Designation: A773/A773M − 14

Standard Test Method for Direct Current Magnetic Properties of Low Coercivity Magnetic Materials Using Hysteresigraphs[1]

This standard is issued under the fixed designation A773/A773M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method provides dc hysteresigraph procedures (*B-H* loop methods) for the determination of basic magnetic properties of materials in the form of ring, spirally wound toroidal, link, double-lapped Epstein cores, or other standard shapes that may be cut, stamped, machined, or ground from cast, compacted, sintered, forged, or rolled materials. It includes tests for normal induction and hysteresis loop determination taken under conditions of continuous sweep magnetization. Rate of sweep may be varied, either manually or automatically at different portions of the curves during measurement.

1.2 The equipment and procedures described in this test method are most suited for soft and semi-hard materials with intrinsic coercivity less than about 100 Oersteds [8 kA/M]. Materials with higher intrinsic coercivities should be tested according to Test Method A977/A977M.

1.3 The values and equations stated in customary (cgs-emu and inch-pound) or SI units are to be regarded separately as standard. Within this standard, SI units are shown in brackets. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in nonconformance with this standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

A34/A34M Practice for Sampling and Procurement Testing of Magnetic Materials

A340 Terminology of Symbols and Definitions Relating to Magnetic Testing

A341/A341M Test Method for Direct Current Magnetic Properties of Materials Using D-C Permeameters and the Ballistic Test Methods

A343/A343M Test Method for Alternating-Current Magnetic Properties of Materials at Power Frequencies Using Wattmeter-Ammeter-Voltmeter Method and 25-cm Epstein Test Frame

A596/A596M Test Method for Direct-Current Magnetic Properties of Materials Using the Ballistic Method and Ring Specimens

A977/A977M Test Method for Magnetic Properties of High-Coercivity Permanent Magnet Materials Using Hysteresigraphs

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

2.2 *Other:*

IEC Publication 60404-4 Ed 2.2 – Part 4: Methods of Measurement of d.c. Magnetic Properties of Magnetically Soft Materials (2008)[3]

3. Terminology

3.1 *Definitions*—The terms and symbols used in this test method are defined in Terminology A340.

4. Summary of Test Method

4.1 A specimen is wound with a magnetizing winding (the primary winding) and a search winding (the secondary winding) for measuring the change in flux. When a magnetizing current, *I*, is applied to the primary winding, a magnetic field, *H*, is produced in the coil. This in turn produces magnetic flux φ in the specimen and the changing flux induces a voltage in the secondary winding which is integrated with respect to time using a fluxmeter. In specimens with uniform cross-sectional area that do not contain air gaps, such as rings, all of the

[1] This test method is under the jurisdiction of ASTM Committee A06 on Magnetic Properties and is the direct responsibility of Subcommittee A06.01 on Test Methods.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from American National Standards Institute, 25 W. 43rd St., 4th Floor, New York, NY 10036.

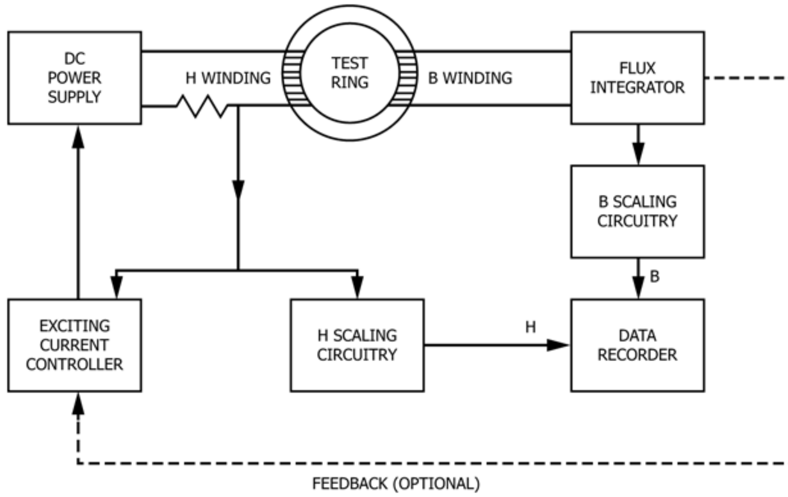

FIG. 1 Block Diagram of Ring Test Apparatus

magnetizing current is used to magnetize the specimen, and H is proportional to I in accordance with the following equation:

$$H = KI \tag{1}$$

where:

H = magnetic field strength, Oe [A/m];
I = current in the magnetizing winding A; and
K = constant determined by the number of primary turns the magnetic path length of the specimen and system of units.

4.1.1 The magnetic flux may be determined by integration of the instantaneous electromotive force that is induced in the secondary winding when the flux is increased or decreased by a varying H. The instantaneous voltage, e, is equal to:

$$e = -NK_1\frac{d\varphi}{dt} \tag{2}$$

or

$$\varphi = \frac{1}{K_1N}\int edt$$

where:

dt = time differential,
N = number of secondary turns,
K_1 = 10^{-8} for cgs-emu system, or $K_1 = 1$ for SI system, and
e = instantaneous voltage in the secondary winging, V.

The flux φ can be obtained if $\int edt$ can be determined. This can be accomplished by several means, as described in *ASTM STP 526*. (**1**) [4] The most common method uses an electronic integrator consisting of an operational amplifier with capacitive feedback. Some fluxmeters employ analog to digital conversion and digital integration techniques. The output voltage of the integrator is given by:

$$E = \frac{1}{RC}\int edt \tag{3}$$

where:

E = output voltage, V;
R = input resistance of the integrator in the secondary circuit, Ω; and
C = the feedback capacitance, F.

By combining the two equations:

$$\varphi = \frac{ERC}{K_1N} \text{ or } E = \frac{\varphi NK_1}{RC} \tag{4}$$

The instantaneous value of flux is thus proportional to the integrated voltage which can be recorded in various ways.

4.1.2 Measurement of magnetic field strength and flux by the hysteresigraph method is illustrated in the block diagram of Fig. 1. The system consists of a magnetizing power source, a magnetizing current controller, an electronic flux integrator, and a data recorder. As magnetizing current is applied to the primary winding, a voltage proportional to I is produced across the current measuring resistor which is connected in series with the primary winding. This voltage is proportional to the value of H.

