DEPARTMENT OF COMMERCE AND LABOR

CIRCULAR
OF THE
BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 17

MAGNETIC TESTING

[2d Edition]
Issued December 1, 1910

WASHINGTON
GOVERNMENT PRINTING OFFICE
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CONTENTS

1. SCOPE OF THE MAGNETIC TESTING

Permeability and hysteresis tests are made by the ballistic method on magnetic materials in the form of round or rectangular bars and sheets. For these tests two specimens of each sample, at least 25 cm, and preferably 35 cm in length, should be furnished. The permissible cross section is determined by the dimensions of the holes of the coils and yokes used. The apparatus on hand at present will receive round rods of the following diameters:

0.95 cm (3/8 inch).
1.00 cm
1.27 cm (1/2 inch).

Rectangular bars may be of any section which will pass through a hole 1.27 cm in diameter. Sheet metal 5 cm wide, or under, and of the same length as for rods, may be used.

For these measurements two rods or strips of the material to be tested have their ends joined by two soft iron yokes so as to form the four sides of a rectangle. Each bar is surrounded by a magnetizing and a test coil. The change in the magnetic flux embraced by the test coil when the magnetizing current is altered is measured ballistically. Further details are given below.

Tests of nonmagnetic materials, such as are used for chronometers and other instruments, and feebly magnetic materials and investigations on magnetic properties at high and low temperatures can also be made. Bismuth spirals, for measurement of magnetic fields, will be calibrated.

The Bureau is prepared to calibrate permeameters and other apparatus used in magnetic measurements and to make investigations on the magnetic properties of materials.

A limited number of bars of carefully aged iron and steel have been prepared and will be supplied to testing laboratories and manufacturers as standards, at little more than the amount of the fee for testing.

Wattmeter tests for energy losses due to alternating magnetization are carried out upon sheet iron and steel, such as is used in the cores of transformers. A special apparatus designed for this purpose is described below. This serves to determine the losses due to hysteresis and eddy currents. A curve showing the relation between the flux density in the test specimen and the wattless component of magnetizing current can also be furnished when desired. Tests to determine the aging quality of this material are also carried on. Not less than 5 pounds (2.5 kg) should be submitted. The losses are measured at 60 cycles and 10 000 gausses, unless otherwise specified, and the results are accurate within 2 per cent.

Transformers are tested for core loss under normal working conditions; and by the measurement of resistances and impedance in addition the efficiencies and regulation can be computed. For tests of instrument transformers, including measurements of ratio, phase angles, regulation, etc., see Bureau Circular No. 20.

2. DESCRIPTION OF WORK

(*a*) GENERAL

The induction which a bar of iron or steel will assume under a given magnetizing force depends upon the previous magnetic condition of the specimen, and upon the rate of change from one magnetic state to another. It is modified by the presence of mechanical vibration and depends to some extent on temperature. It is therefore desirable to state the conditions under which the test is made.

All the ordinary tests on magnetic material except aging are made at a constant temperature of 25° C. This is in view of the fact that all the magnetic quantities, including the normal induction, the hysteresis loop, and the losses due to hysteresis and eddy currents, depend upon the temperature of the specimen. The relation is not a simple one, and is not the same for all materials. In view of these facts, it seems desirable to make all such measurements at a fixed temperature.

It is important that there be no mechanical vibration of the specimen during the test. Such vibrations tend to give an induction greater than normal for increasing magnetizing forces, and too small values for decreasing forces. Hence, the test specimen is always protected from mechanical vibrations in ballistic measurements.

The results found for rolled sheets usually depend upon whether the material is magnetized parallel to the direction of rolling or at right angles to this direction. When not otherwise specified and the dimensions of sheets submitted permit it, the test pieces will be so cut that the flux traverses half of them parallel to the direction of rolling, and half normal thereto.

The measurement of flux density requires a knowledge of the cross-sectional area of the specimen. For rods and bars the cross section is determined from the dimensions. In sheet metal, however, it is not determined by direct measurement, but from values of mass, length, and density. The density of each specimen is experimentally determined, as experience shows that the assumption of any specified value introduces an uncertainty in the result which is greater than the inaccuracy of the magnetic measurements.

