

IEEE Standard for Test Procedures for Magnetic Cores

Circuits and Devices

Communications Technology

Computer

*Electromagnetics and
Radiation*

Energy and Power

IEEE Power Electronics Society

Sponsored by the
Electronics Transformer Technical Committee

*Signals and
Applications*

IEEE Std 393-1991



Published by the Institute of Electrical and Electronics Engineers, Inc., 345 East 47th Street, New York, NY 10017, USA.

March 10, 1992

SH14514

IEEE Standard for Test Procedures for Magnetic Cores

Sponsor
**Electronics Transformer Technical Committee
of the
IEEE Power Electronics Society**

Reaffirmed 26 September 2007
Approved 27 June 1991

IEEE-SA 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

The Institute of Electrical and Electronics Engineers, Inc.
345 East 47th Street, New York, NY 10017-2394, USA

©1992 by the Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 1992
Printed in the United State of America

**Library of Congress Cataloging in Publication Data
will be found on the following pages.**

*No part of this publication may be reproduced in any form,
in an electronic retrieval system or otherwise,
without the prior written permission of the publisher*

IEEE Standards documents are developed within the Technical Committees of the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Board. Members of the committees serve voluntarily and without compensation. They are not necessarily members of the Institute. The standards developed within IEEE represent a consensus of the broad expertise on the subject within the Institute as well as those activities outside of IEEE which have expressed an interest in participating in the development of the standard.

Use of an IEEE Standard is wholly voluntary. The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE Standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE Standard is subjected to review at least every five years for revision or reaffirmation. When a document is more than five years old, and has not been reaffirmed, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE Standard.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of all concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason IEEE and the members of its technical committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration.

Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE Standards Board
445 Hoes Lane
P.O. Box 1331
Piscataway, NJ 08555-1331
USA

IEEE Standards documents are adopted by the Institute of Electrical and Electronics Engineers without regard to whether their adoption may involve patents on articles, materials, or processes. Such adoption does not assume any liability to any patent owner, nor does it assume any obligation whatever to parties adopting the standards documents.

Library of Congress Cataloging in Publication Data

Institute of Electrical and Electronics Engineers.

IEEE standard for test procedures for magnetic cores / sponsor, Electronics Transformer Technical Committee of the IEEE Power Electronics Society.

p. cm.

"Approved June 27, 1991, IEEE Standards Board; approved December 9, 1991, American National Standards Institute."

Includes bibliographical references.

"IEEE Std 393-1991 (revision of IEEE Std 393-1977)."

ISBN 1-55937-143-9

1. Magnetic cores—Testing—Standards—United States. I. IEEE Power Electronics Society. Electronics Transformer Technical Committee. II. Title. TK7872.M25I53 1992

621.3973—dc20

92-2892
CIP

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.

John Silgailis, *Chair*

J. S. Andresen
R. P. Carey
Charles J. Elliott

Herman Fickenschner
P. K. Goethe

Harold E. Lee
Robert L. Sell
John Tardy

The following persons were on the balloting committee that approved this standard for submission to the IEEE Standards Board:

E. D. Belanger
R. P. Carey
Charles J. Elliott
Herman Fickenschner
R. Fisher
Rolf Frantz
P. K. Goethe
Nathan Grossner

O. Kiltie
L. Kirkwood
Harold E. Lee
Rueben Lee
H. W. Lord
William Lucarcz
R. G. Noah
David N. Ratliff

Robert L. Sell
John Silgailis
John Tardy
Ray Taylor
Bruce Thackwray
H. Tillinger
R. G. Wolpert
R. M. Wozniak

When the IEEE Standards Board approved this standard on June 27, 1991, it had the following membership:

Marco W. Migliaro, *Chair*

Donald C. Loughry, *Vice Chair*

Andrew G. Salem, *Secretary*

Dennis Bodson
Paul L. Borrill
Clyde Camp
James M. Daly
Donald C. Fleckenstein
Jay Forster*
David F. Franklin
Ingrid Fromm

Thomas L. Hannan
Donald N. Heirman
Kenneth D. Hendrix
John W. Horch
Ben C. Johnson
Ivor N. Knight
Joseph Koepfinger*
Irving Kolodny
Michael A. Lawler

John E. May, Jr.
Lawrence V. McCall
T. Don Michael*
Stig L. Nilsson
John L. Rankine
Ronald H. Reimer
Gary S. Robinson
Terrance R. Whittemore