4.1.3 In the testing of soft magnetic materials in the form of wire, bars or rods, or materials which cannot be sufficiently magnetized in ring form, or which are anisotropic, it is usually necessary to use a permeameter. This is shown in the block diagram of Fig. 2. When using permeameters, the value of H in the gap is generally not proportional to I that flows through the magnetizing winding of the yoke. In these cases, the value of H is determined by integration of the electromotive force that is induced in an H-coil (or Chattock potentiometer) or from the signal developed by a Hall probe which is placed near the specimen. When using an H-coil, the determination of H is accomplished with an H integrator in exactly the same manner as that used to determine flux with the B integrator described in

[4] The boldface numbers in parentheses refer to a list of references at the end of this standard.

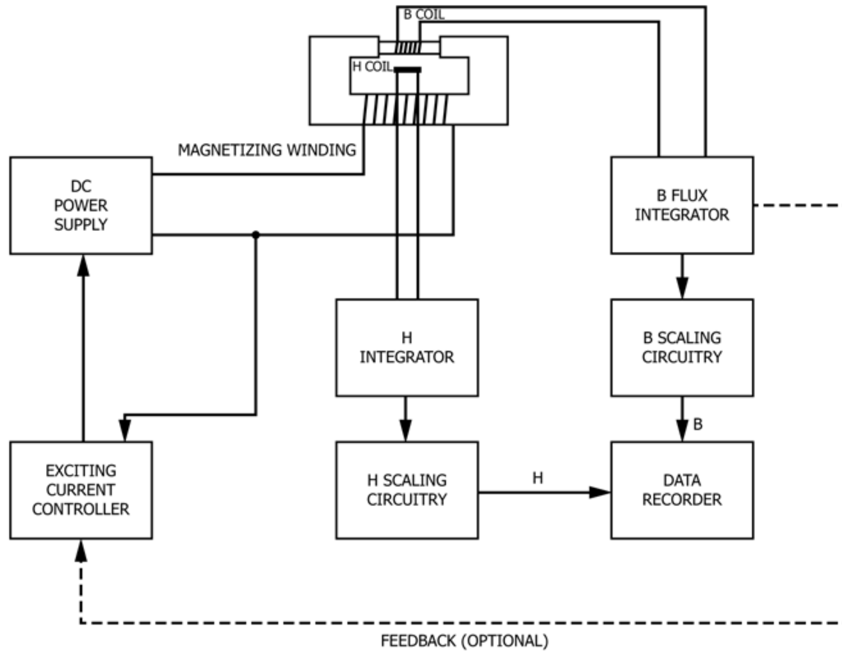

FIG. 2 Block Diagram of Permeator Test Apparatus

4.1. When using a Hall sensor, the *H* values are determined from the voltage output which is linearized to be proportional to *H*.

5. Significance and Use

5.1 Hysteresigraphs permit more rapid and efficient collection of normal induction and dc hysteresis (*B-H* loop) data as compared to the point by point ballistic Test Methods A341/A341M and A596/A596M. The high measurement point density offered by computer-automated systems is often required for computer aided design of electrical components such as transformers, motors, and relays.

5.2 Hysteresigraphs are particularly desirable for testing of semihard and hard magnetic materials, where either the entire second quadrant (demagnetization curve) or entire hysteresis loop is of primary concern. Test Method A977/A977M describes the special requirements for accurate measurement of hard (permanent magnet) materials.

5.3 Hysteresigraphs are not recommended for measurement of initial permeability of materials with high magnetic permeability such as nickel-iron, amorphous, and nanocrystalline materials due to errors associated with integrator drift; in these cases, Test Method A596/A596M is a more appropriate method.

5.4 Provided the test specimen is representative of the bulk sample or lot, this test method is well suited for design, specification acceptance, service evaluation, and research and development.

6. Interferences

6.1 Test methods using suitable ring-type specimens are the preferred methods for determining the basic magnetic properties of a material. When conducting tests on ring specimens, this test method covers a range of magnetic field strengths from about 0.01 Oe [0.8 A/m] up to about 1000 Oe [80 kA/m] or more depending on the specimen dimensions, number of primary turns, available magnetizing power, and the ability to remove heat generated in the primary winding. However, this test method has several important requirements. Unless the inside diameter to outside diameter ratio or ring specimens is greater than 0.82, the magnetic field strength will be excessively nonuniform in the test material and the measured parameters cannot be represented as material properties. The basic quality of materials having directionally sensitive properties cannot be tested satisfactorily with ring specimens. With such materials it is necessary to use Epstein specimens cut with their lengths in the direction of specific interest or to use long link-shaped[5] or spirally wound toroidal core test specimens. The acceptable minimum width of strip used in such test specimens varies with the material under test. At present, it is recommended that the grain-oriented silicon steels should have a strip width of at least 3 cm [30 mm]. When ring specimens are large, it is difficult to provide sufficient magnetizing turns or current-carrying capacity to reach magnetic field strengths above about 1000 Oe [80 kA/m]. In general, magnetic materials tend to have nonuniform properties throughout the body of the test specimens. For this reason, uniformly distributed test windings and uniform specimen cross-sectional area are highly desirable to average nonuniform behavior.

6.2 When conducting permeameter tests on bars, rods, and other appropriate specimens, this test method covers a range of magnetic field strengths from about 0.05 Oe [4 A/m] up to about 20 000 Oe [1600 kA/m] or more, depending on the specimen geometry and the particular permeameter (measuring

[5] Link-shaped specimens are defined in Practice A34/A34M.

TABLE 1 Permeameters Recommended for Use With Hysteresigraphs

NOTE 1—Other permeameters may be suitable for use with dc hysteresigraphs where appropriate modifications are made. Refer to Test Method A341/A341M for other permeameters.

Permeameter	Magnetic Field Strength Range		*H* Measurement Device
	Oe	kA/m	
Babbit (**2**, **3**)	40/100	3.2/8	current, *H* coil
Fahy Simplex (**4-6**)	0.1/300	0.008/24	*H* coil
Fahy Simplex Super H Adapter (**6**)	100/2500	8/200	*H* coil
IEC Type A	12/2500	1/200	*H* coil, Hall probe
IEC Type B	12/620	1/50	*H* coil
Isthmus (**6**, **7**)	100/20 000 +	8/1600 +	*H* coil, Hall probe

fixture) that is used. In general, the lower limit of magnetic field strength is determined by the area-turns of the *H* coil (or the sensitivity of the Hall probe if it is used), the sensitivity of the integrator, and the sensitivities of the measuring and recording components. The upper limit in magnetic field strength is determined by the type of permeameter appropriate for the specimen, the power supply, and the heat generated in the yoke windings. Recommendations of the useful range of magnetic field strength for the various permeameters are shown in Table 1.

