

IEEE Standard Test Procedures for Magnetic Cores

May 27, 1977

SH06189



THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, Inc.

IEEE Standard for Test Procedures for Magnetic Cores

1. Scope

This publication specifies applicable tests to describe the significant properties of magnetic cores used in electronic applications. This publication 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 Publication Applies

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

1.2 Specific Applications to Which this Publication 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, saturating inductors.

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

1.3 Related Standards

1.3.1 IEEE Std 111-1970, Standard for Low-Power Wide-Band Transformers.

1.3.2 IEEE Std 264-1977 Standard for High-Power Wide-Band Transformers (100 W and above).

1.3.3 IEEE Std 272-1967, Standard for Computer Type (Square-Loop) Pulse Transformers.

1.3.4 IEEE Std 295-1969, Standard for Electronics Power Transformers.

1.3.5 IEEE Std 306-1969, Test Procedure for Charging Inductors.

1.3.6 IEEE Std 390-1975, Standard for Low-Pulse Transformers.

1.3.7 ASTM STP 371 S1-1970, Direct-Current Measurements for Soft Magnetic Materials.¹

1.3.8 ASTM 598-60-1959, Standard Method of Test for Magnetic Properties of Magnetic Amplifier Cores.

1.3.9 ASTM Standards Relating to Magnetic Properties: A345-55, A34-68, A341-69, A342-64, A343-69, A344-68, A346-64, A347-68, A348-68, A349-68, A566-68, A596-69, A598-69, A340-65.

1.3.10 MPIF 24-66-1966, Electrical Parameter of Powder Ferrite Cores-Measurement and Presentation.²

1.3.11 IEC 125-1961, General Classification of Ferromagnetic Oxide Materials and Definitions of Terms.³

1.3.12 IEC 218-1966, Guide for the Drafting of Performance Specifications for Cores of Tuned Transformers and Inductors of Ferromagnetic Oxides for Telecommunication.

2. Definitions

Electrical and magnetic terms used in this Standard are in accordance with those given in IEEE Std 100-1972 Dictionary of Electrical and Electronics Terms (ANSI C42.100-1972). Certain parameters of particular significance in the application and evaluation of magnetic

¹ASTM documents are available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pa. 19103.

²MPIF documents are available from Metal Power Industries Federation, 201 East 42nd Street, New York, N.Y. 10017.

³IEC documents are available from the American National Standards Institute, 1430 Broadway, New York, N.Y. 10018.

cores as well as certain terms not included in IEEE Std 100-1972 are further discussed in Section 5., Symbols and Terms, p. 7 of this Standard.

3. Configurations

3.1 The configuration or geometry of the core material has a decided effect on the magnetic properties of the finished product. For example, 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 For reference, the following are recognized as the basic core shapes in which tests are performed:

3.2.1 *Toroid.* Stack of ring stampings (no effective gap); spiral wound strip (very small effective gap); pressed or molded (toroids, beads, tubes).

3.2.2 *Cut Strip-Wound* (C and E cores).

3.2.3 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.

3.2.4 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 — 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

(a) Flat-rolled sheet or strip, for example, silicon-iron, nickel-iron, cobalt-iron

(b) Powdered permalloy (powdered molybdenum-nickel-iron alloy)

(c) Powdered iron.

4.2 Ferrites

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

5. Symbols and Terms

<i>Symbol</i>	<i>Term and (Unit)</i>
a	Hysteresis loss coefficient in Legg's equation (tesla).
A_e	Effective crosssectional area, see Section 5.1 (S I 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. (S I 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.
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. (S I unit: amperes/meter; CGS unit: oersted. 1 Oe = 79.577 A/m).
ΔH	Total cyclic change in field strength, often in the presence of a static magnetic field.
dH	Differential notation for magnetic field strength.
H	Vector representation of the magnetic field strength.
H_c	Coercive force.

