Designation: A348/A348M – 05 (Reapproved 2015)

Standard 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[1]

1. Scope

1.1 This test method covers the determination of the magnetic properties of flat-rolled magnetic materials using Epstein test specimens with double-lap joints in the 25-cm Epstein frame. It covers determination of core loss, rms and peak exciting current, exciting power, magnetic field strength, and permeability. This test method is commonly used to test grain-oriented and nonoriented electrical steels but may also be used to test nickel-iron, cobalt-iron, and other flat-rolled magnetic materials.

1.2 This test method shall be used in conjunction with Practice A34/A34M and Test Method A343/A343M.

1.3 Tests under this test method may be conducted with either normal ac magnetization or with ac magnetization and superimposed dc bias (incremental magnetization).

1.4 In general, this test method has the following limitations:

1.4.1 *Frequency*—The range of this test method normally covers frequencies from 100 to 10 000 Hz. With proper equipment, the test method may be extended above 10 000 Hz. When tests are limited to the use of power sources having frequencies below 100 Hz, they shall use the procedures of Test Method A343/A343M.

1.4.2 *Magnetic Flux Density* (may also be referred to as *Flux Density*)—The range of magnetic flux density for this test method is governed by the test specimen properties and by the available instruments and other equipment components. Normally, for many materials, the magnetic flux density range is from 1 to 15 kG [0.1 to 1.5 T].

1.4.3 *Core Loss and Exciting Power*—These measurements are normally limited to test conditions that do not cause a test specimen temperature rise in excess of 50°C or exceed 100 W/lb [220 W/kg].

1.4.4 *Excitation*—Either rms or peak values of exciting current may be measured at any test point that does not exceed the equipment limitations provided that the impedance of the ammeter shunt is low and its insertion into the test circuit does not cause appreciably increased voltage waveform distortion at the test magnetic flux density.

1.4.5 *Incremental Properties*—Measurement of incremental properties shall be limited to combinations of ac and dc excitations that do not cause secondary voltage waveform distortion, as determined by the form factor method, to exceed a shift of 10 % away from sine wave conditions.

1.5 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 except for the sections concerning calculations where there are separate sections for the respective unit systems. 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.

1.6 *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

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

[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. Summary of Test Method

3.1 A representative sample of the magnetic material is cut into Epstein strips and then annealed or otherwise treated in accordance with the appropriate material specification or as agreed between producer and user. The strips are weighed and loaded into the Epstein frame becoming the transformer core. The primary coil is then excited with ac voltage and current at the frequencies and magnetic flux densities of interest and measurements taken. In some cases, a dc magnetic field strength is superimposed (incremental dc bias). The magnetic parameters are then calculated from the data.

4. Significance and Use

4.1 This test method evaluates the performance of flat-rolled magnetic materials over a wide frequency range of ac excitation with and without incremental dc bias, as used on transformers, motors, and other laminated core devices.

4.2 This test method is suitable for design, specification acceptance, service evaluation, and research.

4.3 The application of test results obtained with this test method to the design or evaluation of a particular magnetic device must recognize the influence of the magnetic circuitry upon its performance. Some specific items to consider are size, shape, holes, welding, staking, bolting, bracketing, shorting between laminations, ac waveform, adjacent magnetic fields, and stress.

5. Test Specimens

5.1 The test specimens shall consist of Epstein strips cut from sheets or coiled strips of magnetic materials in accordance with the test lot and sampling requirements of Practice A34/A34M, Sections 5 and 7, and Test Method A343/A343M, Annex A3 (see Note 1).

NOTE 1—Excessive burr and nonflatness of strips can appreciably affect test results.

5.1.1 If specimen is primarily isotropic, cut one half of the strips with grain and one-half cross grain. If anisotropic, cut all with grain. Other ratios of with and cross grain may be chosen by agreement.

5.2 The test specimen shall consist of multiples of four strips. The total number of strips shall be such as to:

5.2.1 Provide sufficient total losses to register within the range of required accuracy of the wattmeter.

5.2.2 Fill the available vertical opening space in the test frame to at least ¼ of its maximum height and

5.2.3 Contain a minimum of twelve strips.

5.3 Check each strip to assure its length and width are accurate to ±0.04 cm [0.4 mm]. If the length is not 30.5 cm [305 mm], use the actual length as described in Sections 9 and 10.

5.4 Table 1 shows the number of Epstein strips that will provide nominal weights of approximately 125, 250, 500, and 1000 g for various strip thicknesses.

6. Basic Circuit (see Fig. 1)

6.1 Fig. 1 shows the essential apparatus and basic circuit connections for this test. The ac source shall be capable of driving the test circuit with an ac sinusoidal waveform voltage of desired amplitude and frequency. The series resistance components, *r* and wattmeter current shunt, in conjunction with the ac source, shall be such as to provide a pure sine wave voltage either at the test frame transformer primary, or if overall negative feedback is implemented, then the pure sine wave shall be at the test frame transformer secondary. The wiring and switches shall be selected to minimize current or voltage reading errors, for example, the voltage connections across *r* shall be made precisely at the resistor terminals so that no wire resistance is effectively added to that of the resistor. Also, all voltage reading or negative feedback components across the secondary of the test frame transformer shall cause negligible loading, that is, shall draw sufficiently low currents to not appreciably affect power or current readings. When a common ground connection is made between primary and secondary of the test frame transformer, the ac source ground connection must be isolated to eliminate ground loop current.

