shall be maintained.

6.5.1.4.3 Exciting Current. The half-wave exciting current shall be essentially sinusoidal. For values of current from 5 to 25% of peak exciting current, the time interval between an instantaneous value of current on the descending portion of the current waveform to an equal value of current on the ascending portion of the next half-cycle of current shall be within ± 3% of the corresponding time interval for a perfect half-wave sinusoid.

During the interval between pulses when the exciting current is nominally zero, the maximum instantaneous current occurring because of rectifier leakage or other causes is to be less than 0.1% of the peak value of current during a pulse.

The full-wave exciting current shall contain less than 25% harmonic distortion.

The peak value of exciting current shall be measured to an accuracy of ± 2%.

6.5.1.4.4 Peak Magnetizing Force. The following peak magnetizing force shall be applied for the commonly used core materials. The value of peak magnetizing force applies to materials whose tape thickness is 6 mils (0.152 mm) or less when tested at 400 Hz or less, or whose tape thickness is from 6 to 14 mils (0.152 to 0.355 mm) when tested at 60 Hz:

Material	Peak Magnetizing Force When Measuring H_0, H_1, and H_2 (amperes per meter)	Peak Magnetizing Force When Measuring B_m and $(B_m–B_r)$ (amperes per meter)
Cobalt-Iron	480	240
3% Silicon–Iron (oriented)	480	240
50% Nickel–Iron (oriented)	160	80
80% Fe Amorphous	80	40
Co–Fe Amorphous	80	40
79% Nickel–Iron	80	40
Supermalloy	40	20

$$H_m = \frac{N_e I_m}{l} \text{ (amperes per meter)}$$

where

H_m = Peak magnetizing force
N_e = Number of excitation winding turns
I_m = Peak exciting current, in amperes
l = Mean core length, in meters

When conditions other than those covered in the preceding paragraph are employed, the nearest larger value of peak magnetizing force shall be selected and rounded off to one significant figure that is twice the value of the highest sine-current coercive force to be expected.

6.5.1.4.5 Direct-Control Current. The rms ripple of the control current shall not exceed 0.25%.

Control current corresponding to H_0, H_1, and H_2, Fig 14, shall be measured to within ± 1%.

Changes in control current corresponding to ΔH, Fig 14, shall be measured to ± 2%.

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6.5.1.5 Measurement Requirements

6.5.1.5.1 Pickup Windings. The pickup winding on the test jig provides an induced voltage for measuring the dynamic hysteresis loop characteristics of the core under test. The pickup winding shall consist of a single turn when possible, but it may have any convenient number of turns.

All pickup turns shall be maintained in a fixed position relative to the excitation windings and to other nearby equipment during core testing.

Whenever possible, the pickup windings shall be so arranged in relation to the excitation windings that the inductive and capacitive coupling between them is minimized so that, with no core in the jig, no induced voltage appears on the output of the pickup windings with maximum current flowing at the test frequency in the excitation winding.

If the average induced voltage from the pickup winding under the conditions of the preceding paragraph, due to mutual coupling between the excitation and the pickup windings, exceeds 0.5% of the average output voltage corresponding to the peak magnetizing force, then this mutual inductive coupling between the excitation winding and the pickup winding shall be adjusted so as to reduce the induced voltage to less than 0.5%. If necessary, an air-core bucking transformer shall be used for this purpose.

Where differential core matching is desired, two identical pickup windings shall be used, connected in series opposition. Geometric symmetry of the pickup windings in relation to each other and to the excitation windings shall be maintained.

The average output voltage of the differential jig of the preceding paragraph with no cores in the windings and with maximum exciting current flowing at the test frequency shall be less than 0.5% of the average voltage obtained with only one core in the differential test windings. The mutual inductive coupling between one of the excitation and pickup windings of the differential test jig shall be adjusted to reduce the induced voltage to less than 0.5%.

6.5.1.5.2 Flux Voltmeter Input Impedance. The average-sensitive or integrating-flux voltmeter shall have negligible loading effect on the core. Its input impedance must be such that

$$R > 5fN_s^2 \frac{A}{l}\mu_{difm}$$

where

R = Meter input impedance, in ohms
N_s = Pickup winding turns
A = Core cross-sectional area, in square millimeters
l = Mean length of magnetic path of the core, in millimeters
f = Test frequency, hertz

$$\mu_{difm} = \frac{\Delta B_2 - \Delta B_1}{\Delta H} \text{ in } \frac{\text{teslas}}{\text{ampere / meter}}$$

(see Fig 14).

The average-sensitive or integrating flux voltmeter shall have an accuracy of ±1% of reading.

6.5.1.5.3 Standard Test Points. Data shall be taken at the following test points:

(1) B_m at H_m, specified in 6.5.1.4.4
(2) $B_m - B_r$, at control $H = 0$
(3) H_0 at specified ΔB_0 (see the following tabulation)
(4) H_1 at specified ΔB_1 (see the following tabulation)
(5) H_2 at specified ΔB_2 (see the following tabulation)

ΔB_1, ΔB_0, and ΔB_2 as independent variables should be adjusted to the following values:

Material	ΔB in teslas		
	ΔB_1	ΔB_0	ΔB_2
3% Silicon–Iron (oriented)	1.0	1.5	2.0
50% Nickel–Iron (oriented)	1.0	1.5	2.0
79% Nickel–Iron	0.5	0.75	1.0
Supermalloy	0.5	0.75	1.0
Cobalt–Iron	1.33	2.0	2.56
80% Cobalt (amorphous)	0.48	0.70	0.94
92% Iron (amorphous)	1.05	1.55	2.08
75% Fe 20% Co (amorphous)	1.16	1.70	2.28

The value of ΔB_0 was selected to be approximately one half the maximum flux density swing encountered in usual magnetic amplifier designs. Also, ΔB_1 approximates

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one third of this design, ΔB and ΔB_2 approximates two thirds of the design ΔB.

In calibrating the flux voltmeter, which measures total flux change, to read flux density (in teslas) the manufacturer's published gross cross-sectional area of the cores being tested and the following stacking factors shall be employed.

Tape Thickness		
mils	millimeters	Stacking Factor
1/2	0.0127	0.50
1	0.0254	0.75
2	0.0508	0.85
4 through 10	0.102–0.254	0.90
11 through 14	0.279–0.355	0.95

These stacking factors do not necessarily correspond to the manufacturer's stacking factors. As a result, measured values of B_m and B_m–B_r will not agree with manufacturer's published data. To correlate test data the following conversion must be made, and vice versa:

$$B' = \frac{BAk}{A'_e}$$

where

B' = Flux density corresponding to the manufacturer's published core effective area

A'_e = Manufacturer's published core effective area

k = Stacking factor listed above

A = Published gross core cross-sectional area

B = Flux density read from tester

The same stacking factor is employed when testing equivalent cores from various manufacturers in order that the cores may be tested with the same flux swings and that the cores may be specified with one description. The test actually measures flux change, which is the quantity of interest.

6.5.1.5.4 Measurement of B_m. The peak induction (B_m) shall be measured at the peak magnetizing force specified in 6.5.1.4.4 employing full-wave sinusoidal excitation current and zero control current.

6.5.1.5.5 Measurement of H_o. H_o shall be measured in amperes per meter at the value of ΔB_0 utilizing half-wave sinusoidal exciting current as specified in 6.5.1.4.4.

6.5.1.5.6 Measurement of Gain. The value of gain (G) henrys per meter is computed as follows:

$$G = \frac{\Delta B_2 - \Delta B_1}{H_2 - H_1} = \frac{\Delta B_2 - \Delta B_1}{\Delta H}$$

where ΔB_2 and ΔB_1 are specified in 6.5.1.5.3 and ΔH is measured utilizing halfwave sinusoidal exciting current as specified in 6.5.1.4.4.

6.5.1.5.7 Measurement of B_m–B_r. B_m–B_r should be measured by utilizing zero-control current and half-wave sinusoidal current excitation as specified in 6.5.1.4.4. This measurement shall be made directly following the measurement of B_m in order to avoid errors due to magnetic history.

6.5.1.6 Differential Core Matching. When matching cores by the differential method, the tolerance of match shall be determined by measuring the differential output voltage between each core and a reference core at values of magnetizing force specified by the user. The difference so measured, as compared with the nominal peak induction of the core, shall be a measure of the percent tolerance of match between the cores.

6.5.2 Sine-Current-Excitation Core Test Method

6.5.2.1 General Description. The test method described here provides for the measurement of four basic parameters of the saturated major dynamic sine-current hysteresis loop of a core material for magnetic amplifier applications. The core parameters measured are generally considered to be significant in determining the performance of the core material in the magnetic amplifier type of application. These parameters are the ac peak induction (corresponding to the ac peak magnetizing force), the squareness ratio (ratio of residual induction to peak induction), the sine-current coercive force, and the maximum differential permeability (maximum slope of the sides of the dynamic hysteresis loop).