(*b*) NORMAL INDUCTION AND HYSTERESIS LOOP

i). **Normal Induction.**—If a bar of thoroughly demagnetized iron is subjected to a magnetizing force, it experiences a certain induction. This induction will be greater if the magnetizing force is applied suddenly than for a slower growth of magnetizing current. If the magnetizing force is repeatedly applied and removed, the values of the induction obtained differ somewhat. If the magnetizing force is reversed, a change of induction approximately twice the preceding values is obtained. For the first few reversals the change of induction is not constant, but becomes so after a large number of reversals. One-half this constant value of the change in induction on reversal of the magnetizing force is the normal induction, and the locus of such points is the curve of normal induction.

The magnetic properties of a piece of iron or steel may be considered as defined by the curves of normal induction and hysteresis. Before determining the normal induction data, it is necessary that the specimen be freed from its previous magnetization. This is accomplished by subjecting it to a cyclic magnetizing force of one period per second, which is gradually reduced from an initial value, which carries the induction well beyond the point of maximum permeability to a final value somewhat lower than the lowest induction to be studied.

After thorough demagnetization, the lowest magnetizing force to be used is applied and reversed many times, until the iron is brought to a cyclic magnetic state. The induction is then measured and the next higher value of the magnetizing force applied in the same manner. This process is repeated until the required number of points is determined. This is a somewhat laborious operation, but has been found necessary in order to obtain reliable results.

ii). **Hysteresis Loop.**—Before determining the hysteresis loop, the iron is demagnetized as above, and the magnetizing force is applied and increased until the iron is brought up to the maximum induction for which the loop is required. This magnetizing force is repeatedly reversed until the iron is in a normal condition. The magnetizing force is now reduced from its maximum value to a lower one, and the change in magnetic induction corresponding to the change in force is noted. After determining this pair of values, the maximum magnetizing force is again applied and the iron once more brought back to a normal magnetic condition. It is not necessary, however, to repeat the process of demagnetization. Another point is then determined in the same manner as the first. Points corresponding to negative values of the magnetizing force are obtained by simultaneously reversing and reducing the magnetizing force. Before each determination of a point on the loop the iron is brought back to its normal condition.

This method of measuring the magnetic constants differs somewhat from the old "step by step" method which is still employed in many of the modern commercial permeameters. It has the advantage of making the measurement under more nearly the same conditions that occur in commercial practice, and is practically free from the effects of magnetic viscosity. Further, it is possible to get more consistent results by this method than by the older one, as the effects of imperfect initial demagnetization are not so serious. The numerical data obtained by these two methods are not identical, and in publishing results of work of the highest precision it is desirable to specify the method of measurement.

iii). **Selection of Test Points.**—In defining the magnetic properties of a bar of iron or steel, it is neither necessary nor practicable to give complete normal and hysteresis data for all values of the magnetizing force. Certain data may be chosen as characteristic and the magnetic properties inferred from these.

The upper limit of the magnetizing force to be applied is determined by the heating of the magnetizing coil. The magnetic constants for high values of the magnetizing force change slowly and quite regularly, and for a considerable range may be obtained by extrapolation from the data of lower magnetizations. However, magnetizing forces up to 300 gausses can be employed. This upper limit of 300 has reference to the magnetizing force employed in the determination of normal induction data. It is not desirable to carry the cyclic induction measurements through such a wide range. A single hysteresis loop having a maximum induction of 10 000 gausses gives a close index to the hysteretic properties at all inductions. In some cases it might be desirable to supplement these data by the residual induction and coercive force at other values of the maximum induction.

It is, of course, desirable that the number of observations be as small as possible and yet yield the required continuity of data. For most purposes the magnetizing forces required to produce inductions of 5000, 10 000, 15 000, and 20 000 would indicate clearly enough the shape of the normal induction curve. If one is interested in some particular range, measurements in this region could be taken closer together—for instance, every 1000 gausses—or the measurements may be confined to one particular region. A single pair of data may be sufficient for some purposes.