6.2.1 In general, permeameters do not produce a uniform magnetic field in either the axial or radial directions around the test specimen. The field gradients in both of these directions will differ in the various permeameters. Also the *H*-coils and *B*-coils of the different permeameters are not identical in area, in turns, or in length or identically located. Although test specimens are prepared to have uniform physical cross section, they may still have undetected nonuniform magnetic properties radially or axially along the specimen length adjacent to the *H* or *B* coils. Some permeameters may also introduce clamping stresses into the test specimen. For these reasons test results obtained on a test specimen with one type of permeameter may not compare closely with those obtained on the same specimen from another permeameter type.

6.2.2 The limitation in the *B* measurement by this test method is determined by the number of secondary (*B*) turns on the specimen, the specimen cross-sectional area, the permeability, and the gain and drift of the fluxmeter and data recording device. In general, normal induction and hysteresis data may be determined from a flux linkage corresponding to 1000 Maxwell turns [10^{-5} Weber turns] to an upper magnetic flux density that corresponds to the intrinsic saturation.

6.2.3 Some permeameters use compensation coils and require continual adjustment of the current flowing through these coils. This may not be compatible with hysteresigraphs.

6.2.4 The magnetic test results, particularly for high permeability alloys such as nickel-iron alloys, may not exactly agree with test results obtained by the ballistic methods, Test Methods A341/A341M and A596/A596M. For ring specimens, this is due to the influence of eddy currents, the different nature of the magnetizing waveform between hysteresigraph and ballistic testing, and possible disaccomodation. For testing using permeameters, residual magnetism of the yoke can be a significant source of error when measuring high permeability materials, especially when testing at low applied magnetic fields.

6.3 The standard Epstein frame as defined in A343/A343M has an assumed magnetic path length of 94 cm [0.94 m]. This may or may not be correct when conducting dc magnetic tests; however, the user of this test method should use this value for consistency of results.

7. Apparatus

7.1 The apparatus shall consist of as many of the components described in 7.2 – 7.8 as required to perform the tests.

7.1.1 All apparatus used in this test method shall be calibrated against known standards to ensure the accuracy limits given below.

7.2 *Balance or Scales:*

7.2.1 The balance or scales used to weigh the test specimen shall be capable of weighing to an accuracy of ±0.2 % of the measured value.

7.2.2 The micrometer or calipers, or both, used to determine specimen dimensions for calculation of cross-sectional area shall be capable of measuring to an accuracy of at least ±0.1 % of the measured value.

7.3 *Magnetizing Power Source*—The power source may range from batteries to regulated, low-ripple, protected, programmable power supplies. It shall have sufficient capacity to produce the maximum currents required for magnetization of the specimen under test.

7.4 *Magnetizing Current Controller*—Instantaneous value of magnetizing current, and its rate of change, may be controlled entirely manually by means of rheostats, potentiometers, shunts, reversing switches, and so forth; semiautomatically by means of variable-speed motors or sweep generators, and so forth; or entirely automatically by means of rate sensors, and so forth. In all cases, components shall be capable of carrying the required currents without overheating, and controls shall be of such design that the magnetizing current may be increased or decreased in a uniform manner.

7.5 *B Integrator*—The *B* integrator shall be an electronic integrator with a full-scale accuracy of ±0.5 % or better. The integrator shall have a calibration traceable to a national standards laboratory and should preferably have a calibration self-check capability.

7.6 *H Integrator (Optional)*—The *H* integrator shall be an electronic integrator with a full-scale accuracy of ±0.5 % or better. The integrator shall have a calibration traceable to a national standards laboratory and should preferably have a calibration self-check capability. This integrator is only required when testing using a permeameter and an inductive *H* sensor.

7.7 *Current Measuring Resistor*—When the magnetic field strength is to be determined from the magnetizing current, a non-inductive resistor with a low temperature coefficient of resistance shall be used. The resistor shall have a power rating capable of handling the largest currents capable of being produced by the power supply. Ideally, the resistor should be rated for two or more times the expected maximum power dissipation. The rated accuracy of the resistor shall be ±0.5 % or better.

7.8 *Data Recorder*—The *B* and *H* values can be recorded and displayed by either analog or digital *X-Y* chart recorders, dataloggers, or computers. The recording device shall be capable of resolving *B* or *H* values of ±1 % of the full-scale value. For analog to digital converters, twelve-bit resolution or higher is desirable.

8. Test Specimens for Ring and Epstein Strip Measurements

8.1 The information in 8.2 – 8.9 covers the general case for specimens in which magnetic field strength is proportional to the magnetizing current, that is, $H = kI$.

8.2 When the test specimen represents a test lot of material, sampling shall conform to the requirements of Practice A34/A34M, unless superseded by a specification.

8.3 To qualify as a test specimen suitable for evaluation of material properties, the effective ratio of mean diameter to radial width shall be not less than 10 to 1 (or an inside diameter to outside diameter ratio not less than 0.82). When the test specimen has a smaller ratio than the above requirement, the test data shall not be represented as material properties but shall be called core properties because of nonuniform flux and field distribution.

8.4 When link, oval-shaped, or rectangular test specimen forms are used, the requirements of 8.3 apply to the end or corner sections where flux crowding may occur. When straight-sided test specimens are very long relative to the length of the corner or end sections, they are suitable for basic material properties evaluation with relatively unoriented materials, provided the uncertainty in determination of true (effective) magnetic path length is less than ±1 % of the total magnetic path length. When this uncertainty in magnetic path length (shortest or longest relative to the mean magnetic-path length) exceeds ±1 %, the test values shall be reported as core properties and not basic material properties.

8.5 Test specimen cores made from strip may be laminated, machined, spirally wound, or Epstein specimens. The method of selection for Epstein specimens is described in Annex A3 of Test Method A343/A343M. When the material is to be tested half transverse and half longitudinal, the material shall be cut into Epstein strips or square laminations of appropriate dimensional ratio.