H_z	RMS value of the magnetic field strength.
$\hat{i}$	Peak value of the current (amperes).
j	$\sqrt{-1}$
L_0	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 Section 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 ($^{\circ}\text{C}$).
T_c	Curie temperature ($^{\circ}\text{C}$).
$\tan \delta_n$	Tangent of the loss angle.
V_e	Effective volume (cubic meters); see Section 5-1.
α	Turns factor.
δ_n	Loss angle.
μ	Permeability (henry/meter).
$\vec{\mu}$	Permeability vector.
μ_a	Relative amplitude permeability. ¹
μ_i	Relative initial permeability. ¹
μ_0	Magnetic constant, permeability of free space. ($4\pi \cdot 10^{-7}$ henry/meter).
$\bar{\mu}$	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.

¹In the case of qualified versions of permeability, such as pulse permeability, μ_{π} , the relative quantity is meant, unless otherwise stated.

η_i	Hysteresis core constant.
ω	Angular frequency (radians/second).

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:

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 100-1972 (ANSI C42.100-1972) or IEEE Std 270-1966, Definitions of General (Fundamental and Derived) Electrical and Electronics Terms.

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.

$$\mu_i = \frac{1}{\mu_0} \lim_{H \rightarrow 0} \frac{B}{H}$$

When B and H are in CGS units, $\mu_0 = 1$; 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.

$$\mu_a = \frac{1}{\mu_0} \frac{B}{H}$$

μ_a = relative amplitude permeability.

5.2.3 Maximum Permeability. The maximum value of the amplitude permeability as a function of the field strength (or of the induction).

***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.

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

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

μ_{Δ} relative incremental permeability
 ΔH total cyclic variation of the magnetic field strength
 ΔB corresponding total cyclic change in induction.

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.

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

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:

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

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.

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

μ_{dif} relative differential permeability
 dH infinitely small change in field strength
 dB corresponding change induction.

***5.2.8 Impedance Permeability.** An 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

$H_z = \sqrt{2} NI/1$ equivalent peak field strength, amperes/meters
 B_i maximum intrinsic flux density, tesla
 I rms exciting current, amperes
 N exciting coil turns.

5.2.9 Peak Permeability.

$$\mu_{pk} = \frac{B_i}{H_{pk} \mu_o}; \quad H_{pk} = N_i/1.$$

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 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).

$$\begin{aligned} L_s &= \mu'_s L_o \\ R_s &= \omega \mu''_s L_o \\ Z &= R_s + j\omega L_s = j\omega \bar{\mu} L_o \end{aligned}$$

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).

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

- $\bar{\mu}$ 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 paragraphs 5.2.6, 5.5, and 5.6.

5.7.1 Relative Dissipation Factor. 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 100-1972 (ANSI C42.100-1972) for general definition.

For inductive devices it 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:

$$\frac{R_s}{\mu f L_s} = a B + e f + c$$

- a hysteresis loss coefficient,² (tesla)⁻¹
- e eddy current coefficient, seconds
- 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.

S.I. Unit: tesla C G S Unit: gauss (1 T = 10⁴ 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 which is symmetrically 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 airgaps 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 6.2.4.7 and 6.5.2.6.

5.11 Coercive Force H_c . The magnetic field strength at which the magnetic induction is zero, when the core material is in a symmet-

²When C G S units are used, coefficient a has the units of (gauss)⁻¹.

rically cyclically magnetized condition, with a specified maximum value of field strength (for example, loci of points on the hysteresis curve when $B = 0$). See paragraph 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.

(a) Between two given temperatures: (mean coefficient). The relative variation of the quantity considered, divided by the difference in temperature producing it.

(b) 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:

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

$\Delta \mu$ 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.

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

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:

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

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.

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

A_L induction factor, henrys/turns²

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.

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

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.

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

η_i hysteresis core constant (A⁻¹ H^{-1/2})
 $\tan \delta_\eta$ tangent of loss angle due to hysteresis only
 $\hat{i}$ 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 Pulse 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 Section 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 which may be current (I) or voltage (V).

(a) *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 percent and 90 percent of (A_M) and a straight line which 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 .

(b) *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 percent and 90 percent of A_M . Limits other than 10 percent and 90 percent may be specified in special cases.