In the hysteresis data, likewise, the labor of measurement is reduced to a minimum by drawing the curve from the three principal points, namely, the tip of the magnetic cycle, the residual induction remaining when the magnetizing force is removed, and the coercive force or the magnetizing force required to reduce the induction to zero.

Such a determination of four points on the normal induction curve and three points on the hysteresis curve gives a fair idea of the magnetic properties of a sample of iron. If several specimens are thus examined at corresponding points, it is possible to make comparisons of the different specimens and classify them into different grades without drawing complete induction curves as would be necessary if the different specimens are tested at irregular points.

iv). **Standard Specimens.**—If a bar is to be used as a standard of comparison, or for the purpose of calibrating a permeameter, it is necessary to determine a considerable number of points of the curve in the region where the apparatus is to be used. Such measurements should be taken with greater care than those on a specimen typical of a large lot which individually may differ considerably from the mean.

In measurements of the highest precision, the magnetic circuit consists of two rods joined at their ends by two soft iron yokes. The magnetomotive force is applied by means of two solenoids and a set of compensating coils. The magnetizing current in each solenoid is capable of independent adjustment until the fluxes in the two rods are equal. The compensating coils are distributed over the four joints of the magnetic circuit and the current is adjusted so that there is no magnetic leakage between the middle and ends of the test specimens. When the magnetic flux has thus been rendered uniform throughout the circuit the true magnetic force and induction may be determined by the ballistic method.[1]

v). **Form of Specimen.**—The labor of a test is reduced and the precision increased by having a certain degree of uniformity in the test specimens. The minimum length of test piece in the ballistic tests is 25 cm (10 inches). A length of 35 cm (14 inches), however, is preferred, as more precise measurements can be made on the longer specimen. Round rods may be 1 cm or 1.27 cm (½ inch) or 0.95 cm (⅜ inch) in diameter. Specimens of any uniform section which have one pair of parallel sides and will pass through a round hole 1.27 cm (½ inch) in diameter may be submitted.

Two rods of the same material should be submitted for each test. For single rods and for specimens of other dimensions than those indicated a special fee is charged.

For sheet metal the test material consists of four strips 5 cm (2 inches) wide, two cut parallel and two perpendicular to the direction of rolling. The material submitted should be chosen from different parts of the sheet and of sufficient size to permit the final cutting to size being done at this laboratory. For this purpose four strips 7.5 by 40 cm (3 by 16 inches) are satisfactory. Crayon lines should be drawn on each specimen parallel to the direction of rolling.

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[1]A fuller account of the arrangement of the magnetic and electric circuits, of the manner of securing uniformity of flux, and of other details of the ballistic method employed is found in Technical Paper No. 117, reprinted from the Bulletin of the Bureau of Standards, Vol. 6, No. 1.

(c) HYSTERESIS AND EDDY CURRENT LOSSES

The total losses due to the combined effects of hysteresis and eddy currents in sheet iron and steel when subjected to a sine wave of alternating magnetic flux are measured by the method described in full in Technical Paper No. 109 (from Bulletin of this Bureau, vol. 5, pp. 453–482). This paper will be mailed on request. For this test ten small sheets approximately 30 cm (12 inches) square are required. These are cut at this Bureau into strips 5 by 25.4 cm and made up into four bundles, which form the four sides of a square magnetic circuit. The arrangement is similar to that proposed by Epstein, but differs from it in having good magnetic joints at the corners of the square. It is thus possible to secure an accuracy of 1 or 2 per cent with a smaller quantity of material, and yet without appreciable distortion of the wave form. In the paper cited above it is shown that the sheet material in common use varies very widely in quality, and the quality is not closely related to the cost. Some of the results are given in Tables I and II.