TABLE 1 Number of Strips for Various Nominal Specimen Weight Epstein Frames (Minimum Strip Length is 28 cm [280 mm])

Nominal Strip Thickness		Number of Strips for Test Specimens of Nominal Weight			
Thick (cm)	Thick (in.)	125 g	250 g	500 g	1000 g
0.079	0.0310	...	...	12	20
0.071	0.0280	...	...	12	24
0.064	0.0250	...	...	12	24
0.056	0.0220	...	...	16	28
0.047	0.0185	...	12	16	32
0.043	0.0170	...	12	20	36
0.039	0.0155	...	12	20	40
0.036	0.0140	...	12	24	44
0.032	0.0125	...	12	24	48
0.028	0.0110	...	16	28	56
0.025	0.0100	...	16	32	60
0.023	0.0090	...	16	36	68
0.020	0.0080	12	20	40	76
0.018	0.0070	12	24	44	88
0.015	0.0060	12	24	52	[A]
0.013	0.0050	16	32	60	[A]
0.010	0.0040	20	40	76	[A]
0.0076	0.0030	24	52	[A]	[A]
0.0051	0.0020	40	76	[A]	[A]
0.0025	0.0010	76	[A]	[A]	[A]

[A] Not recommended.

7. Apparatus

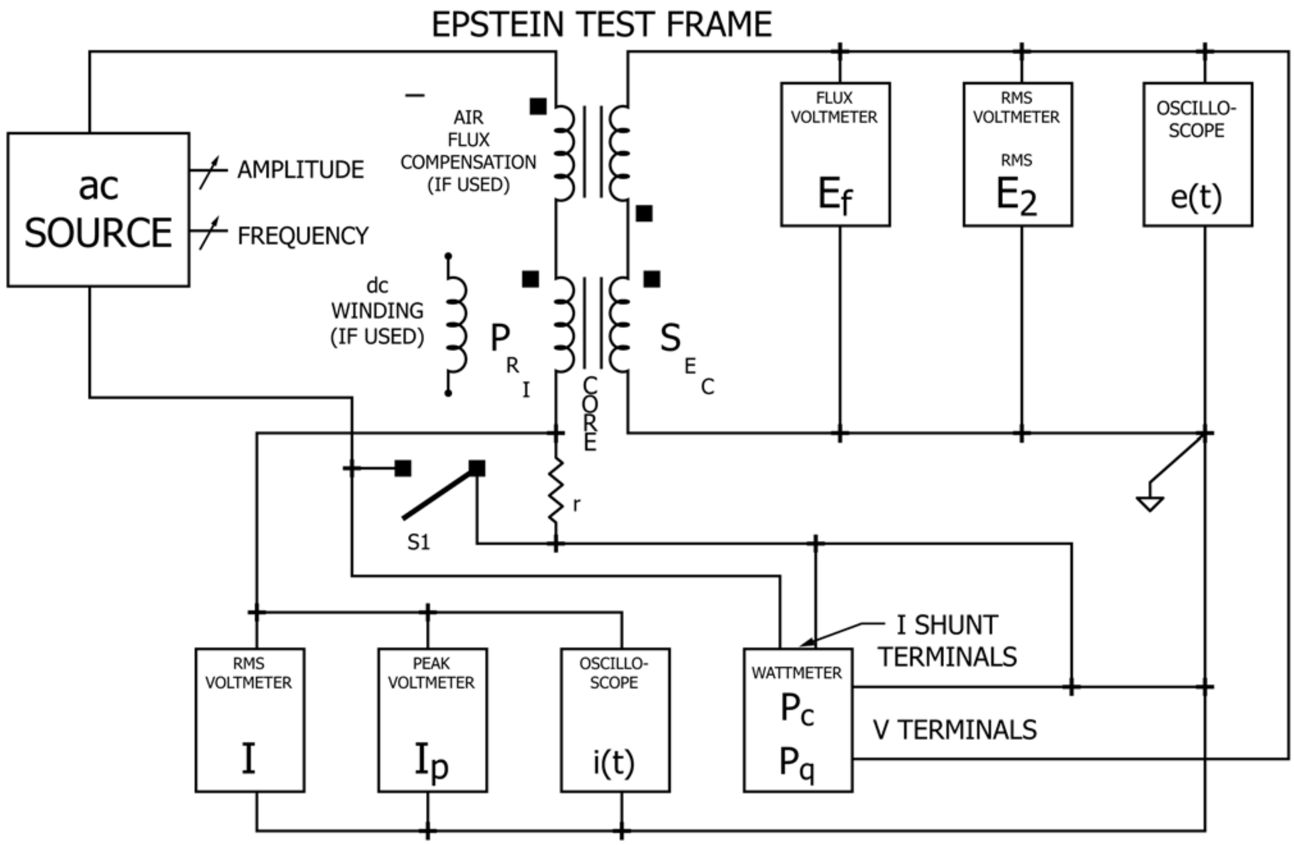
7.1 The test apparatus shall consist of as many of the following components as required to perform the desired measurement functions:

7.2 *Balance or Scale*—The balance or scales used for determining the mass of the test specimen shall weigh to an accuracy of 0.05 %. The calculated test voltage E_f is directly proportional to specimen mass and magnetic flux density (see Note 2).