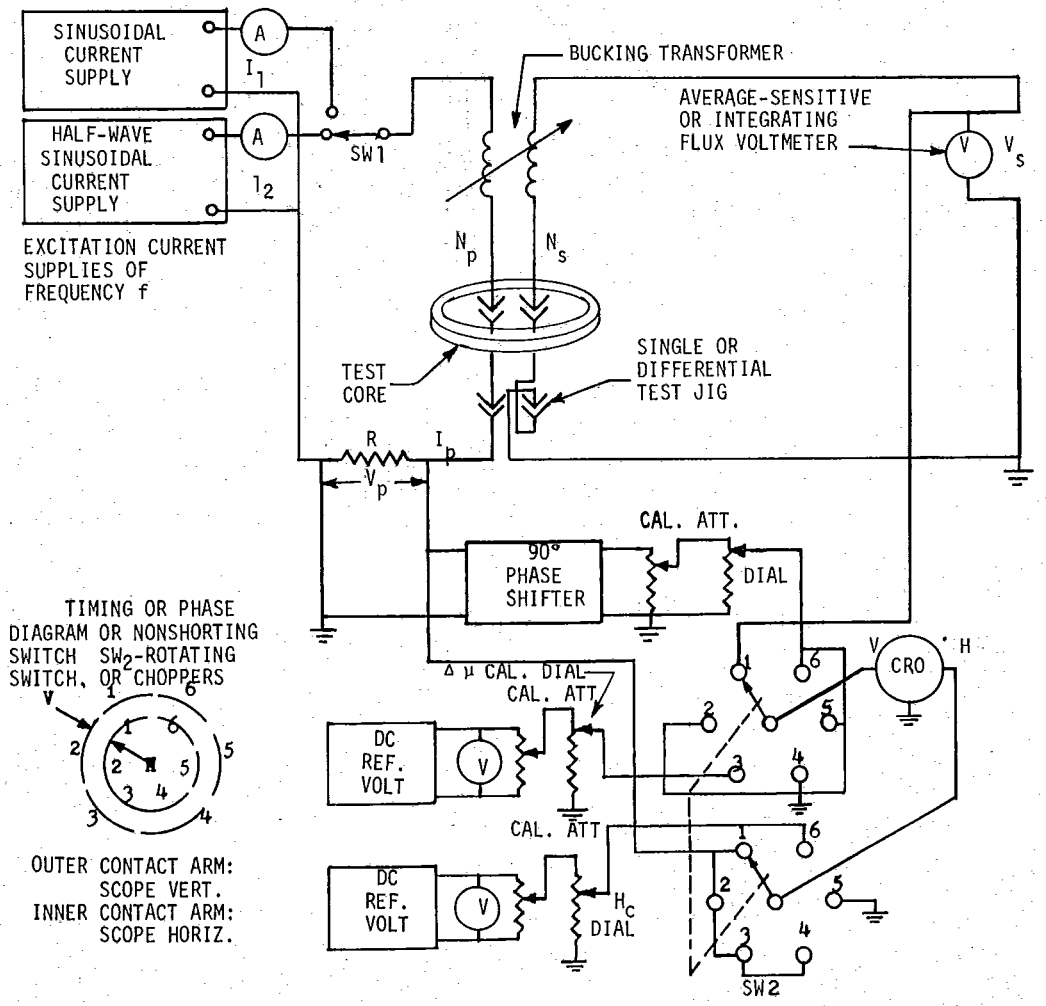
This test method employs a relatively high-impedance excitation source of sine voltage and known frequency, driving the core material under test into relative saturation

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while maintaining a sinusoidal exciting current. Very few excitation and pickup turns are used in order to facilitate rapid jigging of test cores of widely varying sizes. Instrumentation is provided for determining the peak magnetizing force, the peak induction, and for observing the output voltage versus exciting current waveform of the core material. Calibration means are provided whereby the sine-current coercive force and the maximum differential permeability may be measured from the output voltage versus exciting current waveform. Provision is made for excitation of the core with a half-wave of rectified sine current to facilitate the measurement of flux density change (ΔB or $B_m - B_r$), from which the ratio of residual induction to peak induction may be calculated. Provision is also made for matching of cores on a differential basis.

6.5.2.2 Test Circuit. A test circuit such as the one shown in Fig 16 shall be used. A sinusoidal and a half-wave sinusoidal current supply shall be provided. These may be separate current supplies or may be obtained from a common source by suitable switching and rectifying means. The instrumentation is similar to that described in 6.5.1.2 with the addition of the items in the following subsections.

Fig 16
Basic Circuit for Sine-Current Excitation Core Tester



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6.5.2.2.1 Provision for a noninductive voltage-dropping resistor shall be made in series with the source and excitation windings.

NOTE: The purpose of the dropping resistor is to provide a voltage that is proportional to the exciting current.

6.5.2.2.2 Ninety-Degree Phase Shifter and Calibrating Attenuators. A source of sinusoidal voltage with less than 1% distortion shall be provided for the measurement of maximum differential permeability. This sinusoidal voltage, known as the ellipse voltage, shall be 90 degrees out of phase with the exciting current, and may be derived from the voltage across the excitation circuit dropping resistor by shifting its phase by 90 degrees. The function of the ellipse voltage is to provide a locus of constant differential permeability.

The ellipse voltage shall be adjustable by separate calibrating and attenuating potentiometers to provide for calibration and measurement of maximum differential permeability readings in terms of henrys per meter.

6.5.2.2.3 Direct-Current Reference Potential Sources. Two separate reference potential sources shall be provided, each with provision for measuring the reference potential and each with separate calibrating and attenuating potentiometers.

One dc reference potential and attenuator shall be used for calibration of peak magnetizing force in amperes per meter when the exciting-current waveform is not sufficiently distortion free to use an rms ammeter for such calibration. The attenuator is also used in the direct measurement of sine-current coercive force in amperes per meter.

The other dc reference potential and attenuator shall be used for calibration of the ellipse voltage used in measuring the maximum differential permeability. The attenuator may also be used for measurement of the maximum differential permeability in the event that a distortion-free ellipse voltage is not obtainable under all test conditions.

6.5.2.2.4 Rotating Switch or Phased Synchronous Choppers. A rotating double-pole multiposition switch shall be provided for displaying on the oscilloscope various sequences of the core output voltage versus exciting current, eclipse voltage versus exciting current, dc reference potential markers, and zero-reference voltage markers.

In lieu of a suitable rotating switch, two or more single-pole double-throw synchronous choppers may be used, properly phased, to apply the proper sequence of signals to the oscilloscope.

The frequency of rotation of the switch, or driving frequency of the choppers, shall be not greater than one sixth of the fundamental core test frequency.

6.5.2.3 Excitation Requirements

6.5.2.3.1 Voltage Source. The voltage of the excitation source shall be sinusoidal, with a harmonic content of less than 10%.

The frequency of the voltage source shall be known within 1%, and if not known within these limits it shall be measured to an accuracy of 1%.

Standard test frequencies of 60 400 or 1600 Hz may be used within the frequency limitations of the test circuitry and instrumentation. The tolerance on any standard test frequency used shall be ± 5%.

6.5.2.3.2 Excitation Windings. The excitation winding on the test jig shall consist of a single turn, wherever possible, but shall not exceed six turns.

All excitation windings shall be kept in a fixed position in relation to the pickup windings, and to nearby circuits and equipment, during a testing.

When differential core matching is desired, two identical excitation windings shall be used, connected in series. Geometric symmetry of the excitation windings in relation to each other shall be maintained.

6.5.2.3.3 Exciting Current. The exciting current shall be sinusoidal, with a harmonic content of less than 5% at the value of current corresponding to the peak magnetizing force to be used for the core under test. Series resistance may be used to increase the impedance of the excitation source sufficiently to limit harmonics in the exciting current waveform for the smaller core sizes. When necessary, a series-resonant filter shall be used to limit the maximum harmonic current to 5%.

Suitable means for measuring the peak exciting current with an accuracy of 2% shall be provided. When the harmonic content of the exciting current is sufficiently low, a dynamometer type of rms ammeter with an accuracy of 0.5% or better is recommended.

Suitable means shall be provided for varying the exciting current to obtain the

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appropriate peak magnetizing force for the range of core sizes normally encountered. A variable auto-transformer is usually satisfactory for this purpose.

6.5.2.3.4 Peak Magnetizing Force. The following peak magnetizing force shall be applied for the commonly used core materials. The value of peak magnetizing force applies to materials whose tape thickness is 6 mils (0.152 mm) or less, when tested at 400 Hz; or whose tape thickness is from 6 to 14 mils (0.152 to 0.355 mm) when tested at 60 Hz.

Materials	Peak Magnetizing Force (amperes/meter)
3% Silicon–Iron (oriented),	240
Cobalt–Iron	240
50% Nickel–Iron (oriented)	80
80%Cobalt (amorphous)	80
79% Nickel–Iron	40
Supermalloy	20

When conditions other than those covered in the preceding paragraph are employed, the nearest larger value of peak magnetizing force shall be selected and rounded off to one significant figure that is twice the value of the highest sine-current force to be expected.