TABLE I

Hysteresis and Eddy Current Losses

Ordinary steel

Designation	Thickness	Ergs per gram per cycle								Watts per pound at 60 cycles and 10 000 gausses		
		10 000 gausses				5000 gausses						
	cm	60~	30~	Hysteresis	Eddy currents	60~	30~	Hysteresis	Eddy currents	Eddy currents for gage 29*	Hysteresis	Total
E	0.0476	971	853	735	236	304	275	246	58	0.36	2.00	2.36
F	0.0280	766	716	666	100	247	233.5	220	27	0.44	1.81	2.25
G	0.0394	773	668	563	210	247	220	193	54	0.47	1.53	2.00
H	0.0307	558	485	412	146	177.5	158	138.5	39	0.54	1.12	1.66
J	0.0318	543	442	341	202	166.5	139	111.5	55	0.70	0.93	1.63
K	0.0282	518	456	394	124	162	146	130	32	0.54	1.07	1.61
L	0.0346	565	473	381	184	175	150	125	50	0.535	1.035	1.57
B_1	0.0338	554	454	354	200	173	144.5	116	57	0.61	0.96	1.57
M	0.0335	550	461	372	178	173	150	127	46	0.55	1.01	1.56
N	0.0340	531	426	321	210	161	133	105	56	0.63	0.87	1.50
P	0.0437	518	426	334	184	157	132	107	50	0.335	0.91	1.24

* In order to make a fair comparison of quality, the eddy current loss has been computed in each case for a thickness of 0.0357 cm (U. S. standard gage No. 29) on the assumption that the eddy current loss is proportional to the square of the thickness.

TABLE II

Hysteresis and Eddy Current Losses

Silicon steel

Designation.	Thickness	Ergs per gram per cycle								Watts per pound at 60 cycles and 10 000 gausses		
		10 000 gausses				5000 gausses						
	cm	60~	30~	Hysteresis	Eddy currents	60~	30~	Hysteresis	Eddy currents	Eddy currents for gage 29*	Hysteresis	Total
Q	0.0361	357	330	303	54	113	105.5	98	15	0.14	0.82	0.96
R	0.0315	330	309	288	42	104	98.5	93	11	0.15	0.78	0.93
S	0.0452	350	314	278	72	108	99	90	18	0.12	0.76	0.88
T	0.0338	310	280	250	60	96	87	78	18	0.18	0.68	0.86
U	0.0346	312	291	270	42	98	92	86	12	0.12	0.74	0.86
V	0.0310	298	275	251	47	92	85.5	79	13	0.17	0.68	0.85
W	0.0305	240	218	197	43	74.7	68.5	62.3	12.4	0.16	0.54	0.70
X	0.0430	265	232	200	65	80.8	72.5	64.2	16.6	0.12	0.54	0.66

* In order to make a fair comparison of quality, the eddy current loss has been computed in each case for a thickness of 0.0357 cm. (U. S. standard gage No. 29) on the assumption that the eddy current loss is proportional to the square of the thickness.

It is seen that ordinary steel varies from 1.24 to 2.36 watts per pound for United States standard gage No. 29 (thickness 0.0357 cm) at a frequency of 60 cycles per second and a magnetic induction of 10 000 gausses. Silicon steel varies from 0.66 to 1 watt per pound under the same conditions. These figures correspond to 460 and 865 ergs per cycle per gram for ordinary steel and 246 to 368 ergs per cycle per gram for silicon steel. In addition to this variation in the original quality of the material there is a great difference in its constancy with time. Some material shows very decided aging, which in one case amounted to as much as 67 per cent in 500 hours. Other specimens, including most silicon steels, show little or no alteration with use.

The great saving in cost of power due to improvement in core material is generally recognized, but the following example gives a practical illustration.

The benefits derived from the use of high grade material are usually divided between copper and iron losses by judicious designing, but to simplify matters let us assume that the design is fixed for a 5-kilowatt transformer, and using the material *R* in table above the loss is 45 watts. If the material *X* be substituted, the core loss is reduced to 32.2 watts. In operation for 8760 hours, or one year, the saving of 12.8 watts amounts to 112 kilowatt-hours. At a cost of 1 cent per kilowatt-hour this amounts to $1.12, which at 10 per cent (allowing for depreciation as well as interest) represents a capital of $11.20. *In other words the buyer could, with advantage, pay any amount up to $11 more for the sake of getting the better material in his core,* and the manufacturer could pay 28 cents per pound more for the 40 pounds of core material used.

If the better silicon steel were to cost 2.8 cents per pound more than the other (which is improbable), the difference in cost of the steel would be \$1.12, and the user would each year save 100 per cent of the extra cost.