NOTE 2—Errors in the weight of a specimen will cause errors in magnetic flux density, core loss, and exciting power.

7.3 *Epstein Test Frame:*

7.3.1 The dimensions of the windings, their spacing, and the general precautions and construction details of Test Method A343/A343M, Annex A1, shall apply. The Epstein test frame



NOTE 1—The ac source terminals must "float" to prevent ground loop currents. If the wattmeter has a common connection between its V and I terminals, the rest of the circuit must be connected so as to prevent shorting.

NOTE 2—If, during demagnetization, current exceeds the wattmeter maximum rating, Switch S1 is required and is closed.

NOTE 3—A dc winding is required only if incremental properties are to be tested.

NOTE 4—The voltage and current monitoring oscilloscope may be a dual channel type and is optional equipment. Basic circuit-wattmeter-ammeter-voltmeter method, 100 to 10 000 Hz and 25-cm Epstein frame

FIG. 1 Basic Circuit-Wattmeter-Ammeter-Voltmeter Method, 100 to 10 000 Hz and 25–cm Epstein Frame

should be selected to be compatible with the desired test specimen size (see 5.4).

7.3.2 The following numbers of total winding turns are usually commercially available and are suggested for testing at various frequencies:

Frequency, Hz	No. of Turns (Both Primary and Secondary)
Up to 400	700 or 352
400 to 1000	352
1000 to 5000	200 (no air-flux compensator)
5000 to 10 000	100 (no air-flux compensator)

7.3.3 The primary winding is uniformly distributed along the magnetic path and may be wound in multiple layers over the secondary winding. The secondary winding shall be the innermost winding on the coil form and shall be a single layer winding. The primary and secondary shall be wound in the same direction and their starting end connections shall be made at the same corner.

7.3.4 *Air Flux Compensator*—If the Epstein test frame has more than 200 turns, it shall contain an air flux compensator which opposes and balances out the air flux voltage induced in the secondary winding. Such compensation is necessary whenever the permeability of the test specimen is low under high magnetic field strength conditions to avoid serious errors in setting the flux voltage. The air flux compensator allows the true intrinsic induction B_i to be measured. When tests are restricted to moderate magnetic flux density and field strength where test specimen relative permeability remains high, the difference between B and B_i is small and air flux compensation is unnecessary.

7.4 *Flux Voltmeter*—A full wave true average responsive voltmeter calibrated so that its scale reads true average $\times \pi \sqrt{2}/4$, and indicates the same value as an rms voltmeter when measuring pure sine waves, shall be provided for measuring the peak value of the test induction. To meet the precision of this test method, meter error shall not exceed 0.25 % (see Note 3). If the meter impedance is not sufficiently high at the frequency of test, it is necessary to compensate for its loading effect. To evaluate how much the meter loads the circuit, read the rms ammeter and rms voltmeter before and after disconnecting the flux voltmeter. When dc bias is applied to the test frame transformer, the flux voltmeter must be able to respond true average.

NOTE 3—Inaccuracies in setting the test voltage produce errors disproportionately larger in core loss and exciting current. Evaluate meter error in accordance with the manufacturer's information, for example, percent of range, temperature, and frequency.

7.5 *RMS Voltmeter*—A RMS voltmeter shall be provided for evaluating the exciting power and also the form factor of the voltage induced in the secondary winding of the test frame transformer. The meter error shall not exceed 0.25 % at the frequency of test. The meter burden shall have no more than 0.05 % effect on the test frame transformer voltage or current. To evaluate how much the meter loads the circuit, read the RMS ammeter and flux voltmeter before and after disconnecting the RMS voltmeter. When dc bias is applied to the test frame transformer, the RMS meter must be able to indicate true RMS ac voltage.

7.6 *Oscilloscope Voltage Monitor (Optional)*—An oscilloscope may be provided to monitor the waveshape of the secondary voltage. Connection of the oscilloscope shall not affect the voltage or current more than 0.05 %.

7.6.1 The oscilloscope dual input common ground connections shall not cause ground loop currents in any part of the circuit.

7.7 *Wattmeter*—The wattmeter error shall not exceed 0.25 % at unity power factor at the frequency of test. Error shall not exceed 1 % of reading at the lowest power factor encountered. If desired, the reactive power may also be measured or calculated.

7.7.1 The voltage sensing terminals of the wattmeter shall have an input impedance sufficiently high that the voltage or current is changed no more than 0.05 %.

7.7.2 The current sensing terminals of the wattmeter shall have a low impedance so as to not change the test fixture transformer primary current waveshape appreciably. An input impedance of 0.1 Ω is preferred. The wattmeter shall be capable of accepting the maximum peak current encountered without exceeding its crest factor rating.