When a dynamometer-type rms ammeter is used to measure the exciting current, the peak magnetizing force shall be calculated from the formula

$$H_m = \frac{N_e I_m}{l_e}$$

where

N_e = Number of excitation winding turns
I_m = Peak exciting current, in amperes = 1.414 I_{rms} for a pure sine wave
l_e = Mean core length, in meters

When harmonics in the exciting current waveform are large enough to prevent the measurement of peak magnetizing force with the required accuracy, it may be measured from the oscilloscope display using a direct-current reference potential and calibrated attenuator, using the formula

$$H_p = \frac{N_p}{l_e} \cdot \frac{kV}{R} \text{ amperes/meter}$$

where

N_p = Number of excitation winding turns
k = Constant of attenuation of direct-current reference potential source
V = Direct-current reference potential, in volts
R = Excitation-circuit dropping resistance, in ohms

6.5.2.4 Measurement Requirements

6.5.2.4.1 Pickup Windings. The comments of 6.5.1.5.1 are applicable.

6.5.2.4.2 Core Output Measurements. The core output voltage waveform, as appearing on the pickup winding, may be measured by a number of methods to determine the dynamic hysteresis loop characteristics of the core under test.

All instruments used in making output voltage waveform measurements shall have sufficiently high input impedance so as not to load the core output voltage. The minimum input impedance of this instrument shall be determined as

$$R > 5fN_s^2 \frac{A_e}{l_e} \mu_{difm}$$

where

N_s = Pickup winding turns
A_e = Core cross-sectional area, in square meters
l_e = Mean core length, in meters
μ_{difm} = If maximum differential permeability of test core, in henrys per meter
f = Test frequency, in hertz

6.5.2.4.3 Measurement of Peak Induction or Peak Flux (B_m). The measurement of peak induction shall be made by measuring the core output voltage with an average-sensitive or integrating flux voltmeter (Fig 16) using the peak magnetizing force specified in 6.5.2.3.4. The reading shall be calibrated directly in teslas, based on the core cross-sectional area at a specific test frequency.

6.5.2.4.4 Measurement of Sine-Current Coercive Force (H_c). Sine-current coercive force measurements with this test method shall be made by displaying the core output voltage versus exciting current on an oscilloscope and measuring, by means of a

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calibrated potentiometer and dial marker trace, the horizontal distance between the voltage peaks of the oscilloscope display in relation to the known peak magnetizing force, as represented by the overall horizontal width of the display (Fig 17). The dynamic coercive force in amperes per meter is read directly from the H_c dial (Fig 16) after adjusting the H_c dial marker to coincidence with the peak of the core output voltage (Fig 17).

NOTE: It should be borne in mind that this measurement is a close representation of the true dynamic coercive force of the core material under test only if the material has approximately a rectangular dynamic hysteresis loop. Under these conditions, the peak of the induced core output voltage waveform corresponds with the true dynamic coercive force within a few percent. When non-rectangular dynamic hysteresis loop materials are being measured, however, the peak of the output voltage wave may depart from the true coercive force value by a considerable amount, and the value measured is the H at μ_{difm}. This value will generally be somewhat different from the true H_c value, but may be used and specified in the same manner as the H_c value as long as the test conditions and the test results obtained are clearly defined.

6.5.2.4.5 Measurement of Maximum Differential Permeability (μ_{difm}). The measurement of maximum differential permeability shall be made by displaying the core output voltage versus exciting current on an oscilloscope and measuring, by means of a calibrated potentiometer and dial marker trace, the peak value of the output voltage. The maximum differential permeability, in henrys per meter, may be read directly from the μ dial (Fig 16) after adjusting the μ dial marker to coincidence with the peak of the core output voltage (Fig 17).

Calibration of maximum differential permeability shall be accomplished using a dc reference potential and calibrated attenuator.

When the μ_{difm} calibrating marker trace is adjusted to coincidence with the peak value of the ellipse voltage, the maximum differential permeability, in teslas per (ampere/meter), may be calibrated using the following equation:

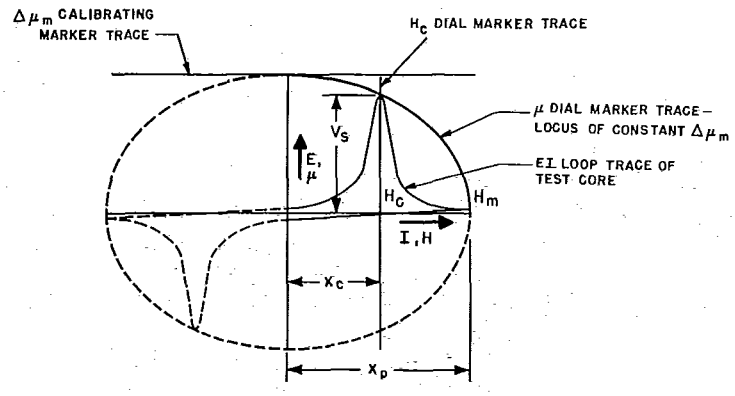
$$\mu_{difm} = \frac{K'V'}{N_s A_e} \cdot \frac{l_e}{N_e I_m} \cdot \frac{1}{\omega \cos \omega t}$$

where

N_e = Number of excitation turns
N_s = Number of pickup turns
V' = Direct-current reference potential, in volts
K' = Attenuation constant of reference-voltage attenuator by setting $\omega t = 0$ and substituting the appropriate constants into the equation
t = Time, in seconds

An alternative calibration of maximum differential permeability may be made by adjusting the μ_{difm} calibrating marker to coincidence with the peak of the core output voltage wave, and using the above equation by setting $\omega t = \sin^{-1}(H_c/H_m)$ and substituting the appropriate constants in the equation.

Fig 17
Oscilloscope Presentation of *E–I* Loop of Test Core, Showing Calibrating and Measuring Marker Traces



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6.5.2.4.6 Measurement of Squareness; Ratio of Residual to Peak Induction. The measurement of squareness shall be made by measuring the change in induction (B_m–B_r) with a half-wave sinusoidal excitation whose peak magnetizing force corresponds to that specified in 6.5.2.3.4. This measurement of the change in induction shall be made in terms of teslas. This measurement shall be made directly following the measurement of B_m in order to avoid errors due to magnetic history. When the ratio of residual to peak induction is required rather than (B_m–B_r), it may be calculated as

$$\frac{B_r}{B_m} = \frac{B_m - (B_m - B_r)}{B_m} = 1 - \frac{B_m - B_r}{B_m}$$

with the value of peak induction B_m measured as in 6.5.2.4.3.

6.5.2.5 Differential Core Matching. When matching of cores by the differential method is desired, the overall match shall be determined as a percentage, plus or minus, using one of the cores in each matched set as a reference. The tolerance of match shall be determined by measuring the differential output voltages between each core and the reference core with an average-sensitive or integrating flux voltmeter (Fig 16). The difference in induction so measured, as compared with B_m of the reference core, shall be a measure of the percent tolerance of match between cores.

6.5.3 Presenting Magnetic Data on Core Materials

6.5.3.1 Magnetic Data

6.5.3.1.1 Direct-Current Magnetization Curve. Tests shall be conducted to H = 800 A/m for cases where the intrinsic flux density increases 5% or less between H = 800 and 4000 A/m. They shall be conducted to H = 4000 A/m for cases where the intrinsic flux density increases more than 5% between H = 900 and 4000 A/m.

6.5.3.1.2 Direct-Current Major Hysteresis Loop. Tests shall be conducted to a peak magnetizing force of H = 80 A/m if the dc coercive force is less than 4 A/m. They shall be conducted to a peak magnetizing force of 800 A/m if the dc coercive force is 4 A/m or greater.

6.5.3.1.3 Major Dynamic Hysteresis Loops. Standard frequencies shall be 60, 400, 1000, and 10 000 Hz, as applicable. In cases where the manufacturer desires to test at other frequencies, the following are preferred: 2 kHz, 5 kHz, 100 kHz, 1 MHZ, and 10 MHz.

The induced voltage shall be sinusoidal, with less than 10% total harmonic distortion.

NOTE: Percentage harmonic distortion =

$$\frac{\text{rms value of harmonics}}{\text{rms value of fundamental and harmonics}} \cdot 100$$

The peak magnetizing forces shall be (1) two times the ac coercive force value and (2) twenty times the ac coercive force value or 800 A/m, whichever is smaller, for each of the frequencies at which tests are made. Tolerance on magnetizing force shall be ± 5%.

6.5.3.2 Standard Test-Core Sizes. The toroidal core shall be 1 5/8 in (41.3 mm) ID × 2 in (50.8) OD × 1/4 in (6.35 mm) in height for frequencies up to 1000 Hz. It shall be 1/2 in (12.7 mm) ID × 3/4 in (19.0 mm) OD × 1/8 in (3.18 mm) in height for frequencies of 1000 Hz and greater. A core composed of double-lapped U-punchings shall have a 1/4 in (6.35 mm) leg, a 1/2 in (12.7 mm) stack height, and a mean length approximately equivalent to that of the larger of the two toroidal cores.

6.5.3.3 Temperature. The tests shall be conducted at a core temperature of 25 ± 100 °C. In cases where the manufacturer desires to test at other temperatures, nominal temperatures of –55 °C, 105 °C, and 200 °C are preferred.

The bibliography in Section 7 includes publications on magnetic data that may be consulted for futher information.

6.6 Methods to Obtain Hysteresis Loops and Magnetization Curves

6.6.1 General Considerations. The tests described in this section are designed for use on "closed" magnetic circuits, such as toroids and ring samples, and are sometimes referred to as Rowland Ring Tests. In addition, these test procedures are applicable to the test of strips of magnetic material when placed in an Epstein Frame where the resulting data is adjusted to compensate for the end effects of butting strips in this frame. These testing procedures are for obtaining (1) dc and (2) dynamic magnetic properties of the materials to be tested.