The comparison between the poorer silicon steel and the ordinary steel is even more marked. The core loss for material *N* would be 73 watts, a difference of 28 watts from *R*. In a year this would amount to 245 kilowatt-hours, costing \$2.45, thus practically reducing the value of the transformer by \$24.50. Yet the difference in cost of material is only \$1.70, if we take the price of silicon steel delivered at the factory to be 7½ cents per pound and that of ordinary steel to be 3¼ cents per pound, and assume 40 pounds to be necessary.

Any frequency from 25 cycles to 90 cycles per second can be used for the test. When it is desired to determine the eddy current and hysteresis losses separately, tests at two frequencies (such as 30 and 60 cycles) are made, from the results of which the two components of the loss can be approximately calculated.

Any flux densities between 1000 and 14 000 gausses may be specified. The flux density stated for any measurement is the average value for all the material. The deviations from this value in different parts of the steel are small. The maximum flux Φ is computed from the effective voltage E induced in a secondary winding from the relation $\Phi = \frac{10^8 E}{4.44\, Nn}$ where

n = frequency.
N = number of turns in secondary winding.

When so desired, an ammeter is included in the magnetizing circuit, its reading giving the effective value of the current in the magnetizing coil. With the aid of the wattmeter and voltmeter readings the wattless component of the equivalent sine wave can be computed. A curve giving the relation between this quantity and the magnetic induction is for most purposes more valuable than a curve showing the permeability, since this curve indicates the *effective* value of the current necessary to magnetize, while the permeability indicates the *maximum* current necessary to magnetize, to a given value of magnetic induction.

Aging tests are carried on by heating the material in an oven, the usual period being two weeks and the temperature between 90° and 100° C. Other periods and temperatures can be used when desired. Measurements of energy loss are made at the beginning and end of this heating, and are made at two frequencies, in order to determine whether the change is merely in the hysteresis or also in the electrical conductivity of the material. The flux density used should have the value which will be applied to the material in practice, since the hysteresis changes differently for different values of flux density, the change usually being greater in the region of maximum permeability than for the higher flux densities now common in power transformers.

3. TECHNICAL PAPERS ON MAGNETIC WORK.

The following papers upon magnetic subjects have been published by the Bureau. They are issued in pamphlet form and will be sent upon request. They may be designated by the numbers which precede the titles in the list. A complete list of the technical publications of the Bureau, with brief abstracts of contents, will also be sent upon application.

No. 38. Experiments on Heusler Magnetic Alloys. K. E. Guthe and L. W. Austin.

No. 78. On the Best Method of Demagnetizing Iron in Magnetic Testing. C. W. Burrows.

No. 87. Apparatus for the Determination of the Form of a Wave of Magnetic Flux. M. G. Lloyd and J. V. S. Fisher.

No. 88. Effect of Wave Form upon the Iron Losses in Transformers. M. G. Lloyd.

No. 106. Dependence of Hysteresis upon Wave Form. M. G. Lloyd.

No. 108. Errors in Magnetic Testing with Ring Specimens. M. G. Lloyd.

No. 109. The Testing of Transformer Steel. M. G. Lloyd and J. V. S. Fisher.

No. 117. The Determination of the Magnetic Induction in Straight Bars. C. W. Burrows.

4. REGULATIONS

(*a*) **Application for Test.**—The request for test of an instrument or specimen should state explicitly the points at which test is to be made and the temperature or any other conditions which it is desired should be observed. Whenever possible, the request should be accompanied by the fee as shown in the appended schedules.

(*b*) **Identification Marks.**—Instruments or specimens and the packages in which they are shipped should both be plainly marked to facilitate identification, preferably with the name of the shipper, and a special reference number given to the article and mentioned in the letter requesting the test.

(*c*) **Shipping Directions.**—Instruments should be securely packed in cases or packages which may be used in returning them to the owner. Tops of cases should be screwed down whenever possible. Transportation charges are payable by the party desiring the test, and should be prepaid. Instruments and standard bars will be returned by express "collect," but specimens of material will not be returned unless requested.