7.8 *RMS Ammeter*—A RMS ammeter consisting of a RMS voltmeter connected across the terminals of the current sensing resistor (*r* in Fig. 1) shall be provided. The RMS voltmeter shall have an error no greater than 0.25 % considering the maximum crest factor and all frequencies and amplitudes encountered in the measurement. Connection to the circuit shall not cause appreciable changes in voltage or waveform. The current sensing resistor shall be accurate to 0.1 % and be essentially noninductive at the frequency of test. It shall have a power rating several times the maximum power to be experienced during the test. Voltmeter connections to the resistor shall be made precisely at the resistor terminals so that wire resistance does not add to the known resistor value and cause error. The resistor value shall be 0.1 Ω or, if higher, shall not cause a voltage drop greater than 5 % of the test frame voltage.

7.9 *Peak Ammeter*—A true peak, or peak-to-peak, ammeter consisting of a true peak or peak-to-peak voltmeter connected across the terminals of the current sensing resistor (*r* in Fig. 1) shall be provided to measure the peak value of the current waveform. Accuracy shall be 2 %. Alternatively, an oscilloscope with voltage measurement capability can be used. An oscilloscope, when used, shall not cause shorting of any part of the circuit through its dual input common ground.

7.10 *Oscilloscope Current Monitor (Optional)*—Extreme current wave peaking occurs as the magnetic core material goes into saturation. This is readily observable on an oscilloscope connected across the current sensing resistor. An oscilloscope also makes it possible to recognize current waveform nonsymmetry with positive and negative polarity. Such nonsymmetry results when a dc component is present along with the ac in the primary winding of the test frame, causing nonsymmetrical *B* versus *H* excitation. This condition causes serious peak current reading errors. Temporarily inverting the waveform by flipping the oscilloscope "invert" switch is an effective way to observe waveform symmetry. Some oscilloscopes have a provision for automatically and digitally displaying the peak of a waveform and thus may be used to read the peak current instead of a peak reading voltmeter. An oscilloscope, when used, shall not cause unwanted shorting of any part in the circuit through its dual input ground.

7.11 *ac Source* (see Fig. 2)—A precisely controllable source of sinusoidal test voltage characterized by low internal impedance, low harmonic distortion (1 %), excellent voltage stability (0.1 %), and excellent frequency stability (0.1 %) is required.

7.11.1 The ac source shall be ac coupled to prevent dc bias in the test fixture transformer. The ac source would typically consist of some or all of the following components:

7.11.1.1 *Sine Wave Generator*.

7.11.1.2 *Power Amplifier*.

7.11.1.3 *Isolation Transformer or Coupling Capacitor*.

7.11.1.4 *Impedance Matching Tapped Transformer or Autotransformer*.

7.11.2 *Sine Wave Generator*—A sinusoidal wave generator or synthesizer capable of generating the signal described above shall be provided. This signal is input to the power amplifier.

7.11.3 *Power Amplifier*—An amplifier of voltage and current to be fed to the test frame transformer shall be provided. It shall be capable of amplifying the signal while maintaining the waveform and meeting specifications described above. It may use negative feedback to meet the low source impedance and low waveform distortion requirements. It may consist, for example, of an audio amplifier with several hundred watts rating. If it is a dc-coupled amplifier, an ac isolation transformer or capacitor shown in Fig. 2 is required.

7.11.4 *Isolation Transformer*—The isolation transformer, if required, shall have sufficient bandwidth, coupling, and power-handling capacity to maintain signal integrity and low source

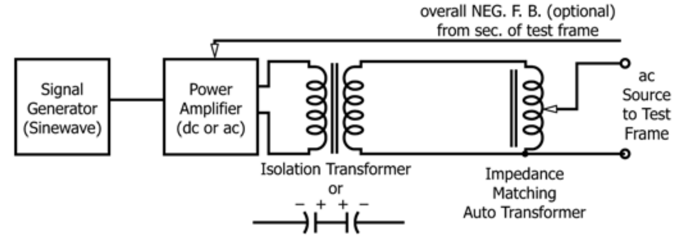


FIG. 2 Circuit Diagram of Typical ac Source

impedance, even with dc offset of a dc coupled amplifier feeding it. Its output shall be routed to the test frame transformer primary.

7.11.5 *Coupling Capacitor*—The coupling capacitors, which are an alternate to the isolation transformer, shall be a pair of electrolytic capacitors connected back to back with sufficient effective capacitance to maintain the low source impedance of the power amplifier. Alternatively, an ac-rated capacitor may be used.

7.11.6 *Impedance Matching Tapped Transformer or Autotransformer*—A transformer or autotransformer with fixed or variable taps shall be provided if necessary to match the power amplifier source impedance to that of the test frame transformer. It shall have bandwidth and power-handling capacity to maintain signal integrity. If this is a transformer with isolated primary and secondary windings, the isolation transformer or coupling capacitor mentioned above may be omitted.

8. Procedure

8.1 Check the specimen strips to assure that no dented, twisted, or distorted strips showing evidence of mechanical abuse have been included. Strips having readily noticeable burr (greater than 0.0005 in. [0.02 mm]) may also be unsuitable for testing. Verify that the strips are of uniform length and width and that the appropriate number of strips with the appropriate grain direction are available (see Table 1). Weigh strips on a scale or balance capable of determining the mass to within ±0.05 %.

8.2 *Calculate Magnetic Flux Density*—Calculate and record the flux voltage values corresponding to all the magnetic flux density levels to be tested (see Sections 9 and 10). A data sheet form should be prepared with spaces to enter every required meter reading and other data (see Note 4).