8.6 Test specimens used for basic material evaluation shall be cut, machined, ground, slit, or otherwise formed to have a cross section that remains sufficiently uniform that its nonuniformity will not materially affect the accuracy of establishing and measuring magnetic flux density, *B*, or magnetic field strength, *H*, in the test specimen. It is recommended that the cross-sectional not vary by more than ±1 % anywhere in the magnetic path. The possible effects of mechanical preparation on the magnetic properties must be considered prior to testing.

8.7 Laminated ring specimens or specimens of strain sensitive materials shall be enclosed by a nonmagnetic, nonconductive core box prior to applying the primary and secondary windings unless it has been established by prior testing that the test results are not materially affected. Air flux correction will typically be required when core boxes are used if testing is to be done at high magnetic field strengths.

TABLE 2 Number of Test Strip

Nominal Thickness in.	Nominal Thickness mm	Electrical Sheet Gage Number	Number of Strips
0.0100 to 0.0250	0.254 to 0.635	32 to 24	12
0.0280 to 0.0435	0.711 to 1.105	23 to 19	8
0.0500 and over	1.270 and over	18 and thicker	4

8.8 For laminated ring and spirally wound cores, the specimen cross-sectional area shall be computed from the mass, magnetic path length, and density.[6] For Epstein specimens, the specimen cross-sectional area shall be computed from the mass, physical length, and density.

8.9 When required for material properties development, the test specimen shall have received a stress relief or other heat treatment after specimen preparation. This heat treatment is subject to agreement between the producer and the user.

9. Test Specimens for Permeameter Measurements

9.1 The information in 9.2 – 9.9 covers the general case for specimens that must be tested using a permeameter, and where the magnetic field strength is not proportional to the magnetizing current.

9.2 When the test specimen represents a test lot of material, sampling shall conform to the requirements of Practice A34/A34M, unless superseded by a specification.

9.3 Test specimens in bar form may be of round, square, or rectangular cross-section. In some permeameters, the bar specimen may be a half round or any shape having a uniform cross-sectional area. Permeameters must have a good magnetic joint between the ends of the test specimen and the permeameter yoke or pole faces. Generally, to achieve a good magnetic joint, the test specimen must be of square or rectangular cross section and must be machined or ground to have straight and parallel surfaces. For permeameters using specimens butted to the pole tips, the specimen ends must be smooth and parallel.

9.4 Where possible, test specimen cross-sectional area shall be directly measured using calipers or micrometers. If not possible because of cross-sectional shape or surface roughness, then the cross-sectional area shall be determined from the mass, length, and density of the test specimen. For testing Epstein specimens in permeameters, the cross-sectional area shall be determined from the mass, length, and density.

9.5 When the material is in flat-rolled form and is to be evaluated as half transverse-half longitudinal, the test sample shall be sheared to have strip specimens in accordance with Table 2 except that multiples of four are not required. When flat-rolled material is to be evaluated in only one direction, the test specimen shall conform to Table 2 or to the requirements

[6] Densities of magnetic materials can be found in Practice A34/A34M.

for best test quality for the particular permeameter being used. For flat-rolled materials of thickness 0.0100 in. [0.254 mm] or thinner, the test specimen cross-sectional area shall be not less than 0.310 in.^{2} [200 mm^2] and not more than 0.620 in.^{2} [400 mm^2].

9.6 When the test specimen for strip materials is to be half transverse and half longitudinal, the preferred method is to test the transverse strips as one specimen and the longitudinal strips as another specimen. Mixing the specimens when significant anisotropy is present could result in unrealistic test results.

9.7 For best testing accuracy, the length and size of the test specimen must meet the requirements of the permeameter being used. Generally for most permeameters, a test specimen length of 10 in. [254 mm] or more is required. Shorter specimens with some permeameters require the use of pole-piece extensions and may cause a reduction in testing accuracy. Other permeameters are designed for short specimens without loss of testing accuracy.

9.8 All test specimen forms shall be cut, machined, or ground to have a uniform cross-sectional area along the active length of the test specimen. The cross-sectional area shall be sufficiently uniform so that its nonuniformity does not materially affect the accuracy of establishing and measuring flux density in the test specimen. It is recommended that the cross-sectional area not vary by more than ±1 % anywhere in the magnetic path. The possible effects of mechanical preparation on the magnetic properties must be considered prior to testing.

9.9 When required for development of material properties, the test specimen shall receive a stress relief or other heat treatment after preparation. This anneal is subject to agreement between the producer and the user.

10. Calibration of Integrator(s)

10.1 The integrator(s) shall be calibrated either by a national standards laboratory or using secondary standards traceable to a national standards laboratory to ensure an integration accuracy of at least ±0.5 %. Calibration may be accomplished by means of a certified Maxwell-turns generator, or volt-seconds generator, or mutual inductor. The integrators may have built-in volt-second sources that require periodic return to the equipment manufacturer for calibration.

11. Calibration of Current Measuring Resistor

11.1 In cases in which the magnetic field strength is proportional to the magnetizing current, such as in ring and Epstein specimens, the resistance of the current measuring resistor(s) shall be verified to be accurate to within ±0.5 % of the stated value when measured at the maximum current at which the resistor will be used when making tests.

12. Calibration of H-Coils and Hall Probes

12.1 The area-turns of *H*-coils shall be calibrated either by a national standards laboratory or using secondary standards traceable to a national standards laboratory.

12.2 Hall Probes shall be calibrated using standards traceable to a national standards laboratory.

13. Calibration of Data Recorder

13.1 The various scales of the data recorder shall be calibrated by means of a verified voltage source to at least the quoted accuracy of the recorder in use. The data recorder shall be calibrated using standards traceable to a national standards laboratory.

14. System Calibration Checks

14.1 Due to the nature of measurement systems, it is not always possible to check the calibration of the individual components. In some instances, attempts to do so may void the equipment manufacturer's warranty. Accordingly, it is strongly recommended that users of these measurement systems create or obtain a set of master specimens representative of the magnetic materials routinely tested by them. These specimens should be periodically tested to verify the overall functioning of the measurement system. The use of control charting techniques is recommended. It is recommended but not required that these masters specimens be tested periodically by a national standards laboratory or by using equipment whose calibration is traceable to a national standards laboratory.