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

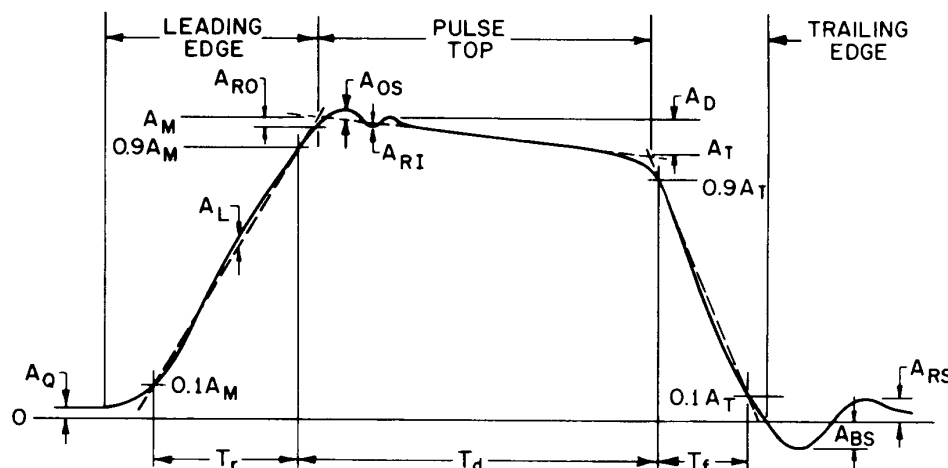


Fig 1
Reference Pulse Shape

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 percent of A_M . (2) Pulse duration may be specified at a value other than 90 percent of A_M and A_T in special cases.

(d) **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 percent and 10 percent of A_T .

(e) **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 percent and 10 percent of A_T and the straight line segment fitted to the top of the pulse in determining A_M .

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

(g) **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 .

(h) **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 .

(i) **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 .

(j) **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 .

(k) **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 .

(l) **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 percent and 90 percent A_M amplitude points used in determining rise time. It is expressed in amplitude units or in percent of $0.8 A_M$.

(m) **quiescent value (base magnitude) (A_Q)**. The maximum value existing between pulses.

(n) **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 .

(o) *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 .

(p) *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 Section 6.2.4.

6.2.2 Pulse Magnetization Characteristics

6.2.2.1 General Considerations. The non-linear 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.

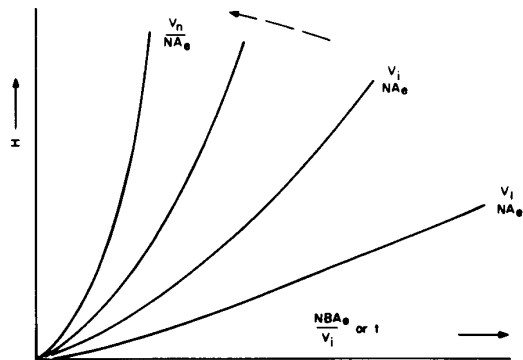


Fig 2
Pulse Magnetization Characteristic

Symbols in Fig 2 denote the following:

- H magnetizing force, in amperes per meter
- t time, in seconds, from application of excitation
- V_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 degree Celsius.

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

$$V_1 < V_2 < \dots V_i < \dots V_n.$$

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

$$v = N \frac{d\Phi}{dt} \quad (\text{Eq 1})$$

where v 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

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

$$dB = \frac{v dt}{N A_e} \quad (\text{Eq 2})$$

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

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

so that

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

Substituting Eq (3) in Eq (2):

$$\mu_\Delta dH = \frac{v dt}{N A_e}$$

$$dH = \frac{1}{\mu_\Delta} \cdot \frac{v dt}{N A_e} \quad (\text{Eq 4})$$

For the practical purposes of this test, consider a constant applied voltage, V_i , and rewrite Eq (4) with $v = V_i$.

$$dH = \frac{1}{\mu_\Delta} \cdot \frac{V_i dt}{N A_e} \quad (\text{Eq 5})$$

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 percent during the necessary time interval is shown in