NOTE 4—The calculations may be performed and a data sheet printout obtained by use of a computer appropriately programmed. Use of data acquisition instrumentation allows automatic setting of the apparatus and automatic measurement as well, if desired. Refer to the Appendix of Test Method A343/A343M, "Computerization of Magnetic Test Data."

8.3 Insert the test specimen strips into the test frame and prepare them for test as described in Test Method A343/A343M. Connect the apparatus as indicated in the circuit diagram of Fig. 1 and perform the various tests following the procedures outlined below. It is recommended to check for symmetry of the current waveform when initially setting up the equipment.

8.4 *Demagnetization*—The specimen should be demagnetized before measurements of any magnetic property are made. Demagnetize by applying a voltage from the power source to the primary circuit that is sufficient to magnetize the specimen to a magnetic flux density above the knee of its magnetization curve (where the exciting current increases sharply for small increases in flux density). At this point, decrease the applied voltage slowly and progressively during an elapsed time of 5 to 10 s (or longer) so that the flux density is reduced smoothly to a point below the lowest flux density at which tests are to be performed and near zero flux density. Demagnetization to near zero magnetic flux density is especially critical when measuring properties at very low flux density (for example, 100 G). After demagnetization, take care not to jar or move the specimen in any way that will destroy the desired reproducible magnetic state of negligible magnetic flux density. Tests should be made immediately after demagnetization (within 2 to 3 min) for the desired test points using the following sequence of testing:

8.4.1 Begin the tests at the lowest test magnetic flux density and test in order of increasing maximum magnetic flux density. Do not overshoot the target magnetic flux density level appreciably, especially at low magnetic flux densities.

8.4.2 When frequency is varied at constant magnetic flux density, begin the tests at the lowest frequency and test in order of increasing frequency.

8.4.3 Repeat the demagnetization before determining a test point at either a lower magnetic flux density or lower frequency than that of the previous test point.

8.5 *Meter Readings*—Once the magnetic flux density level is correct and steady, proceed to record the following:

E_f = flux voltage (secondary),
E_2 = rms voltage (secondary),
W = core wattage,
P_q = core volt-amperes reactive (optional),
I = rms exciting current (primary), or
E_r = rms voltage across r,
I_p = peak exciting current (primary), or
E_{pr} = peak voltage across r, or
$I_{p\text{-}p}$ = peak-to-peak exciting current (primary), or
$E_{p\text{-}pr}$ = peak-to-peak voltage across r,
f = frequency (if more than one frequency), and
r = shunt resistance.

NOTE 5—Voltages E_{pr} and $E_{p\text{-}pr}$ may also be observed or measured or both with an oscilloscope. Gather information on test frame transformer secondary voltmeter and wattmeter burdens and record them so corrections can be made if necessary, that is, if they affect accuracy by more than 0.1 %.

8.6 *Incremental Properties*—Incremental properties are core loss, exciting power, permeability, and so forth taken under conditions of a superimposed constant dc magnetic field. The test frame shall have a separate winding for this purpose (see Fig. 3). This winding is to be uniformly distributed over the other windings. The dc supply shall be a constant current source with good current regulation. A constant direct current source feeding the dc bias winding has no shorting effect on the ac field because its ac source impedance approaches infinity. Should the dc come directly from a voltage-regulated source, its low impedance would effectively short the other windings

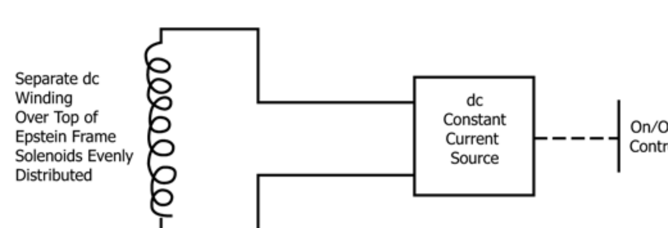


FIG. 3 Circuit Diagram dc Biasing of Test Frame Transformer for Measurement of Incremental Properties

and produce low ac voltages not characteristic of true incremental properties. See Fig. 4 for a typical constant dc source circuit diagram (see Note 6).

NOTE 6—In Fig. 4, if $V_{dc} = 50$ V, and $V_{in} = 6$ V, then $V_e \cong 5$ V. For $R_e = 5$ Ω, $I_{dc} = 1.0$ A. Adjust R_2 for exact current. Circuit source impedance is extremely high.

8.6.1 Alternatively, other methods to raise the dc source impedance may be used. For example, an inductor with sufficient inductance and bandwidth to present a high impedance at the ac frequency can be placed in series with the dc power supply. As exciting current may rise sharply under incremental conditions, watch carefully the ammeter and wattmeter readings to avoid damage to the equipment.

8.6.2 Use the following incremental testing procedures to obtain good repeatability of test values: first, demagnetize at low frequency (see 8.4), then establish in the biasing winding the lowest value of biasing current, without overshooting, which is to be used. Then without any change or variation in the biasing current, slowly raise the ac voltage, without overshoot, to the desired test magnetic flux density. Set other magnetic flux densities at the same level of dc bias in ascending order of magnetic flux density. For each separate biasing level again demagnetize the test specimen. (**Warning**—Switches in series with the dc bias current should never be opened or closed until the dc bias supply voltage has been reduced to zero.)