Since the time when IEEE Std 393-1977 was written, two major changes in available instrumentation have occurred that have

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significantly changed the techniques used to measure magnetic parameters. These newer techniques yield more accurate results in less time and are, therefore, the recommended ones.

Because many organizations still own and use the instrumentation described in IEEE Std 393-1977, however, the methods recommended for using such equipment are presented in the Appendix. Since the American Society for Testing and Materials (ASTM) has covered certain aspects of this older type of instrumentation that were not considered in IEEE Std 393-1977, the Appendix also refers to certain sections of these ASTM standards.

The new instrumentation mentioned earlier are (1) extremely accurate, very stable, fully electronic integrating fluxmeters and (2) precision-adjustable bipolar electronic current supplies. The electronic fluxmeters have replaced ballistic galvanometers and/or electromechanical fluxmeters, while the bipolar supplies eliminated the use of reversing switches and current-adjusting resistors. Because of the extremely low drift rate in the presently available fluxmeters, either the hysteresis loop or the virgin magnetization curves can be obtained in one simple continuous operation rather than by the stepwise operation described in the Appendix. This continuous operation both reduces the probability of operator error and increases speed.

6.6.1.2 Test Specimen. This standard is primarily intended to be used in determining the magnetic properties of assembled magnetic cores rather than the properties of basic magnetic materials. The ring tests described in this section can be applied to closed magnetic cores of any shape and are also adaptable to cores containing either distributed or lumped air gaps, providing that the role of the air gap is properly treated in the analysis of the measured values. However, the same tests are also the basic techniques for the determination of magnetic material properties, and, for such purposes, the size and shape of the test specimen may have considerable influence on how accurately material properties can be determined.

A ring sample or toroid with a large radial width, that is, with a low ratio of inside to outside diameter, will have nonuniform flux distribution over its radial width. The measured properties, therefore, will, in general, not be representative of the material. An inside to outside diameter ratio of not less than 0.82 is suggested where material properties are to be examined. Also, ring samples are generally not acceptable for evaluating oriented or anisotropic materials. With such materials, it is usually necessary to use Epstein strips cut with their lengths in the direction of specific interest. Strip specimens can be evaluated when mounted in rectangular- or oval-shaped test forms, such as the Epstein frame. The proper preparation of strip materials to be used in such tests and methods for handling the air gaps introduced at the corners or end sections are described in ANSI/ASTM A-343-82 (86) [1].

6.6.1.3 Determination of the Basic Symmetrical Hysteresis Loop. The most convenient procedure to measure the magnetic flux flowing through a solid member like the test core is to place several turns of wire around the core and measure the time integral of the voltage induced in these turns when the flux level in the core is changed. This procedure is based upon adaptation of one of Maxwell's equations, i.e., $N\Delta 0 = Edt$, where N is the number of turns in a coil through which the flux has been changed by an amount $\Delta 0$, and E is the resulting voltage induced in these turns.

This procedure yields the change of the flux level in a magnetic circuit and not a discrete level of flux. The best way to employ this measurement technique is to drive the flux in the sample from saturation flux density in one direction to saturation in the opposite direction. The fluxmeter will then indicate the change equal to $2B_s$, where B_s is the saturation flux density of the magnetic material under test. Then intermediate values of B can be obtained on additional cycles of B from $+B_s$ to $-B_s$. The following procedure describes how to obtain a major dc hysteresis loop of the sample.

6.6.1.3.1 Elementary DC Hysteresis Loop Testing—Major Loop. An elementary tester for obtaining the dc hysteresis loop of a magnetic material is shown in Fig 18. Through the choice of the proper current capabilities for the bipolar current supply, all levels of excition and flux density can be obtained for a particular magnetic material.

Using the system of Fig 18, an operator can obtain B and H values to construct a dc hysteresis loop. B is read directly from the fluxmeter in gauss, while H is calculated

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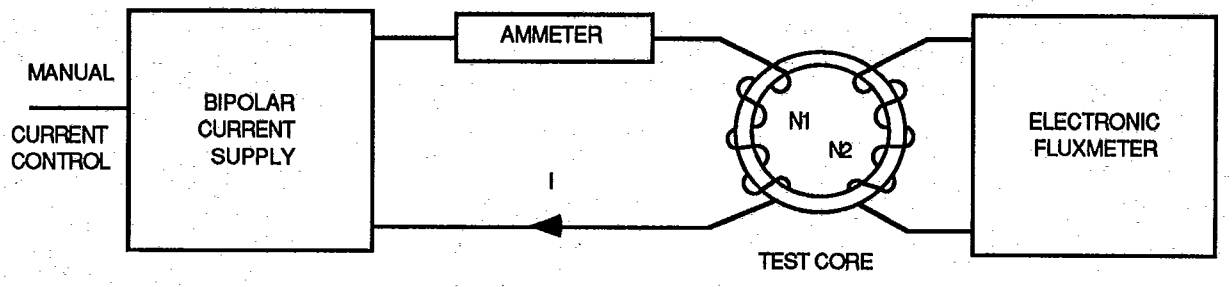


Fig 18
Elementary DC Hysteresis Loop Tester

using the relationship $H = 1.26N1/L_m$, where I is in amperes, L_m is the mean length of the ring sample in centimeters, and H is in oersteds. The CGS system of units is used here because most commercial literature for "soft" electrical steels or magnetic materials present all their data in CGS units.

The procedure recommended for operating the system of Fig 18 is as follows:

Step 1: The exciting current I should be increased from zero until the indicated B increases approximately one gauss for one additional oersted of H, where H is related to I as given above.

The sample is then saturated for practical purposes. Ten percent lesser or larger values of I will have negligible effect upon the data taken in the rest of the major hysteresis loop.

Step 2: The current reached in Step 1 should be reduced to zero and then increased in the opposite polarity until indicated B increases approximately one gauss per additional oested of H, where H is related to I as given above. The sample is then saturated. This current will be labeled $-I_s$ and may be smaller or greater in magnitude than that of the maximum current reached in Step 1, depending on the prior state of magnetization of the sample at the beginning of Step 1.

Step 3: The current should be reduced again to zero, and then increased back up to $+I_s$, which will complete one cycle of excitation. $+I_s$ may be greater or smaller in magnitude than the current level reached in Step 1, depending on the sample's magnetic condition prior to Step 1.

Step 4: Steps 1, 2, and 3 should be repeated to ensure that the material under test is on its major hysteresis loop. This second cycle can be referred to as Steps 1a, 2a, and 3a and should take at least 15 s to permit the flux to reach saturation at the end of each step. At the beginning of Step 3a, while the current is still at $+I_s$, the fluxmeter should be zeroed. Then, when the current reaches $-I_s$ at the end of Step 3a, the fluxmeter will read twice the saturation value of B; i.e., $2B_s$. Of course, the range selected for the fluxmeter should be such that the fluxmeter readings will not go off scale.

(During all of the above steps, as I progresses from $+I_s$ to $-I_s$ or from $-I_s$ to $+I_s$, the direction of progression must not be reversed. Any reversal of the direction of progression, except at $+I_s$ or $-I_s$, will introduce a minor hysteresis loop and destroy the major loop. The material under test could then be placed back onto its major hysteresis loop only by repeating Steps 1, 2, and 3 as well as Steps 1a, 2a, and 3a.)

Step 5: Upon the completion of Step 3a, the fluxmeter should be zeroed with the current at $+I_s$ and recording of data started. The current should be decreased from $+I_s$ to $-I_s$ in at least 10 equal increments where an increment would be $0.2I_s$. The resulting 10 data points will constitute one half of the major hysteresis loop. It is not necessary to obtain data points progressing from $-I_s$ to $+I_s$ because the material under test will produce a symmetrical hysteresis loop.

Although the fluxmeter will indicate $2B_s$ at the end of Step 4, the data from the fluxmeter should be interpreted and recorded as $+B_s$ and $-B_s$ with $B = 0$ being halfway between $+B_s$ and $-B_s$. Of course, $B = 0$ will not occur at $I = 0$, but

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at some negative value of I. If the material under test has a sharp "knee" in its hysteresis loop, it may be necessary to use several smaller increments, such as 0.1 I_s or even 0/01 I_s, in the current region around zero current. This can be determined only by trial and error.

6.6.1.3.2 Automated Hysteresis Loop Testing—Major Loop. The operation of the system of Fig 18 can be automated by the use of an hysteresigraph. A simplified version of a hysteresigraph is shown in Fig 19.

The current delivered by the bipolar current supply of Fig 19 can be controlled either manually or with the function generator. The function generator can deliver sinusoidal, square wave, ramp, or special function signals to the bipolar current supply. These signals can be generated at frequencies from 0.01 Hz to 20 kHz. The current shunt yields a calibrated voltage proportional to the current I from the bipolar current supply.

A recorder, either a paper X-Y recorder or an electronic oscilloscope, is used to record both the current I and the magnetic flux density B. The scaling attenuator is used to scale the shunt signal to satisfy the relationship previously mentioned, that $H = 1.26NI/L_m$. The X-Y recorder is used when a dc hysteresis loop is to be obtained along with the oscilloscope for an ac or dynamic hysteresis loop.