15. Procedure

15.1 The following test procedure is representative of most analog and digital hysteresigraphs. The details of some operating steps may vary with the particular make and model of hysteresigraph. However, the general test procedures are similar in all units. The following procedure covers manual current sweeping, automatic current sweeping, and automatic current sweeping with symmetrical tracing.

15.2 *Setup*—The procedures of 15.2.1 – 15.2.6 should be observed for all methods of current sweep.

15.2.1 Before beginning a test, allow a minimum warm-up period for all apparatus and instrumentation as recommended by the equipment manufacturer.

15.2.2 Connect the specimen, observing polarity so that the first quadrant of the hysteresis loop is being measured on initial application of the magnetizing current. (It is imperative that proper polarity be established before demagnetization of the test specimen.) Some computer controlled equipment automatically corrects the polarity if it is reversed.

15.2.3 Before testing, demagnetize the specimen by establishing a magnetic field strength sufficiently large to reach a point well above the knee of the magnetization curve. Then, while continuously cycling the magnetization between + and - polarity, slowly reduce the magnetizing current to zero. (In the demagnetization process, down-switching of voltage taps to reduce current may result in current surges. It is advisable to select voltage sources and controls that have the ability to reduce current to a low value without switching taps, preferably to a current level that does not exceed a value of 0.1 times the coercivity of the material.)

15.2.4 For the *B* measurement, set the *B* integrator range and scaling circuitry or software so that B is displayed or recorded, or both, directly.

15.2.5 For the H measurement, select the appropriate current measuring resistor (current range) and set the scaling circuitry or software so that H is displayed or recorded, or both, directly.

15.2.6 Before starting the current sweep, adjust the integrator drift to a minimum. It is recommended that the drift be observed for a period approximately equal to the expected measuring time. Many modern integrating fluxmeters automatically check and adjust for minimum drift in the course of normal operation.

15.3 *Manual Sweep Method*—If a specimen is completely demagnetized, it is possible to obtain a normal induction curve and symmetrical hysteresis loop by using manual sweep methods. However, since it is difficult to obtain smooth curves by manual control, recording by manual sweep is recommended only when the test specimens have relatively low permeabilities, large cross sections, and a large number of secondary turns.[7]

15.3.1 Before testing, follow the setup procedure described in 15.2.1 – 15.2.6.

15.3.2 The controller shall be used in the manual mode.

15.3.3 If X-Y recorders are used, center the pen at the origin of the coordinates. Set the H sweep control at zero (center tap of control). Determine the normal induction curve by adjusting the control until the measurement reaches the desired $+H_m$ on the recording device. At $+H_m$ adjust the control to decrease the magnetic field strength until the measurement traverses to point B_r (center tap of control) where the current reverses. Continue to adjust the control, increasing the current in the negative polarity, until the measurement reaches points $-H_c$ and $-H_m$. Then smoothly adjust the current to $+H_m$ to complete the loop measurement. Minor loops are obtainable at any point of the major loop by reversing the control in incremental amounts.

15.3.4 If the loop obtained in 15.3.3 is symmetrical about the origin, the curve from the origin to H_m is the normal induction curve; any point on the major loop is valid and may be read directly. If the major loop is only moderately displaced, approximate values for points (H_m, B_m), H_c, and B_r can be obtained by averaging corresponding positive and negative values. However, if the loop is significantly displaced as a result of incomplete demagnetization, the initial curve is not a valid normal induction curve and the permeabilities cannot be accurately determined.

15.3.5 In obtaining magnetization and hysteresis data by hysteresigraph methods, the H_c value of the specimen is often very small relative to H_m so that H_c and B_r cannot be resolved with high accuracy. However, this can be overcome by increasing the H sensitivity when the measurement reaches B_r (or $H = 0$). When recording manually, stop the current sweep at $+B_r$ then change the current range setting to give the appropriate sensitivity to measure H_c accurately (ratios of 2.5 to 300 are possible). An alternative method is simply to expand the H scale on the recorder when the measurement reaches $+B_r$. If extreme changes in sensitivity are required, a combination of both methods may be used.

15.3.6 In obtaining a major hysteresis loop, a minimum of two loops should be recorded to assure that the specimen is in a symmetrically cyclically magnetized state and to assure that significant drift has not occurred during the test.

15.4 *Automatic Sweep Method*—In obtaining magnetization and hysteresis data by hysteresigraph methods, automatic sweeps are preferable because of better control of the sweep current for tracing smooth loops. If a specimen is completely demagnetized, it is possible to obtain normal induction curves and symmetrical hysteresis loops.

15.4.1 Before testing, follow the setup procedure described in 15.2.1 – 15.2.6.

15.4.2 Switch the magnetizing current controller to the automatic mode.

15.4.3 Select the appropriate current range (current measuring resistor) and set the H-scaling control or software to give the desired full scale magnetic field strength.

15.4.4 Set the magnetizing current control or software to give the desired peak magnetic field strength, which may be less than full scale magnetic field strength.

15.4.5 Set the sweep speed of the controller to 20 s or longer per loop, adjust the integrator drift to a minimum, and, if used, place the pen of the X-Y recorder in the down position at the origin. If constant flux change (dB/dt) sweeping is used, the maximum sweep speed shall be 2 kG [0.2 T] per second. Significantly slower sweep speeds may be required for materials with relative permeability greater than 10 000 such as some Ni-Fe alloys.

15.4.6 Begin the current sweep. If the specimen is completely demagnetized, a normal induction curve will be measured in the first quadrant to ($+H_m$, B_m), then H is automatically reduced and the measurement proceeds to ($0, +B_r$). The current sweep is automatically switched in polarity, and the second and third quadrants are measured. At ($-H_m$, $-B_m$) the current sweep is again reduced, and the remaining half of the hysteresis loop is measured. It is advisable to record at least two complete loops to ascertain if significant drift has occurred during the measurement.

15.4.7 If the loop determined in 15.4.6 is symmetrical about the origin, the curve from the origin to H_m is the normal induction curve; any point on the major loop is valid and may be read directly. If the major loop is only moderately displaced, approximate values for points B_r, H_c, H_m, B_m or any other point on the loop may be obtained by averaging corresponding positive and negative values. However, if the loop is significantly displaced as a result of incomplete demagnetization, the initial curve is not a valid normal induction curve and the permeabilities cannot be accurately determined.