8.6.3 dc biasing tends to cause waveform distortion. Do not make measurements when the ac flux waveform distortion exceeds 10 % as determined by the form factor method (see 9.4 and 10.4). An oscilloscope monitoring the secondary voltage waveform is recommended.

9. Calculations (Customary Units)

9.1 *Symbols*—Use the symbols listed below in the equations or descriptions of this test method. For the official complete list of symbols and definitions, see Terminology A340.

A	=	effective cross-sectional area of test specimen in the Epstein frame, cm ^{2}
B	=	normal induction, G
B_i	=	intrinsic induction, G
E	=	rms voltage, V
E_2	=	rms voltage in an unloaded secondary winding, V
E_f	=	flux voltage, V
E_p	=	peak value of voltage, V
$E_{p\text{-}p}$	=	peak-to-peak voltage, V
e	=	eddy-current loss, %
F	=	error in form factor, %
f	=	frequency, Hz
H_b	=	dc biasing magnetic field strength, Oe
H_L	=	inductance magnetic field strength from the reactive component of rms exciting current, Oe
H_p	=	peak magnetic field strength from measured peak value of exciting current, Oe
H_z	=	apparent ac magnetic field strength from measured rms exciting current and assumed value $I_p = \sqrt{2}$ I, Oe
$H_{\Delta z}$	=	apparent ac magnetic field strength from rms exciting current with dc incremental bias, Oe
h	=	hysteresis loss, %
I	=	rms exciting current, A
I_p	=	peak value of exciting current (measured), A
K	=	voltage ratio squared $(E_2/E_f)^2$
l	=	length of test strips, cm
l_1	=	effective magnetic path length, cm

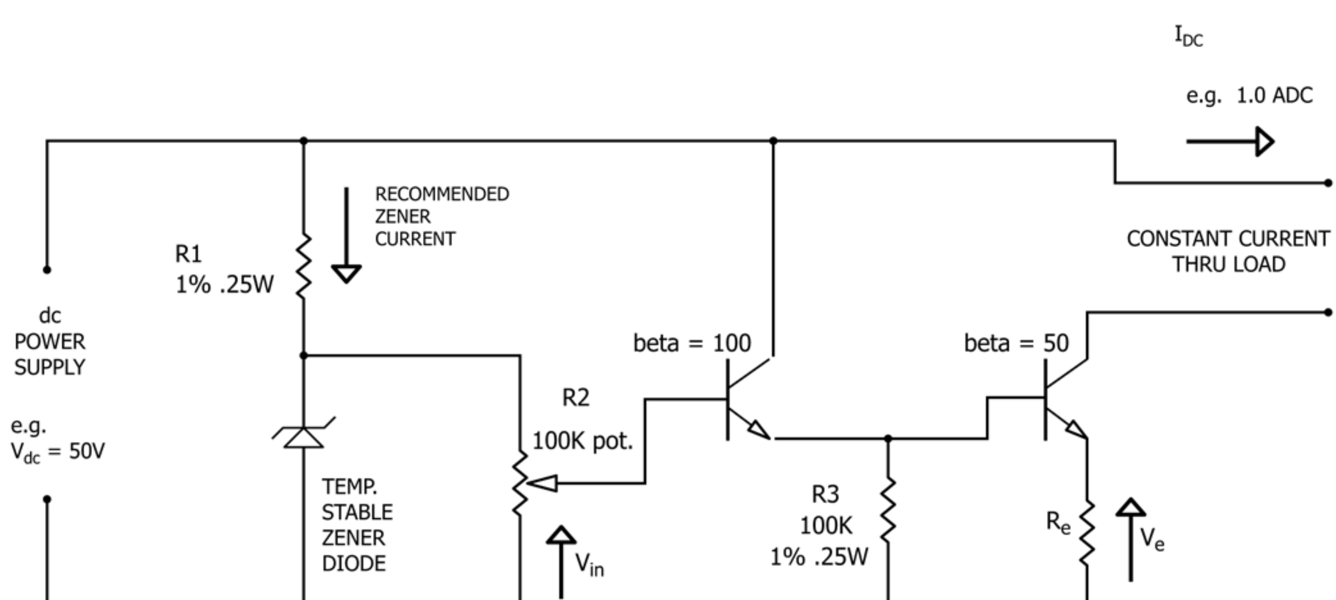


FIG. 4 Typical Constant Current dc Source

m = mass of test specimen, g
m_1 = active mass of test specimen, g
N_1, N_2 = total number of turns in Epstein frame primary or secondary windings, respectively
$P_c(B{:}f)$ = specific core loss, W/lb at magnetic flux density B and frequency f
$P_z(B{:}f)$ = specific exciting power, VA/lb at magnetic flux density B and frequency f
R = effective resistance of secondary instrument burden and circuit including wattmeter potential resistance, voltmeter resistance, and any other burden, Ω
r = shunt resistance for the ammeter, Ω
P_q = total reactive power, vars
W = total power measured by the wattmeter, W
$\mu_{subscript}$ = permeability from $B/H_{subscript}$ where $_{subscript}$ is same as that of H
δ = density, g/cm³