*Member Emeritus

Kristin M. Dittmann
IEEE Standards Department Project Editor

Contents

SECTION	PAGE
1. Scope	9
1.1 Specific Types of Magnetic Cores to Which this Standard Applies.....	9
1.2 Specific Applications to Which this Standard Is Directed.....	9
1.3 References and Related Standards	9
1.3.1 References	9
1.3.2 General Related Standards.....	9
2. Definitions.....	10
3. Configurations.....	10
3.1 Effect of the Configuration or Geometry of the Core Material on Finished Product	10
3.2 Basic Core Shapes	11
3.3 Epstein Strip Core	11
4. Materials.....	11
4.1 Ferromagnetic	11
4.2 Ferrites.....	11
5. Symbols and Terms	12
5.1 Effective Parameters.....	12
5.2 Permeability.....	12
5.2.1 Initial Permeability	12
5.2.2 Amplitude Permeability	12
5.2.3 Maximum Permeability.....	12
5.2.4 Incremental Permeability.....	13
5.2.5 Pulse Permeability	13
5.2.6 Complex Permeability	13
5.2.7 Differential Permeability	13
5.2.8 Impedance Permeability.....	13
5.2.9 Peak Permeability.....	13
5.3 Core Loss	13
5.3.1 Specific Core Loss	13
5.4 Apparent Core Loss	13
5.4.1 Specific Apparent Core Loss	14
5.5 Equivalent Series Circuit Elements	14
5.6 Equivalent Parallel Circuit Elements	14
5.7 Loss Angle (Dissipation Factor)	14
5.7.1 Relative Dissipation Factor	14
5.7.2 Quality Factor, Q	14
5.8 Legg's Equation Parameters	14
5.9 Saturation Induction, B_s	15
5.9.1 Peak Induction, B_m	15
5.10 Residual Induction, B_r	15
5.10.1 Remanent Induction	15
5.10.2 Squareness Ratio	15
5.11 Coercive Field or Force, H_c	15
5.12 H_1 and H_2 Reset Field Strengths	15
5.12.1 ΔH	15
5.12.2 Reset Gain, G	15
5.13 Temperature Coefficient.....	15

SECTION	PAGE
5.14 Temperature Factor of Permeability	15
5.15 Curie Temperature or Curie Point, T_c	15
5.16 Disaccommodation	15
5.16.1 Disaccommodation Factor	16
5.17 Magnetic Aging	16
5.18 Turns Factor	16
5.19 Induction Factor, A_L	16
5.20 Volt—Second-Area	16
5.21 Hysteresis Constant, η_h	16
5.21.1 Hysteresis Core Constant, η_i	16
6. Test Methods	17
6.1 Permeability Measurements	17
6.2 Tests for Evaluating Cores With Pulsed Excitation	17
6.2.1 Reference Pulse Shape	17
6.2.2 Pulse Magnetization Characteristics	18
6.2.3 Pulse Permeability	24
6.2.4 Tests for Computer-Type Cores Used in Switching and Memory Applications	24
6.3 Bridge Measurements	29
6.3.1 Series Bridge, Low Impedance	30
6.3.2 Series Bridge (Low Q)	30
6.3.3 Parallel Bridge (High Q)	31
6.3.4 Parallel Bridge (Low Q)	31
6.4 Core Loss and Apparent Core Loss	31
6.4.1 Core-Loss Measurements With Sinusoidal/Voltage Excitation	31
6.4.2 Core-Loss Measurements in Core Excited by Nonsinusoidal Signals	31
6.5 Saturating Core Tests	36
6.5.1 Constant-Current Flux-Reset (CCFR) Core Test Method	36
6.5.2 Sine-Current-Excitation Core Test Method	39
6.5.3 Presenting Magnetic Data on Core Materials	44
6.6 Methods to Obtain Hysteresis Loops and Magnetization Curves	44
6.6.1 General Considerations	44
6.7 Direct Measurement of Flux Density	48
6.7.1 Hall-Effect Gaussmeter	48
6.8 Dynamic Hysteresis Loop Measurement	49
6.8.1 Oscilloscope Techniques	49
6.9 Voltmeter—Ammeter Methods	50
6.9.1 Impedance Permeability	50
6.9.2 Sine-Flux Test	50
6.9.3 Sine-Current Test	52
6.9.4 Calculation of Mean Path Length	53
6.9.5 Calculation of Flux-Path Cross-Sectional Area	53
6.9.6 Standard Test Conditions	53
6.9.7 Calculations of Induced Voltage	53
6.9.8 Test Procedure	53
7. Bibliography	53