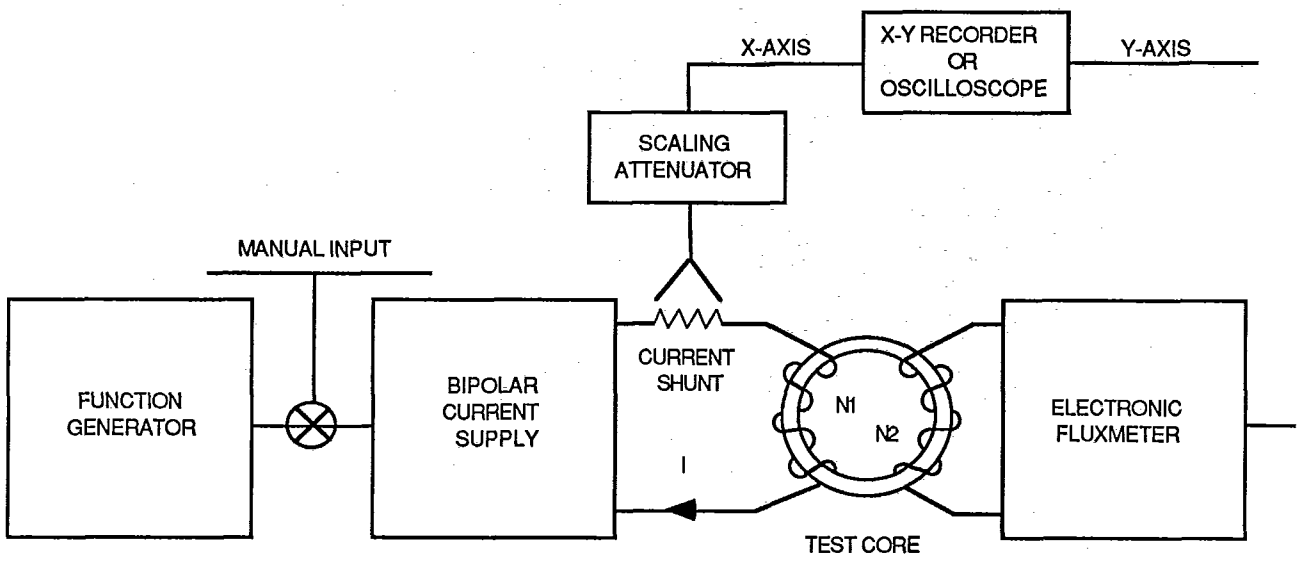
6.6.1.3.3 Automated DC Hysteresis Loop Testing. Steps 1, 2, and 3 and Steps 1a, 2a, and 3a of 6.6.1.3.1 should be carried out using the manual input to the bipolar current supply. The resulting B/H loops are plotted on paper by the X-Y recorder, which greatly simplifies data taking and the establishment of I_s. Because the initial B/H loop is not a major hysteresis loop, these initial traces or plots should not be considered final data.

Upon the completion of Step 3a above, the procedure of Step 4 of 6.1.6.3.1 should be repeated, using the manual input, with the exception that I is not changed in discrete increments, but is changed smoothly with the manual input control. The speed of change in the vicinity of zero I must be kept slow enough that the plotting pen can follow.

As with the system of Fig 18, the resulting plot does not contain the location of the B and H axes. These must be produced using the manual controls on the front panel of the X-Y recorder in the following fashion:

(1) *Y-Axis*
   (a) Lift the recorder pen off the paper;
   (b) Short-out the current shunt;

Fig 19
Simplified Hysteresigraph



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(c) Lower the pen onto the paper;
(d) Using the manual *Y*-axis control on the front panel of the recorder, drive the pen up and down on the paper to produce the *Y* or *B* axis.

(2) *X-Axis*
(a) Again, raise the pen off the paper;
(b) Zero the fluxmeter;
(c) Manually compute the zero *B* position, which will be halfway between the maximum and minimum values of plotted *B*;
(d) Using the manual controls on the recorder, the raised pen should be located at the *Y* position identified in (c);
(e) Lower the pen onto the paper;
(f) Using the recorder's manual *X*-axis control, drive the pen across the paper generating the *X* or *H* axis.

Recently a more sophisticated system has evolved, in which the same computer is used to drive the bipolar current supply, digitize the resulting *B* and *H* data, and display it in several fashions. The final records can be stored on magnetic medium or printed out with a printer. This equipment is beyond the scope of this standard at this time.

6.6.1.3.4 Minor DC Hysteresis Loop. Minor dc hysteresis loops can be obtained using lower values of maximum *I* than used in 6.6.1.3.1 and 6.6.1.3.2 and the procedures of these two sections. Such loops can be used to illustrate the effects of saturation, to study the squareness ratio, etc.

6.6.1.4 Determination of the Normal Magnetization Characteristic. The normal magnetization curve is defined as the locus of points made by the tips of hysteresis loops for decreasing values of maximum excitation. Therefore, this characteristic is obtained by first determining a number of hysteresis loops as described in the sections above for different values of the maximum excitation current *I*.

6.6.1.5 Determination of the Virgin Magnetization Curve. This characteristic is obtained from a core that is initially in a completely demagnetized state. Such demagnetization is achieved by initially applying $+I_s$ to the sample. Then a negative current of magnitude slightly less than the magnitude of $+I_s$, is applied. Following this, a positive excitation current of magnitude less than that of the preceding negative current is used. This process of applying exciting currents of alternating polarities with successively smaller magnitudes is continued until both *B* and *H* reach zero together. This demagnetization Process is most easily carried out using the system of Fig 19 with its visual record.

Once the demagnetization process is completed, the virgin magnetization curve is obtained by increasing the excitation current *I* to I_s using the manual control of either Fig 18 or Fig 19.

As with the hysteresis loop, the virgin magnetization curve may be used to derive many other magnetic parameters, including flux density, field strength, and initial permeability. Obtaining the latter parameter is one of the principal reasons for measuring the virgin magnetization. It should also be noted that to accurately determine the initial permeability, great care and precision is required in the flux and current measurements of very low magnitudes near the origin.

6.7 Direct Measurement of Flux Density

6.7.1 Hall-Effect Gaussmeter

6.7.1.1 General Considerations. The most common direct-reading flux measuring devices are based upon a class of semiconductor sensing elements that, when placed in the presence of a magnetic field, produce a change in their output parameter as a function of the flux density of the magnetic field. The most common sensor is a Hall voltage generator generally constructed of indium arsenide, indium antimonide films, etc.

The Hall gaussmeters make use of the Hall generator type of probe to obtain a signal proportional to flux density. This signal is amplified and conditioned and read out on an analog or digital indicating instrument whose scale markings are in terms of flux density, usually gauss. Calibration is achieved by means of a stable permanent magnet of known flux density or by means of calculatable air fields, such as in a long solenoid. Hall sensors or probes can be constructed to be very thin, down to approximately 0.02 in including insulation and supporting structure. However, this is still a finite thickness and thus Hall gaussmeters measure only fields in air regions and cannot directly measure the field within a magnetic material. As mentioned in 6.6.1, only fluxmeters in

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conjunction with a coil around the magnetic material can measure flux within the material.

6.7.1.2 Operation. Hall gaussmeters are used to directly measure both ac and dc flux densities in air gaps of cut cores, rotating machines, and relays; permanent magnet fields; and leakage or air flux densities associated with all magnetic devices. Accuracies of the portable type gaussmeters generally range between 1 and 3%. Measuring ranges are available from 1 G full scale to 100 kG full scale. Lower range measurements con be obtained with special designs. Limitations of Hall gaussmeters include the structural delicacy of the probes and a relatively high variation of the Hall voltage coefficient with temperature. Care should be taken to prevent damage to the Hall probes at all times, but especially when making measurements in an air gap that can change dimensions with flux density. The thinner probes have no capability of resisting any level of mechanical shock and can withstand very little compressive or tensile force. The variation of the Hall voltage (the probe output) with temperature is typically from −0.80%/°C to −1%/°C. Commercial gaussmeters have a frequency response of dc and the low-power frequencies up to about 100 kHz.

6.8 Dynamic Hysteresis Loop Measurement

6.8.1 Oscilloscope Techniques

6.8.1.1 General Considerations. One of the most useful techniques in the study of the magnetic properties of magnetic cores is the visual display of core hysteresis loops on an oscilloscope screen, for these traces can be obtained under the actual operating conditions and environment of the core and as a function of real time. Loops can be obtained over the entire frequency spectrum, from near dc up to the frequencies limited only by the measuring circuitry or the core parameters. Although this technique has been used primarily with sinusoidal excitation, it is adaptable to excitation of almost any type of waveform.

With storage scopes or similar devices, the hysteresis characteristics of a core excited by discrete pulses or discontinuous functions are readily observable. *Care must be taken when nonsinusoidal or discontinuous excitation of the core is being studied to ensure that the associated circuitry and pickup devices do not introduce extraneous effects as a result of the presence of high-frequency components and steep wavefronts. Likewise, the observed results must be interpreted more carefully under such excitation, and are not necessarily related to results with sinusoidal excitation.* This technique has been most valuable in the analysis of magnetic cores and other components used in inverter, chopper, and rectifier circuits, where nonsinusoidal waveforms are the rule.