9.2 *Magnetic Flux Density:*

9.2.1 The intrinsic induction B_i is related to E_f by:

$$E_f = \pi\sqrt{2}B_i AN_2 f(10^{-8})V \quad (1)$$

To eliminate Epstein strip stacking factor considerations, and since mass, density, and length of the specimens can be accurately determined, the value of cross-sectional area, A, is calculated from these quantities and the sample density. Since the sample is divided into four parts, then each leg of the test frame has a cross-sectional area:

$$A = m/(4\ l\ \delta),\ cm^2 \quad (2)$$

Hence E_f becomes:

$$E_f = \pi\sqrt{2}B_i N_2 fm/[4\ l\ \delta\ (10^8)],\ V \quad (3)$$

If the test frame secondary meter burdens are not negligible, they will cause a voltage drop in the winding resistance. If this voltage drop is 0.1 % or greater, it lowers the apparent magnetic flux density and reduces accuracy. Calculate E_f for all values of magnetic flux density to be tested and enter into the data sheet.

9.3 *Specific Core Loss:*

9.3.1 To obtain the specific core loss of the specimen in watts per unit mass, it is necessary to subtract all secondary circuit power included in the wattmeter indication before dividing by the active mass of the specimen. The specific core loss at a particular magnetic flux density and frequency is:

$$P_{c(B:f)} = 453.6(W - E_2{}^2/R)/m_1,\quad \text{W/lb} \quad (4)$$

9.3.2 In the 25-cm Epstein frame, it is assumed that 94 cm is the effective magnetic path length with specimens 28 cm or longer. For the purpose of computing core loss, the active mass is assumed to be:

$$m_1 = l_1 m/(4l) = 94m/(4l) = 23.5\ m/l,\ \text{g} \quad (5)$$

9.4 *Form Factor Correction*—The percent error in form factor is given by the equation (see Note 7):

$$F = 100(E_2 - E_f)/E_f \quad (6)$$

The corrected core loss, that shall be computed when F is greater (see Note 8) than ±1 %, is:

$$\text{corrected } P_{c(B:f)} = \left(\text{observed } P_{c(B:f)}\right) 100/(h + eK) \quad (7)$$

where:

observed $P_{c(B:f)}$ = specific core loss calculated by the equations in 9.3,
h = percentage hysteresis loss at magnetic flux density B,
e = percentage eddy-current loss at magnetic flux density B,
K = $(E_2/E_f)^2$, and
h = 100 − e.

Values of h and e for materials may be obtained using core loss separation methods (see Note 9) and are a matter of agreement between the producer and the user.

NOTE 7—In determining the form factor error, it is assumed that the hysteresis component of core loss will be independent of the form factor if the maximum value of magnetic flux density is at the correct value (as it will be if a flux voltmeter is used to establish the value of the magnetic flux density) but that the eddy-current component of core loss, being a function of the rms value of the voltage, will be in error for nonsinusoidal voltages. While it is true that frequency or form factor separations do not yield accurate values for the hysteresis and eddy-current components, yet they do separate the core loss into two components, one which approximately varies as the second power of the form factor and the other which is relatively unaffected by form factor variations. Regardless of the academic difficulties associated with characterizing these components as hysteresis and eddy-current loss, it is observed that this method does accomplish the desired correction under all practical conditions if the distortion is not excessive.

NOTE 8—It is recommended that tests made under conditions in which the percent error in form factor, F, is greater than 10 % be considered as likely to be in error by an excessive amount and that such conditions be avoided.

NOTE 9—Core loss separation into separate hysteresis and eddy-current components may be determined by "Two Form Factor Method" for example. See Annex A2.

9.5 *Specific Exciting Power:*

9.5.1 The specific exciting power at a particular magnetic flux density and frequency is calculated from the rms current in the primary of the test frame and the rms voltage induced in the secondary as follows:

$$P_{Z(B:f)} = 453.6 E_2 I/m_1,\ \text{V} - \text{A/lb} \quad (8)$$

9.5.2 In the 25-cm Epstein frame, it is assumed that 94 cm is the effective magnetic path length with specimens 28 cm or longer. For the purpose of computing exciting power, the active mass is assumed to be:

$$m_1 = l_1 m/(4l) = 94m/(4l) = 23.5\ m/l,\ \text{g} \quad (9)$$

9.6 *Exciting Current and Magnetic Field Strength:*

9.6.1 Exciting current is assumed to be the rms value I unless otherwise specified.

The magnetic field strength H determined from I is based upon the assumption that the peak value of current is $\sqrt{2}\ I$. In fact, this is not true because the current waveform is generally distorted and nonsinusoidal for sine voltage waveforms. This is due to the nonlinear characteristics of ferromagnetic materials. However, this is accepted practice. Hence:

$$H_z\ (\text{impedance magnetic field strength}) = 0.4\pi\ \sqrt{2}N_1 I/l_1,\ \text{Oe} \quad (10)$$

where: N_1 is number of turns in the test frame primary.