(*d*) **Address.**—Articles should be addressed simply, "Bureau of Standards, Washington, D. C." Delays incident to other forms of address will thus be avoided. Articles delivered in person or by messenger should be left at the office of the Bureau and should be accompanied by a written statement of the test desired.

(*e*) **Remittances.**—Fees may be sent by money order or check drawn to the order of the "Bureau of Standards." Delays in forwarding fees will involve corresponding delays in the completion of tests, as certificates are not issued, nor articles returned, until all fees due thereon have been received.

5. SCHEDULES OF FEES

EFFECTIVE JANUARY 1, 1910

Schedules 90 and 91 are for tests made on specimens of the form indicated in paragraph 2 (*b*) v.

Schedule 90.—*Short ballistic test*

Including normal data of one of the two specimens supplied for the following inductions: 5000, 10 000, 15 000, 20 000, or any four values produced by forces under 300 gausses; and hysteresis data for a maximum induction of 10 000 gausses, giving the residual induction under no magnetizing force, and the coercive force, or force necessary to reduce the induction to zero.

(*a*) Normal induction and permeability	$3.00
(*b*) Hysteresis data	3.00
(*c*) Normal and hysteresis data	5.00
(*d*) Curve (extra)	.50

If both specimens are to be tested the fee for the second is one-half the above schedule.

Schedule 91.—*Complete ballistic test.*

Including normal data of one of the two specimens supplied, for every 2000 gausses up to 20 000, produced by forces under 300 gausses; and hysteresis data for a maximum induction of 10 000 gausses, including the following ten points of the loop: 0, ±2000, ±4000, ±6000, ±8000, and 10 000.

(*a*) Normal induction and permeability	$6.00
(*b*) Hysteresis data	6.00
(*c*) Normal and hysteresis data	10.00
(*d*) Curve (extra)	.75

Special tests not enumerated above will be charged at reasonable rates.

If both specimens are to be tested, the fee for the second is one-half the above schedule.

Schedule 92.—*Standard bars*

These bars, of lengths 25, 30, and 35 cm, are carefully aged and supplied with a certificate containing the data of the precision test of schedule 91.

Material.	Diameter of section.
Annealed wrought iron (round)	0.95 cm (3/8 inch)
Annealed wrought iron (round)	1.00 cm
Annealed wrought iron (round)	1.27 cm (1/2 inch)
Low carbon steel (round)	0.95 cm (3/8 inch)
Low carbon steel (round)	1.00 cm
Low carbon steel (round)	1.27 cm (1/2 inch)

ONE BAR

(*a*) Normal data	$7.00
(*b*) Hysteresis data	7.00
(*c*) Normal and hysteresis data	11.00
(*d*) Standard bars without certificate	2.00

TWO BARS

(*h*) Normal data	$11.00
(*i*) Hysteresis data	11.00
(*j*) Normal and hysteresis data	17.00

Schedule 93.—*Wattmeter measurements*

(*a*) For test of energy loss at one frequency and one flux density	$4.00
(*b*) For each additional flux density	.50
(*c*) For each additional frequency	1.00
(*d*) For values of wattless component of magnetizing current (extra)	1.00
(*e*) When not otherwise specified, test will be made at 30 cycles and 60 cycles for a flux density of 10 000 gausses, fee	5.00
(*h*) Aging test, two weeks at 90–100° C, with repetition of test (*a*)	8.00

Special tests not mentioned above will be charged at reasonable rates.

Schedule 94.—*Miscellaneous.*

(*a*) For tests not enumerated above reasonable fees will be charged.

The Bureau will cooperate with manufacturers, scientists, and others interested in the subjects of methods of measurement, measuring instruments, and physical constants, and will place at the disposal of those interested such information relative to these subjects as may be in its possession.

The Bureau will also aid in the solution of problems arising in technical or scientific work, within its scope, and to this end correspondence is invited. Persons interested in magnetic problems and magnetic measuring instruments and methods are welcome to visit the laboratories of the Bureau, where many of the leading types of apparatus may be seen. Communications should be addressed simply "Bureau of Standards, Washington, D. C."

S. W. Stratton,
Director.

Approved:
Benj. S. Cable,
Acting Secretary.

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