High accuracy is generally not possible with this technique, primarily due to the small size and difficulty in accurately scaling the oscilloscope screen. Other sources of error include the frequency response of the integrator and amplifiers, and stray inductive pickup in leads and shunts.

6.8.1.2 Sinusoidal Excitation. The dynamic hysteresis loop may be obtained with two modes of excitation of the core:

6.8.1.2.1 Sine Voltage. The core is excited with a sinusoidal alternating voltage source with low output impedance to minimize distortion caused by the nonlinear exciting current. The total harmonic distortion of the induced voltage should be less than 5% to avoid distortion of the hysteresis loop.

6.8.1.2.2 Sine Current. The core is excited with a sinusoidal alternating current provided by a high-impedance source to minimize the distortion of the current wave by the voltage induced across the test coil.

The excitation source requirements are the same as for the CCFR test (see 6.5.1).

(1) *The excitation winding.* When sinusoidal voltage excitation is required, the test winding shall consist of a sufficient number of turns to keep the exciting current within the capability of the voltage source, with a maximum of 5% harmonic distortion.

When sinusoidal current excitation is desired, the number of turns is kept to a minimum. The excitation winding requirements for the CCFR test are applicable to this case.

(2) *Current pickup.* The magnetizing current shall be detected as the voltage across a resistor in series with the exciting winding. The resistance shall be so selected that it will not significantly alter the conditions of the existing circuit, particularly in the case of sinusoidal voltage excitation.

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The voltage from this resistor is applied to the horizontal deflection input of the oscilloscope, and may be scaled and amplified to provide a deflection with known constant of proportionality to the field strength. The frequency response of this channel, including all components from the measuring resistor to the display tube deflection, should be sufficient to limit any phase shift to 0.5 degrees maximum. The magnetic field strength and the exciting current are proportional, following the relation:

$$H = \frac{N \cdot I}{l_e} \text{ amperes / meter}$$

where

H = Magnetizing field strength
N = Number of turns in the excitation winding
I = Current in the winding, amperes
l_e = Effective magnetic path length in core, meters

(3) *Pickup Winding.* The pickup indications for the CCFR (6.5.1.5.1) test may be used as a guide.

The instantaneous value of the induced voltage in the pickup winding is as follows:

$$e = N\frac{d\phi}{dt} = N \cdot A_e \frac{dB}{dt} \text{ volts}$$

where

e = Instantaneous induced voltage
N = Number of turns in pickup winding
A_e = effective core cross-sectional area, m^2
$d\phi/dt$ = Time rate of change of flux in the core, webers/ second
dB/dt = Time rate of change of induction in core, teslas/ second

This voltage must be electronically integrated a voltage proportional to the instantaneous value of induction. The impedance loading the pickup coil should conform to the requirements specified in the CCFR test.

The electronic fluxmeter of Fig 19 will supply the necessary integration and will produce negligible loading on the pickup coil. In addition, the function generator of Fig 19 will provide the several types of waveform of 6.8.1.1.

6.9 Voltmeter—Ammeter Methods

6.9.1 Impedance Permeability. Impedance permeability is calculated from the total exciting current of the test core. This procedure ignores the core loss as a separate component of the magnetizing current and the calculated permeability value is based on the assumption that all the current is reactive current.

Two circuit conditions are in common use and, in general, the indicated permeability depends critically upon the circuit used. The important difference between the circuit conditions is the ratio of the primary source voltage to the induced voltage in the primary winding. Of additional importance is the response of the voltage and current-indicating instruments to nonsinusoidal waveforms.

6.9.2 Sine-Flux Test. When the impedance in the primary circuit is low, the ratio of the primary source voltage to the primary induced voltage approaches unity. With a sinusoidal source voltage, the induced voltage is nearly sinusoidal. However, the exciting current is, in the general case and especially at higher inductions, nonsinusoidal. A secondary voltage having more than 5% harmonics is considered to have deviated from sine-flux test conditions.

6.9.2.1 The circuit diagram of Fig 20 shows the components of the test circuit. The following describes each item:

(1) *Adjustable power source.* At power frequencies, this is conveniently a continuously variable autotransformer connected to the power source. For other frequencies an electronic amplifier having a low-output impedance is useful. The variable autotransformer may be omitted and the test level adjusted at the output to the amplifier.

The frequency of the source shall be known to within 1% and the harmonic content of the source shall be less than 10%.

(2) *Isolation transformer T1.* This transformer not only isolates the test circuit from the power supply for safety reasons but also establishes ground reference in the test circuit to eliminate common-mode voltages. The secondary taps permit a choice of full-scale output voltage close to the required test voltage to permit a more precise adjustment of the applied potential.

(3) *Test sample windings N1 and N2.* The primary winding may consist of any convenient number of turns. However, the

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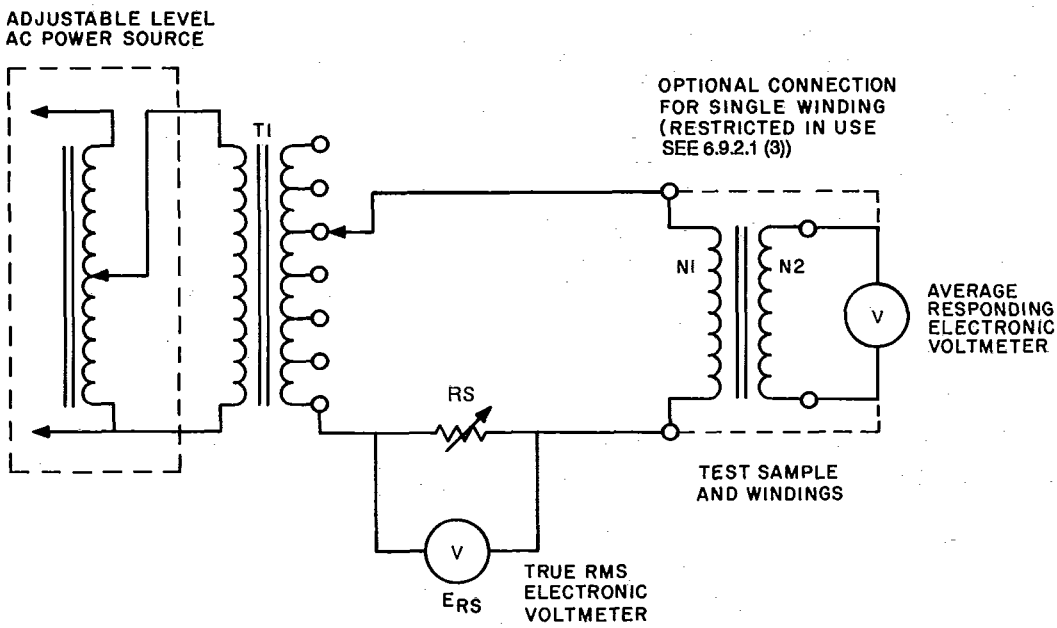


Fig 20
Sine-Flux Impedance Permeability Test

sum of the primary winding dc resistance, the current metering shunt resistance, the secondary resistance of T1 at the tap used, and the source impedance reflected through the turns ratio of T1 must be sufficiently low to meet the requirements of 6.9.2. Core specimens may be tested with only one winding if the voltage drop caused by the winding resistance is negligible.

A secondary winding, if used, must be wound as close to the core as possible. It must have a sufficient number of turns so that the induced voltage may be read with adequate precision by the associated voltmeter.

(4) *Current shunt RS.* This is most conveniently an adjustable resistance. It may be set to

$$R_s = \frac{0.01\sqrt{(2N_1)}}{l_e}$$

where N_1 is the number of primary turns and l_e is the mean magnetic path in meters.

Under this condition, the voltage across this resistance is equal to 1/100th of the impedance current excitation H_z in ampere-turns/meter such that the relative impedance permeability is

$$\mu_{ZR} = \frac{l_e}{\mu_o}\frac{B_m}{H_z}$$

where B_m is the ac induction in teslas, and μ_o is the permeability of free space = $4\pi \cdot 10^{-7}$.

For other values of R_s,

$$H_{ZR} = \frac{N_1\sqrt{2}E_{rs}}{\mu_o l_e R_s}.$$

This resistance must be capable of carrying the required excitation current without exceeding its dissipation capability within its accuracy rating. Its value should be known to ± 0.5%.

(5) *Current-indicating electronic voltmeter.* This voltmeter must indicate the true rms value of the excitation current. The accuracy of the reading shall be within ± 1%.

(6) *Induced voltage electronic voltmeter.* This voltmeter must respond to the average value of the induced voltage. Such voltmeters are usually calibrated to read 1.11 times the average value so that they indicate the rms value of a true sine wave. This voltmeter must have a high input impedance so that its current drain is not reflected significantly in the current measured by RS. The accuracy of the voltage indication shall be within ± 1%.

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6.9.3 Sine-Current Test. The sine-current test is indicated where it is inconvenient to make the primary source impedance low as compared to the sample or when the primary induced voltage is necessarily small as compared to the primary source voltage. The primary source impedance is established at a value such that the primary source voltage is at least 25 times the average voltage induced in the primary winding. Usually, the voltage drop in the primary winding resistance will be large as compared to the induced voltage. Therefore, a secondary winding is required to measure the induced voltage.