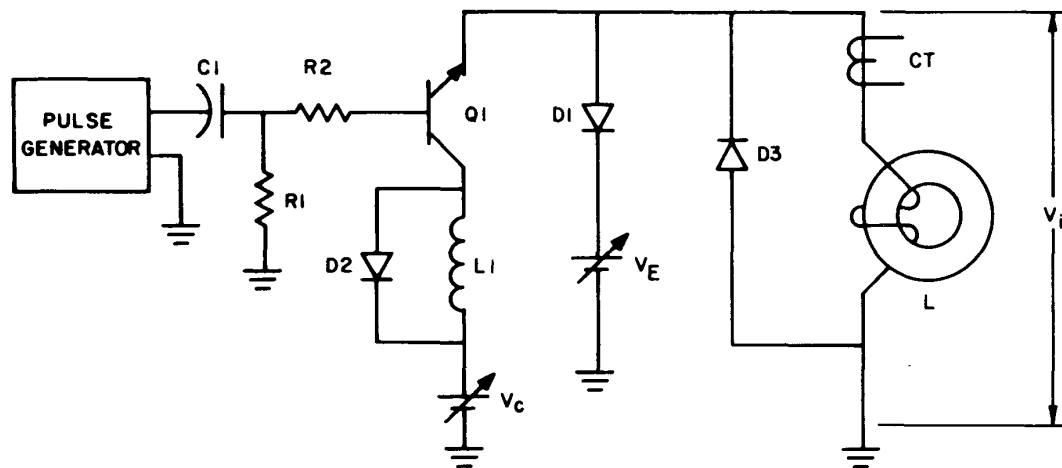


Fig 3
Test Circuit A

Fig 3 [1]. 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:
 $Q1 = 2N3253$; $R1 = 3300\ \Omega$; $R2 = 47\ \Omega$;
 $C1 = 0.05\ \mu F$.

$R1$ 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 characteristics, 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 V_E , is to maintain the constant voltage, V_i , across the test sample, L , throughout the measurement interval. The voltage, V_i , is equal to the sum of V_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 V_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. V_c , as the test sample demands it, and thus does prolong the conduction of the cur-

rent sink with its constant voltage characteristic.

V_E is initially adjusted to the desired value of V_i less the value of the forward voltage drop of $D1$. V_c is adjusted to minimize the droop of V_i .

The circuit of Fig 4 is more convenient for the usual laboratory or production testing [2]. It is a transistor switch which connects the constant voltage source, V_{cc} , across the test core winding. The tilt associated with this circuit is of the order of 1 percent. 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 $V_i = V_{cc} - V_{ce}$, 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: $R1 = 51\ \Omega$; $R2 = 300\ \Omega$; $R3 = 47\ \Omega$; $R4 = 100\ \Omega$ (all resistors are $\frac{1}{2}$ W, noninductive); $C1 = 500\ pF$; $C2 = 50\ \mu F$, 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 magnetiza-