FIGURES	PAGE
Fig 1	Reference Pulse Shape 18
Fig 2	Pulse Magnetization Characteristic.....19
Fig 3	Test Circuit A.....20
Fig 4	Test Circuit B.....21
Fig 5	Pulse Magnetization Characteristics on Major and Minor Loops 21
Fig 6	Pulse Magnetization Characteristics With Reset.....21
Fig 7	Pulse Magnetization Characteristics With and Without Bias 22
Fig 8	Core Pulse Magnetization Characteristic.....23
Fig 9	Pulse Permeability Test Circuit 24
Fig 10	Read Response Pulses.....26
Fig 11	Typical Test Circuit 27
Fig 12	Bridge Circuits 32-33
Fig 13	Block Diagram of Wattmeter 35
Fig 14	Test Points for the Constant-Current Flux-Reset Core Test Method.....36
Fig 15	Circuit for the Constant-Current Flux-Reset Core Test Method.....36
Fig 16	Basic Circuit for Sine-Current Excitation Core Tester 40
Fig 17	Oscilloscope Presentation of $E-I$ Loop of Test Core, Showing Calibrating and Measuring Marker Traces 43
Fig 18	Elementary DC Hysteresis Loop Tester 46
Fig 19	Simplified Hysteresigraph 47
Fig 20	Sine-Flux Impedance Permeability Test 51
Fig 21	Sine-Current Impedance Permeability Test 52

APPENDIX

Methods to Obtain Hysteresis Loops and Magnetization Curves With Older Equipment.....	56
A1. Determination of the Basic Symmetrical Hysteresis Loop.....	56
A2. Determination of the Normal Magnetization Characteristic.....	58
A3. Determination of the Virgin Magnetization Curve.....	58

APPENDIX FIGURES

Fig A1	Hysteresis Loop Test Circuit.....	56
Fig A2	Hysteresis Loop	57

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.

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

²IEEE 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.

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 Resistivity 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

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

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-

⁴IEEE 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.

⁵The 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.

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

<i>Symbol</i>	<i>Term and (Unit)</i>
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.
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.
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.

$\hat{i}$	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
$\bar{\mu}_i$	Relative initial permeability. ⁷
μ_o	Magnetic constant, permeability of free space ($4 \pi 10^{-7}$ 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.
η_i	Hysteresis core constant.

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

⁷See footnote 6.

ω Angular frequency (radian 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 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.

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

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.

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:

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

* 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.

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.

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

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

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

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

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).

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

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).

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

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

⁸When CGS units are used, coefficient a has the units of (gauss)⁻¹.

- 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.

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

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

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

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/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.

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

where

- η_b = Hysteresis material constant (in [tesla]⁻¹)
- δ_η = The loss angle due to hysteresis only
- μ_c = Relative effective permeability
- $\bar{B}$ = 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.

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

where

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

- 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 .

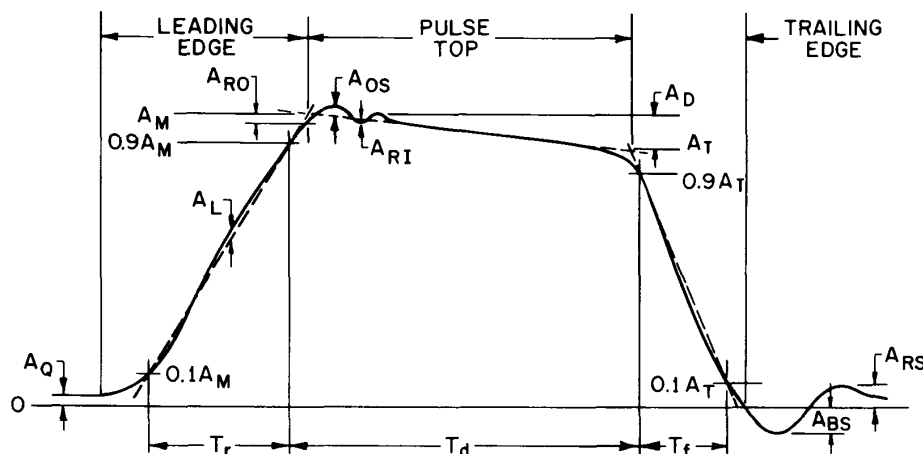


Fig 1
Reference Pulse Shape

(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) *Ringling* (first transition ringling) (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.

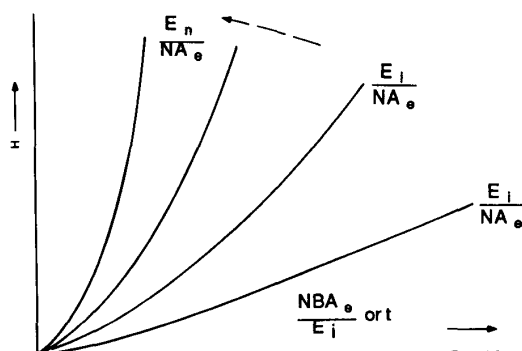


Fig 2
Pulse Magnetization Characteristic

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

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

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

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

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

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

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:

$$\mu_\Delta dH = \frac{edt}{N A_e} \quad (\text{Eq 4})$$

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

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

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% 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:

$$Q1 = 2N3253; R1 = 3300 \Omega; R2 = 47 \Omega; C1 = 0.05 \mu F.$$

$R1$ 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 characteris-