15.4.8 If the H_c value of the specimen is very small relative to H_m so that H_c and B_r cannot be resolved with high accuracy, the H scale may be expanded to give increased sensitivity for accurate reading of B_r and H_c. Follow the procedures as described in 15.3.5.

[7] When unsure of the proper sweep speed, the following procedure can be used. Measure the B-H loop at a selected sweep speed. Then repeat the measurement with a significantly slower sweep speed. If the value of H remains unchanged, the first sweep speed was slow enough. If H_c decreased at the slower sweep speed, repeat the measurement with an even slower sweep speed. Continue until a further decrease of sweep speed as no effect on H_c.

15.4.9 Minor hysteresis loops are obtainable at any point of the major loop by reversing the current sweep in incremental amounts.

15.5 *Automatic Sweep With Symmetrical Measurement Method*—The preferred method for obtaining magnetization and hysteresis data by hysteresigraph methods is to use symmetrical measurement circuitry or software control which enables the creation of symmetrical hysteresis loops about the origin. By this method, a loop is measured symmetrically about the origin regardless of the degree of residual magnetism in the specimen. In using the automatic symmetrical method of hysteresigraph testing, a commutation curve is determined (point by point) from the positive tips of hysteresis loops. This commutation curve is a very good approximation to the normal induction curve in most instances. The curve is obtained by recording a number of symmetrical loops, starting at low values of H and progressively increasing the size of the loops in convenient steps.

15.5.1 Before testing a specimen, follow the setup procedure described in 15.2.1 to 15.2.6. The use of symmetrical measurement does not eliminate the need for demagnetization.

15.5.2 Set the controller to the automatic symmetrical mode. This introduces the circuitry or calculations for automatic control of magnetizing current and automatic recording of symmetrical hysteresis loops.

15.5.3 Select the appropriate current range (current measuring resistor) and set the H-scaling control or software to give the desired full-scale magnetic field strength.

15.5.4 For maximum use of chart area when using X-Y recorders, select the origin at a convenient location in the lower left-hand section of the chart. This only applies when the first quadrant is of primary interest.

15.5.5 Set the sweep speed of the controller to 20 s or longer per loop and adjust the drift to a minimum. For constant flux change (dB/dt) sweeping, the maximum speed shall be 2 kG [0.2 T] per second. Significantly slower sweep speeds may be required for materials with relative permeabilities greater than 10 000, such as some Ni-Fe alloys.

15.5.6 Set the H control to give a small value of magnetic field strength for measuring a small loop. Start the current sweep.

15.5.7 To obtain additional test points, increase the H_m settings by convenient amounts to obtain successively larger loops. A plot of the tips of the various hysteresis loops will give a commutation curve.

15.5.8 To ascertain if significant drift has occurred and to assure that the specimen is in a symmetrically cyclically magnetized state, it is suggested that a minimum of two loops be traced for each value of H_m.

15.5.9 If the H_c value of the specimen is very small relative to H_m so that H_c and B_r cannot be resolved with high accuracy, the H scale may be expanded to give increased sensitivity for accurate reading of B_r and H_c as described in 15.3.5. When testing in the automatic symmetrical mode, the procedure for obtaining H_c is identical to that in 15.3.5 with the exception that the change in sensitivity is made at $-B_r$, in which case the value of $+H_c$ is recorded on the chart.

15.5.10 The procedures described in 15.5.1 – 15.5.9 cover the point-by-point method for obtaining normal induction properties when using hysteresigraphs with automatic symmetry. Full loop properties, including minor hysteresis loops, may be obtained by the same procedure by placing the origin at the center of the chart and recording the entire loop. Minor hysteresis loops may be determined at any point of a major loop by reversing the current sweep in incremental amounts.

15.6 The procedures for obtaining magnetization properties of rod- and bar-type specimens typically require the use of an appropriate permeameter. However, the procedures are identical to the methods described in 15.1 – 15.5 with the following exceptions: First, the H measurement may be made with an H sensor (since H is not proportional to magnetizing current); hence, the hysteresigraph must be equipped with a second integrator or Hall-effect gaussmeter. Secondly, since the magnetic field strength is usually not proportional to the current flow in the magnetizing windings, the current resulting in a particular value of H must be determined by trial and error. Since this is normally done with the test specimen in place, demagnetization shall be required before conducting the actual test.

16. Calculations When Using Permeameter Procedures

16.1 Where possible, test specimen cross-sectional area shall be directly measured using calipers or micrometers. If not possible as a result of cross-sectional shape or surface roughness, then the cross-sectional area shall be determined from the mass, length, and density of the test specimen as follows:

$$A_c = \frac{m}{l\delta} \tag{5}$$

where:

A_c = cross-sectional area, cm^2 [m^2];
m = specimen mass, g, [kg];
δ = material density, g/cm^3 [kg/m^3]; and
l = specimen length, cm [m].

16.2 In permeameters where the B-coil is a compensated coil set (measures intrinsic flux density or intrinsic induction, B_i), the area of the specimen can be smaller than the area of the coil without requiring any air flux compensation. In permeameters where an uncompensated B-coil is used and the area of the B-coil is much larger than the test specimen, a correction, K_2, is required. Make this correction as follows:

16.2.1 Determine the correction, K_2, as follows:

$$K_2 = \frac{a_c - A_c}{A_c} \tag{6}$$

where:

a_c = cross-sectional area of B-coil, cm^2 [m^2] and
A_c = cross-sectional area of test specimen, cm^2 [m^2].

16.2.2 Determine the magnetic flux density in the test specimen, B, as follows:

$$B = B_{obs} - K_2\Gamma_m H \tag{7}$$

where:

B = magnetic flux density, G [T];

H = magnetic field strength, Oe [A/m]; and
Γ_m = magnetic constant of free space
= 1 G/Oe (cgs-emu)
= $4\pi \times 10^{-7}$ H/m (SI)

16.2.3 For hysteresis loops:

$$B_{true} = B_m - (\Delta B_{obs} - K_2 \Gamma_m \Delta H) \tag{8}$$

where:

B_{true} = magnetic flux density at the test point on hysteresis curve, G [T];
B_m = maximum value of magnetic flux density for hysteresis, G [T];
ΔB_{obs} = change in magnetic flux density from B_m to B_{true}, G [T]; and
ΔH = change in magnetic field strength, Oe [A/m].