6.9.3.1 The circuit diagram of Fig 21 shows the components of the test circuit. The following is a description of each item.

(1) *Adjustable power source.* This may be the same as described in 6.9.2.1.1 except the requirement of low-source impedance is not required.

(2) *Isolation transformer, T1.* The same as described in 6.9.2.1 (2).

(3) *Test sample windings, N1, N2.* The primary winding N1 is usually as few turns as is necessary to develop the required excitation. This keeps the applied voltage from T1 at a low value.

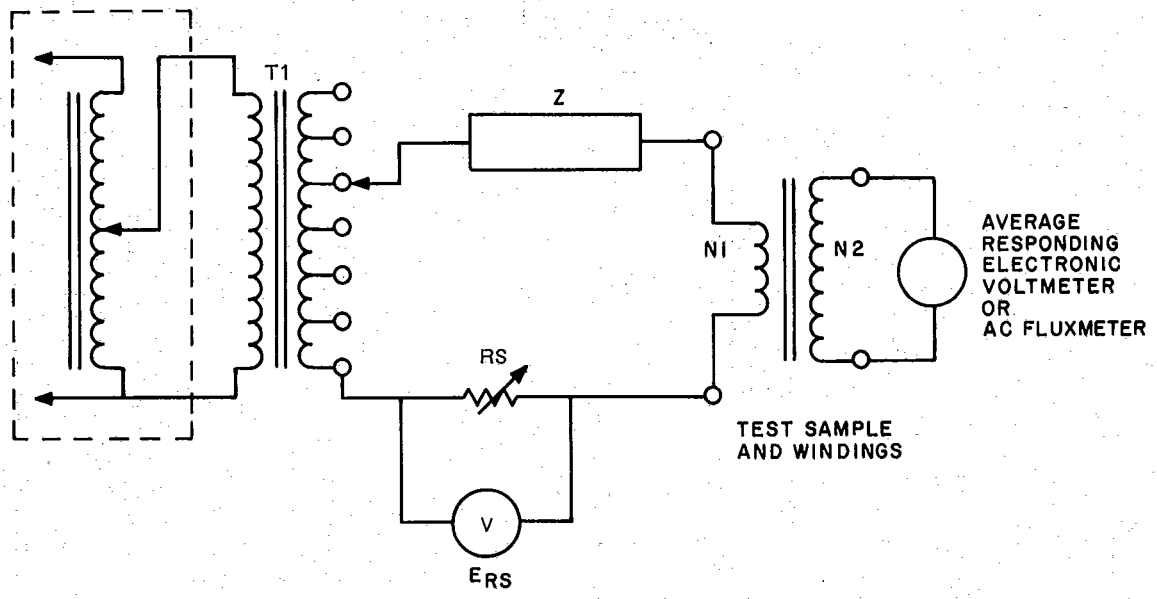
The secondary winding N2 should be wound as close to the core as possible. It may have any convenient number of turns as long as the induced voltage can be measured with adequate precision on the associated voltmeter.

(4) *Current shunt.* This resistance can be as specified in 6.9.2.1 (4) except there is no need to keep its value small. It is often convenient to make it some power of ten larger. Alternatively, the resistance and the electronic voltmeter indicator may be replaced by a moving iron or dynamometer ammeter of appropriate scale.

(5) *Current indicating electronic voltmeter.* This instrument may be as specified in 6.9.2.1 (5). However, since the current is nominally sinusoidal, the necessity of having a true rms indicating instrument disappears. An average responding instrument indicating 1.11 times the average value is acceptable.

(6) *Induced voltage electronic voltmeter.* This may be similar to the instrument specified in 6.9.2.1 (6). However, at high levels of induction, the voltage induced in some cores becomes very distorted and the waveform exhibits a high peak-to-average ratio. The circuits of some voltmeters fail to respond to the true average of such voltages. Such conditions indicate the use of an ac fluxmeter where waveform integration and measurement of the peak-to-peak value of the resulting waveform is used.

Fig 21
Sine-Current Impedance Permeability Test



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(7) *Series impedance Z.* This impedance must be large enough to constrain the current in the primary circuit to be sinusoidal. Its value must be large enough so that the total applied voltage in the primary circuit is at least 25 times the average of the voltage induced by the sample core in the primary turns.

6.9.4 Calculation of Mean Path Length. For the purpose of impedance permeability measurement, the mean path length shall be used. This is conveniently calculated as the mean of the maximum path length and the minimum path length of the flux path in the core. The units of measurement for use in the formulas are meters.

6.9.5 Calculation of Flux-Path Cross-Sectional Area. The cross-sectional area shall be determined from that portion of the core structure around which the coil is placed. It shall represent the solid material cross section. In laminated structures, uncertainties of the surface conditions between laminations make it desirable to determine the stack height from the sample weight and material density.

$$h = \frac{M}{A_s \rho}$$

where h is the stack height, in meters; M is the stack weight, in kilograms; A_s is the lamination surface area, in square meters; and ρ is the material density, in kilograms/cubic meter.

If t is the width of the section on which the test coil is placed, in meters, the cross-section area is then

$A_e = ht$ square meters.

6.9.6 Standard Test Conditions. The preferred test frequencies are the following, in hertz:

50	1000
	10 000
60	20 000
100	50 000
400	100 000

The preferred test inductions, in tesla, are $1{\cdot}10^{-4}$, $1{\cdot}10^{-3}$, $2{\cdot}10^{-3}$, $4{\cdot}10^{-3}$, $1{\cdot}10^{-2}$, 0.1, 0.2.

At each test condition, the selection of frequency and induction shall be appropriate for the material.

6.9.7 Calculations of Induced Voltage. The induced voltage at the test condition is determined by the following formula:

$$E = 4.44 B_m N f A_e$$

where

E = 1.11 times the average voltage in each half cycle;
N = Number turns in the coil on which the voltage is measured;
B_m = The induction, in teslas;
A_e = The core cross-sectional area, in square meters

6.9.8 Test Procedure

6.9.8.1 Assemble the core and the test coil.

6.9.8.2 Demagnetize the core. Demagnetization may be accomplished by means of a number of methods. At low frequencies, a high induction established with sufficient current to exceed the knee of the magnetization wave, then slowly and smoothly reduced to an induction less than the test induction.

6.9.8.3 Set the test induction. Adjust the excitation level so that the induced voltage indicator indicates the value calculated in 6.9.7. If this voltage is inadvertently exceeded, the demagnetization of 6.9.8.2 must be repeated. If more than one induction is to be measured, they shall be measured in an increasing order, that is, smallest one first.

6.9.8.4 Perform calculations. The impedance permeability is

$$\mu_z = \frac{l_e}{\mu_o} \frac{B_m}{H_z}$$

where B_m is the induction, in teslas; and H_z is the equivalent sine-wave peak excitation, in ampere turns per meter.

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This bibliography includes a listing of publications that may be consulted for further information. Required references and related standards are listed in 1.3.

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Appendix
Methods to Obtain Hysteresis Loops and Magnitization Curves With Older Equipment

(This Appendix is not a part of IEEE Std 393-1991, IEEE Standard for Test Procedures for Magnetic Cores, but is included for information only.)

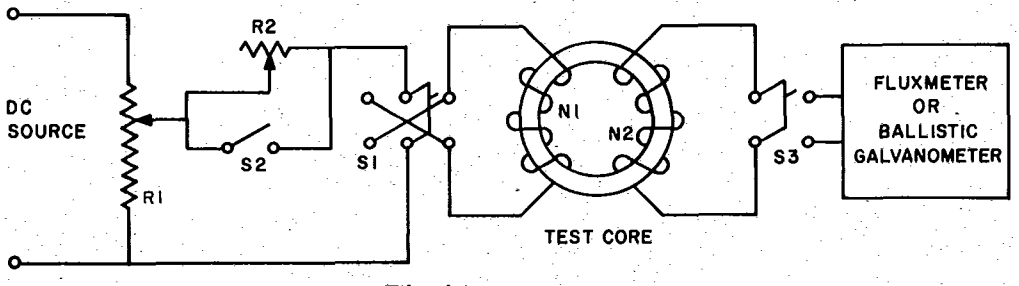


Fig A1
Hysteresis Loop Test Circuit

A1. Determination of the Basic Symmetrical Hysteresis Loop

Figure A1 illustrates a simple form of a circuit capable of determining the core or material hysteresis loop as well as many other magnetic properties at all levels of excitation and flux density. This circuit can be modified or made more automatic depending upon the time and equipment available for the test. For example, when a laminated or powdered core is to be tested, a variable ac source (such as a variable autotransformer) can be introduced at switch 1 for the purpose of faster demagnetization. Likewise, if no instrument calibration is available, a standard mutual inductor can be introduced for this purpose. Electronic fluxmeters contain calibrating circuits and the mechanically integrating type of fluxmeter have external calibrating devices that generally make such a technique unnecessary.

Changing the position of S1 will generate an arc that could produce sufficient RF energy to cause an error in the output of an electronic fluxmeter. This arcing should be reduced to a minimum, compatible with the fluxmeter error that can be tolerated, by the use of suppression components on the contacts of S1 or by the use of a form of S1 that has mercury-wetted contacts.

A1.1 Components Required. The components required in Fig A1 are as follows:

(1) *DC voltage source.* This should be an unregulated supply, preferably a battery, in order to eliminate any compensation or modification of the voltage as the step changes of current are made during the test.