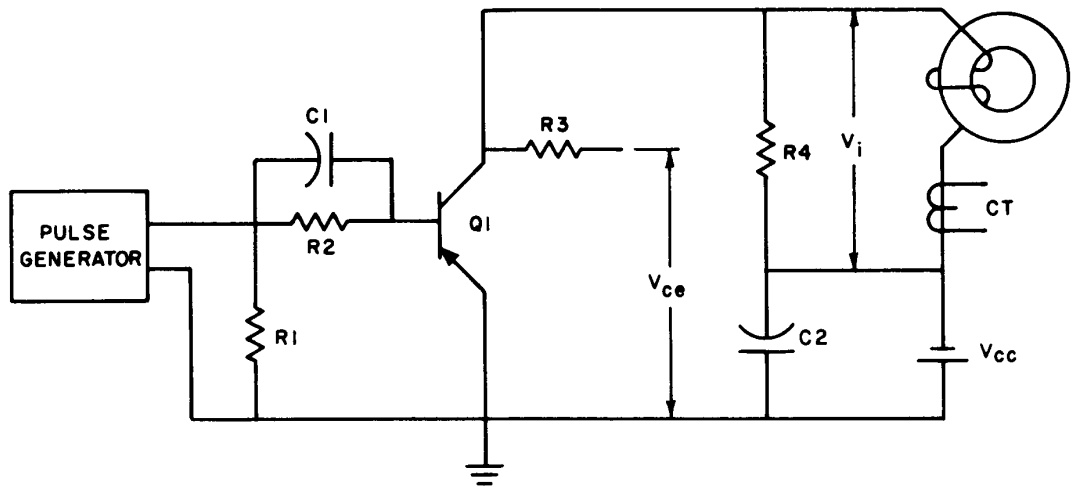


Fig 4
Test Circuit B

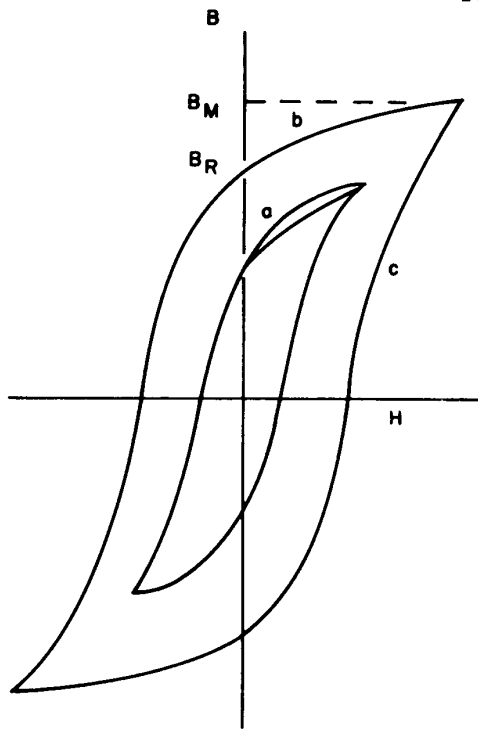


Fig 5
Pulse Magnetization Characteristics on
Major and Minor Loops

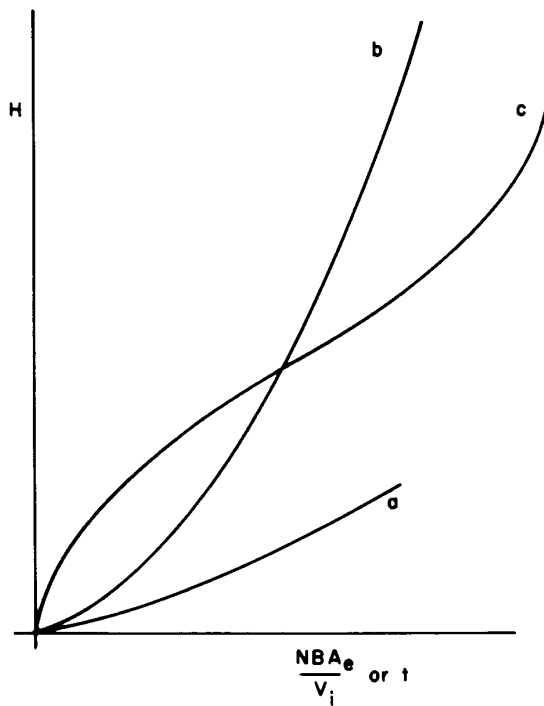


Fig 6
Pulse Magnetization Characteristics with Reset

tion 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). Figs 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.

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 will 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.

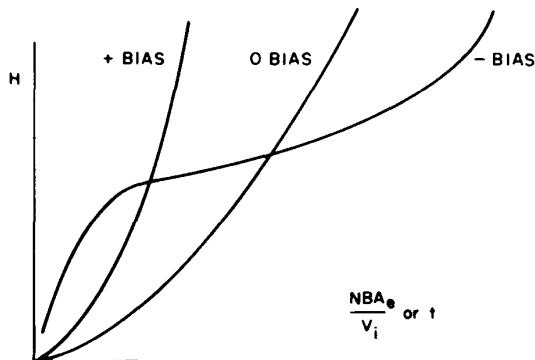


Fig 7
Pulse Magnetization Characteristics
With and Without Bias

Fig 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.

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.

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 $\pm 2^\circ\text{C}$ throughout the measurements.

Time Interval. If v is set equal to V_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.

Voltage Increments. The curves will be generated for uniform increments of V_i/NA_e over a span suitable for the material such as 2×10^4 , 4×10^4 , 6×10^4 , ..., 16×10^4 , 18×10^4 , 20×10^4 .

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, twenty-five (25) turns are recommended. For high permeability cores, five (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.

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.