17. Report When Using Permeameter Procedures

17.1 The test report shall include the following information along with the test results:

17.1.1 Complete identification of test specimen type or shape.

17.1.2 Test specimen dimensions.

17.1.3 Heat treatment (if any) of the test specimen.

17.1.4 The cross-sectional area and magnetic path length.

17.1.5 The type of permeameter.

17.1.6 Number of secondary winding or *B*-coil turns.

17.1.7 Magnetizing current sweep speed or value of dB/dt if held constant.

17.1.8 Test specimen temperature.

17.1.9 When magnetic flux density values are reported, the corresponding value of magnetic field strength.

17.1.10 When magnetic permeability other than maximum permeability is reported, the corresponding value of either *B* or *H* at which it was determined.

17.1.11 When hysteresis-loop properties are reported, the value of peak magnetic field strength or peak magnetic flux density used for the measurement of the coercive field strength, residual induction, and hysteresis loop area.

18. Precision and Bias When Using Permeameter Procedures

18.1 *Precision*—It is not possible to specify the precision of the procedure in Test Method A773/A773M since no interlaboratory data are available.

18.2 *Bias*—It is not possible to specify the bias of the procedure in Test Method A773/A773M since permeameter specimens having an accepted reference value are not available.

19. Calculations When Using Ring Test Procedures

19.1 The average magnetic field strength applied to the test specimen by the current through the magnetizing winding is determined from the equation:

$$H = \frac{K_3 N I}{l_m} \tag{9}$$

where:

H = magnetic field strength, Oe [A/m];
N = number of turns in magnetizing winding N_1;
I = current through the magnetizing winding, [A];
l_m = mean magnetic path length, cm [m]; and
K_3 = constant equal to 0.4π for cgs-emu units and 1 for SI units.

19.1.1 For a ring specimen, l_m is determined from the mean circumference. For the Epstein frame, the mean magnetic path length is assumed to be 94 cm (940 mm), and the equation for the 700-turn Epstein test frame is as follows:

$$H = \frac{0.4\pi \times 700I}{94} = 9.358I \text{ Oe} \tag{10}$$

$$H = 744.7I\ [\text{A/m}]$$

19.1.2 For the 352-turn Epstein frame:

$$H = \frac{0.4\pi \times 352I}{94} = 4.706I \text{ Oe} \tag{11}$$

$$H = 374.5I\ [\text{A/m}]$$

19.2 When nonlaminated test specimens have very smooth surfaces and precise uniform dimensions, the cross-sectional area shall be determined from physical measurements. In all other cases, the effective test specimen area shall be determined from measurements of mass, length, and density as follows:

$$A_c = \frac{m}{l\delta} \tag{12}$$

where:

A_c = test specimen cross-sectional area, cm^2 [m^2];
m = test specimen mass, g [kg];
l = test specimen length, cm[m]; and
δ = density of test specimen material, g/cm^3 [kg/m ^{3}].

19.2.1 For the Epstein test frame:

$$A_c = \frac{m}{4l\delta} \tag{13}$$

where:

A_c = test specimen cross-sectional area, cm^2 [m^2];
m = test specimen mass, g [kg];
l = Epstein test specimen length, cm [m]; and
δ = density of test specimen material, g/cm^3 [kg/m^3].

19.3 The Epstein test frame coils are built considerably larger than the test specimen cross-sectional area. To avoid the need for manual air-flux correction, a compensating mutual inductor is built into the test frame. This means that the magnetic flux density measurements are intrinsic magnetic flux density, B_i, measurements. To obtain magnetic flux density, B, the following equation must be used:

$$B = B_i + \Gamma_m H \tag{14}$$

where:

B = magnetic flux density in test sample, G [T];
B_i = intrinsic magnetic flux density in test specimen, G [T];
H = magnetic field strength, Oe [A/m]; and
Γ_m = magnetic constant of free space
= 1 G/Oe (cgs-emu)
= $4\pi \times 10^{-7}$ H/m (SI)

19.4 When ring testing is conducted at high field strength, and particularly when the secondary winding surrounds an appreciable air flux in addition to the core flux, the test values may be corrected for air flux as follows. Wind a duplicate set of windings around a nonmagnetic core of identical size. Connect the magnetizing windings in series aiding and the secondary windings in series opposition. This provides air-flux compensation and the measurements become intrinsic magnetic flux density, B_i, as for the Epstein test frames. This method is usually more accurate than estimating the air-flux linking the secondary winding.

19.5 When the air-flux corrections must be calculated from estimated winding areas, the procedures described in 16.2.1 and 16.2.2 should be used.

20. Report When Using Ring Test Procedures

20.1 The test report shall include the following information along with the test results:

20.1.1 Complete identification of test specimen type or shape.

20.1.2 Test specimen dimensions.

20.1.3 Heat treatment (if any) of the test specimen.

20.1.4 The cross-sectional area and magnetic path length.

20.1.5 Number of primary and secondary winding turns.

20.1.6 Magnetizing current sweep speed or value of dB/dt if held constant.

20.1.7 Test specimen temperature.

20.1.8 When magnetic flux density values are reported, the corresponding value of magnetic field strength.

20.1.9 When magnetic permeability other than maximum permeability is reported, the corresponding value of either *B* or *H* at which it was determined.

20.1.10 When hysteresis-loop properties are reported, the value of peak magnetic field strength or peak magnetic flux density used for the measurement of the coercive field strength, residual induction, and hysteresis loop area.

21. Precision and Bias When Using Ring Test Procedures

21.1 *Interlaboratory Test Program*—An interlaboratory study was conducted in which three different soft magnetic materials in the form of ring specimens were tested. The three materials were selected to show the influence of magnetic permeability on the precision and bias. The three materials used were:

(a) High permeability nickel – molybdenum – iron alloy (relative maximum permeability of about 370 000)

(b) High purity iron (relative maximum permeability of about 10 900)

(c) Free-machining ferritic stainless steel (relative maximum permeability of about 1230)

The same three specimens were circulated to ten participants. Practice E691 was followed for the design of the experiment and the analysis of the data. The details of the study are given in ASTM Research Report No. RR:A06-1001[8] and have been published ((**8**).