(2) *Resistors, R1 and R2.* These may be of any type capable of handling the current levels to be used during the test.

(3) *Switches, S1, S2, and S3.* Likewise, these devices should be chosen mainly on the basis of current-carrying capacity. Switch S3 is often a part of the sensing instrument and contained in that package; it requires a negligible current-carrying capacity. All switches must have no contact bounce.

(4) *Excitation winding, N1.* For the determination of material properties, this winding should be uniformly distributed around the entire magnetic circuit in order to reduce leakage and produce uniform excitation of the magnetic material. For the determination of core properties, the coil configuration should be as close to that of the application in which the core is to be used as possible. The number of turns in the coil must be determined on the basis of required excitation levels desired and the current levels to be used.

(5) *Sensing coil, N2.* For use with both ballistic galvanometers and fluxmeters, the required current-carrying capacity of this coil is negligible, but the coil resistance is important for the proper operation of the sensing instrument. The permissible range of resistance for proper instrument operation is

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generally specified by the instrument manufacturer and must be considered in designing this coil. Again, for determining material properties, it is desirable to have this coil distributed along the entire magnetic circuit length.

(6) *Ammeter.* This should be of the d'Arsonval type with high accuracy.

The determination of a hysteresis loop consists of three basic steps: sample demagnetization, establishing a specific loop, and the step-by-step determination of points on the specific loop. Note that the resulting measured values using either a ballistic galvanometer or fluxmeter are magnetic flux (webers or volt-seconds) as a function of exciting amperes (or exciting ampere-turns when N1 is known). Flux density, magnetic field strength, and various permeabilities can often be derived from the basic loop if the core dimensions and stacking factor are accurately known. See Section 5 of this standard for definitions and formula.

Before proceeding with the test, the operation and protection of the sensing instrument should be studied. Both types of instruments are extremely delicate and must be handled with great care. In general, the mechanical integrating fluxmeter and the ballistic galvanometer can be used only on level surfaces and leveling devices are usually contained within the instrument. However, both types of fluxmeters are portable. Ballistic galvanometers are especially sensitive to vibration and are often mechanically isolated from the structure on which they are mounted. The time constants associated with the deflection and indication of ballistic galvanometers vary with the instrument sensitivity and are generally long. The mechanical-integrating fluxmeter indication is near instantaneous, but the instrument pointer or light tends to drift considerably almost immediately after a reading has been made. Electronic fluxmeters are generally free from both of these nuisances.

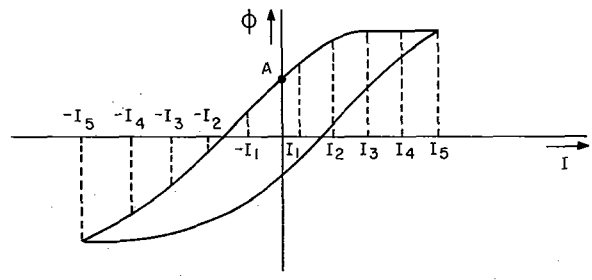
A1.2 Procedure. The procedure for determining a symmetrical hysteresis loop is as follows:

(1) *Demagnetization.* With S3 open, S2 closed, and S1 in either position, adjust the current in N1 by means of R1 (or other means of controlling the source voltage) to a value high enough to saturate the magnetic circuit. Then alternate the position of S1 while slowly reducing the source voltage by means of R1 until there is zero voltage applied to N1. As noted above, this process can be greatly speeded up using variable ac source for this purpose, except when the core is of large size and solid material.

(2) *Setting the specific loop excitation.* For this process, refer to Fig A2, which shows a typical set of excitation levels, I_1–I_5. The number and magnitude of these excitation values is determined by the requirements of the specific test to be performed. With S3 open, S2 and S1 closed, and R2 set at its minimum value, adjust the source voltage to give the maximum desired excitation level, I_5, in the exciting coil N1. Then open S2 and adjust R2 to give the next largest exciting current, I_4. Mark this setting of R2 so that it can be repeated. Repeat this process of obtaining R2 settings for the remaining exciting current levels, marking each setting. Open S1. Unless this process has been performed in such a manner as to give only monotonically changing current in N1, which is normally very difficult, the demagnetization setup, above, should be repeated. Now, with the source back at its setting required to give the maximum current, I_5, with S3 open and S2 closed, close S1. Alternate the position of S1 a number of times, which causes the current in N1 to reverse between plus and minus maximum values. This establishes a stable hysteresis loop in the core.

(3) *Measurements.* Throughout the entire remaining portion of the test during which the magnetic measurements are obtained, a very specific switching routine must be observed in order to "stay on the loop" that was set up in the preceding step. If any error is made in going

Fig A2
Hysteresis Loop



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through this sequence, minor hysteresis loops will be traversed and the readings will be meaningless in terms of the major loop of Fig A2. When a mistake is made, the core should be demagnetized and the process begun new. The sequence is as follows: The conditions of the circuit at the end of step (2) and above (S3 open, S2 closed, and S1 closed in either position) results in the maximum exciting current, I_5, flowing through N1. This current may arbitrarily be defined as the positive (or negative) I_5, and represents the starting point for traversing the hysteresis loop. Next, set R2 on the value that will result in the next value of exciting current, I_4. Close S3. Quickly open S2, noting the resulting indication on the sensing instrument. Also, accurately read and record both currents, I_5 and I_4. Using the proper instrument calibration factors, the sensing instrument reading can be related to the *change* of flux in the core as the current changes from I_5 to I_4. The accuracy of the overall measurement is largely dependent upon the accuracy of the current measurement. Next, traverse the loop in a counterclockwise manner to get back to the starting point or I_5. This is done by opening S1, which gives position *A* in Fig A2; next, close S2; close S1 in the opposite position, which gives the $-I_5$ position in Fig A2; then reverse S1 to its original closed position, which returns the core to the I_5 position or the beginning of the loop. Now, set R2 to its second value, which will result in current, I_3. Quickly open S2, and read the *change* in flux for a current change of I_5 to I_3. Then return the core in a counterclockwise manner as above to the beginning of the loop and repeat for I_2. This process is repeated until the final step, which is when the current is changed from I_5 to zero. The data so obtained permit one to plot the first quadrant points of the loop. The remaining half of the upper trace of the loop is obtained as follows: Starting from position *A*, which is the last condition set in obtaining the first quadrant points, make sure R2 is still in its maximum setting and that S2 is open, and then close S1 to its opposite position, and note the indication on the sensing instrument. This gives flux change for a current change from zero to $-I_1$. The loop is then traversed back to point *A* in a clockwise manner and then the flux change from zero to $-I_2$ can be read in a similar manner. By repeating this process, the remaining points on the upper half of the loop can be determined. Since loop symmetry has been assumed, the lower half of the loop trace can be plotted as the mirror image of the upper half.

Other magnetic parameters can be derived from the flux versus current hysteresis loop, such as flux density, magnetic field strength, incremental permeability, amplitude permeability, etc. See Section 5 for the formulas used in these calculations. Also, the above hysteresis loop may be repeated at different values of maximum excitation to illustrate the effects of saturation, to study the squareness ratio, etc.

A2. Determination of the Normal Magnetization Characteristic

The normal magnetization curve is defined as the locus of points made by the tips of hysteresis loops for decreasing values of maximum excitation. Therefore, this characteristic is obtained by first determining a number of hysteresis loops as described in A1 for different values of the maximum excitation current, I_5.

A3. Determination of the Virgin Magnetization Curve

This characteristic is obtained from a core that is initially in a completely demagnetized state. The circuit of Fig A1 and a switching technique similar to that used in obtaining symmetrical hysteresis loops are also applicable for obtaining the virgin magnetization curve. This curve is generally plotted in the first quadrant only, since there is symmetry about the origin. Measurements by this technique are again in terms of magnetic flux (webers) and current (amperes) as for the hysteresis loop measurements. The procedure is as follows:

Resistance R2 is again used to determine the exciting current values, I_1–I_5. These values must be preset and marked on the resistance before proceeding with the test, as in step (2) of the hysteresis loop procedure in A1.2. The core is next demagnetized, which brings the magnetic state to the origin of Fig A2. Switch S3 should remain open during both of these steps

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to protect the sensing instrument. Following demagnetization, open S1 and reset R1 or the voltage source to its initial condition. This condition should be that which results in a current through N1 of I_5 A with R2 at its minimum value. To proceed with the test, set R2 at its maximum value, close S3, and open S2. Quickly close S1 to either closed position and read the sensing instrument and ammeter. These readings will give, using proper instrument calibration factors, the value of magnetic flux in the core resulting from current I_1. With no other change in the circuit from this condition, suddenly change the value of R2 to its next lesser value, that is, the value which results in current I_2, and read the instruments as before. These readings give the *change in flux* due to an exciting current change of I_1 to I_2. This process is repeated until I_5 is reached.

As with the hysteresis loop, the virgin magnetization curve may be used to derive many other magnetic parameters, including flux density, field strength, and initial permeability. Obtaining the latter parameter is one of the principal reasons for measuring the virgin magnetization. It should also be noted that to accurately determine the initial permeability, great care and precision is required in the flux and current measurements of very low magnitudes near the origin.

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