21.2 *Test Results*—Refer to either the ASTM research report or the publication for the actual test results.

21.3 *Precision*—The results of the interlaboratory study showed that while the 95 % repeatability (within laboratory) was typically better than 2 % for the materials and parameters measured, the 95 % reproducibility (between laboratories) was much worse. The best reproducibility was for the maximum flux density and residual induction. The worst reproducibility was for the maximum permeability and coercive field strength. Analysis of the results suggests that there were issues with centering the hysteresis loops leading to significant errors in determination of maximum permeability and coercive field strength. A second issue was that some of the hysteresigraphs used in the study were not well suited for the measurement of high magnetic permeability alloy. Most likely this was due to lack of resolution of the very small magnetizing currents needed to measure high permeability alloy. The least that can be stated about the precision is that the reproducibility declines with increasing magnetic permeability.

21.4 *Bias*—The test specimens were measured at the completion of the interlaboratory study by the National Physical Laboratory, Teddington, UK to establish the bias. The bias results reflected the issues with the reproducibility. The lowest bias came from the measurement of maximum flux density with a maximum absolute bias of 0.13 %. Surprisingly, the lowest bias measured was for the maximum flux density of the Ni-Mo-Fe alloy and was reported to 0.03 %. The highest bias was for the coercive field strength of the same alloy, measured at 34.7 %.

21.5 Given the above, it is strongly recommended that prior to purchase of a dc hysteresigraph, tests using specimens traceable to a national standards laboratory be conducted to assure proper functioning and accurate measurement.

22. Keywords

22.1 dc hysteresigraph; dc hysteresis; Epstein test; Hall probe; hysteresis loop; permeameter; ring-type specimen

[8] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:A06-1001. Contact ASTM Customer Service at service@astm.org.

ANNEX

(Mandatory Information)

A1. COMPUTER SOFTWARE REQUIREMENTS

A1.1 All contemporary commercially produced dc hysteresigraphs feature computer aided control, data acquisition, and analysis. The user normally does not have the capability to review or modify the source codes since they are proprietary. The software used on such hysteresigraphs must have the following capabilities in order to be in conformance with this ASTM test method.

A1.1.1 *Units of Measurement*—The software shall provide the capability to use either cgs-emu or SI units at the operator's discretion.

A1.1.2 *Magnetizing Current Control*—The software shall have the capability to control the magnetizing current either by controlling the sweep speed, or by maintaining a user selectable constant rate of flux change (dB/dt), or some combination of the two, with the constant rate of flux change being the preferred method.

A1.1.3 *Demagnetizing Current Control*—The software shall allow for automatic demagnetization with user selectable parameters to optimize the demagnetization process for various materials. The software must include the ability to report a quantitative measure of demagnetization upon completion of the demagnetization cycle.

A1.1.4 *Symmetry Correction*—The software shall re-center the hysteresis loop, based on symmetry, upon completion of testing and prior to doing data analysis. This capability is vital for accurate measurement of the normal induction curve and magnetic permeability.

A1.1.5 *Hysteresis Loop Points Measurement*—The software shall determine the coercive field strength (H_c), residual induction (B_r), and maximum magnetic flux density (B_m) or maximum magnetic field strength (H_m) by averaging both positive and negative values determined from the full hysteresis loop.

A1.1.6 *Fluxmeter Calibration*—The software shall require a calibration check of the fluxmeters upon startup of the unit and periodically during its use assuming the fluxmeters have an internal calibration check source. This requirement is waived if the fluxmeters lack an internal calibration check source.

A1.1.7 *Fluxmeter Drift Correction*—The software shall have the capability to mathematically correct for integrator drift, or shall, at a minimum report the amount of drift accumulated during a measurement to allow for an assessment of the measurement quality. The sampling period for drift should be at least 20 seconds.

A1.1.8 *Air Flux Correction*—The software shall have the ability to correct for air flux in the secondary (*B*) coil.

A1.1.9 *Epstein Frame*—When an Epstein Frame is used, the software must have the ability to interpret the secondary or flux signal as proportional to intrinsic magnetization (*B-H* or 4πM) instead of normal magnetization (*B*), since the Epstein Frame includes a hard-wired air-flux compensator. The software shall have the capability of reporting either intrinsic or normal magnetization at the user's discretion.

A1.1.10 *Test Report*—The software shall report all the information listed in Sections 17 and 20.

APPENDIX

(Nonmandatory Information)

X1. SYMMETRICAL HYSTERESIS LOOPS

X1.1 General

X1.1.1 When measuring *B-H* loops, it is often difficult to obtain symmetrical loops because of residual magnetism in the test specimen. It is desirable for accuracy and efficient operation that the controller either be provided with electronic circuitry for centering *B-H* loops or a simple manual procedure be established to accomplish the centering. When digital data acquisition is used, centering can be done mathematically. The manual procedure is outlined in Section X1.2. Note that this manual procedure is only suitable for the full hysteresis loop determination, not determination of the normal induction curve.

X1.2 Manual Procedure

X1.2.1 Centering can be accomplished by attenuating the output of the flux integrator by half, plotting a half-size loop, adjusting the *Y* axis of the recorder to position the loop, and then restoring the output of the integrator to its original state and proceeding to plot the final loop.

X1.2.2 With the recorder pen off the paper, plot an imaginary loop by cycling the test specimen several times from $+H_{max}$ to $-H_{max}$ to ensure that the material under test is on the major hysteresis loop. During these several cycles, the integrator sensitivity should be adjusted to yield the desired excursion of the pen along the *B* axis.

X1.2.3 After the specimen has been conditioned through several cycles and following the − H excursion, the H level is returned to zero (which corresponds to $-B_r$). At this point, the integrator sensitivity is set at half value, the integrator is zeroed, and the pen, still off the paper, is positioned at the intersection of the B and H axis.

X1.3 The H drive of the hysteresigraph is then varied from $H = 0$ to $+ H_{max}$ back to $H = 0$. The pen is placed on the paper, the integrator sensitivity is restored to its original level, and the desired hysteresis loop is recorded on the paper with the center of this loop coinciding with the intersection of the B and H axis.

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