9.6.2 *Peak Exciting Current*—The measured peak current, I_p , is given by:

$$I_P = I_{p-p}/2, A \ or$$
$$I_P = E_p/r, A \ or$$
$$I_P = E_{p-p}/2r, A. \quad (11)$$

Hence:

$$H_p \left(\text{peak magnetic field strength}\right) = 0.4\pi N_1 I_p/l_1, \text{ Oe} \quad (12)$$

9.6.3 *Inductance Exciting Current (Optional)*—The inductive or reactive component of the exciting current, I_L, is usually determined from the measured value of reactive power, P_q in vars, where:

$$I_L = P_q/E_2 \ A \quad (13)$$

Hence:

$$H_L\left(\text{inductance magnetic field strength}\right) = 0.4\pi\sqrt{2}N_1 I_L/l_1 \text{ , Oe} \quad (14)$$

9.7 *Permeability:*

9.7.1 Several different types of ac permeability may be calculated using data collected from tests described in this test method. These different permeabilities are based upon several different definitions of magnetic field strength. The general form of the equation for permeability is:

$$\mu = B/H \left(\text{a dimensionless quantity}\right) \quad (15)$$

where $B = B_i + H_p$. For convenience in calculating permeability, the intrinsic induction B_i, may be used instead of the normal induction, B, for most testing. This entails no loss of accuracy until H_p becomes appreciable in magnitude relative to B_i. If greater accuracy is required, B should be used.

9.7.2 *Impedance Permeability:*

$$\mu_z = B/H_z \quad (16)$$

9.7.3 *Peak Permeability:*

$$\mu_p = B/H_p \quad (17)$$

9.7.4 *Inductance Permeability:*

$$\mu_L = B/H_L \quad (18)$$

9.8 *Incremental dc (Biasing) and Magnetic Field Strength:*

$$H_b\left(\text{dc magnetic field strength}\right) = 0.4\pi \ N_{dc}I_{dc}/l_1, \text{ Oe} \quad (19)$$

where:

N_{dc} = dc winding turns of the test frame and
I_{dc} = dc bias current (measured).

When the dc magnetic field strength H_b is present, the values of core loss, exciting current, var, and so forth measured and their derived properties, specific core loss, specific exciting power, and permeability are all considered to be incremental values, for example, $P_{\Delta c}$, I_Δ, $P_{\Delta q}$, $P_{\Delta c}(B:f)$, $P_{\Delta z}(B:f)$, and $\mu_{\Delta z}$. These are measured and calculated as though the dc bias was not present.

10. Calculations (SI Units)

10.1 *Symbols*—In the equations or descriptions of this test method, use the symbols listed below. For the official complete list of symbols and definitions, see Terminology A340.

A = effective cross-sectional area of test specimen in the Epstein frame, m^2
B = normal induction, T
B_i = intrinsic induction, T
E = rms voltage, V
E_2 = rms voltage in an unloaded secondary winding, V
E_f = flux voltage, V
E_p = peak value of voltage, V
$E_{p\text{-}p}$ = peak-to-peak voltage, V
e = eddy-current loss, %
F = error in form factor, %
f = frequency, Hz
H_b = dc biasing magnetic field strength, A/m
H_L = inductance magnetic field strength from the reactive component of rms exciting current, A/m
H_p = peak magnetic field strength from measured peak value of exciting current, A/m
H_z = apparent ac magnetic field strength from measured rms exciting current and assumed value $I_p = \sqrt{2}I$, A/m
$H_{\Delta z}$ = apparent ac magnetic field strength from rms exciting current with dc incremental bias, A/m
h = hysteresis loss, %
I = rms exciting current, A
I_p = peak value of exciting current (measured), A
K = voltage ratio squared $(E_2/E_f)^2$
l = length of test strips, m
l_1 = effective magnetic path length, m
m = mass of test specimen, kg
m_1 = active mass of test specimen, kg
N_1, N_2 = total number of turns in Epstein frame primary or secondary windings, respectively
$P_c(B:f)$ = specific core loss, W/kg, at magnetic flux density B and frequency f
$P_z(B:f)$ = specific exciting power, VA/kg at magnetic flux density B and frequency f
R = effective resistance of secondary instrument burden and circuit including wattmeter potential resistance, voltmeter resistance, and any other burden, Ω
r = shunt resistance for the ammeter, Ω
P_q = total reactive power, vars
W = total power measured by the wattmeter, W
$\mu_{subscript}$ = permeability from $B/H_{subscript}$ where $_{subscript}$ is same as that of H
δ = density, kg/m^3
Γ_m = magnetic constant $4\pi \times 10^{-7}$ H/m

10.2 *Magnetic Flux Density:*

10.2.1 The intrinsic induction B_i is related to E_f by:

$$E_f = \pi\sqrt{2}B_i AN_2 f, \ V \quad (20)$$

To eliminate Epstein strip stacking factor considerations, and since mass, density, and length of the specimens can be accurately determined, the value of cross-sectional area, A, is calculated from these quantities and the sample density. Since the sample is divided into four parts, then each leg of the test frame has a cross-sectional area:

$$A = m/\left(4l\delta\right) \quad (21)$$

Hence E_f becomes:

$$E_f = \pi\sqrt{2}B_i N_2 fm/(4l\delta),\ V \quad (22)$$

If the test frame secondary meter burdens are not negligible, they will cause a voltage drop in the winding resistance. If this voltage drop is 0.1 % or greater, it causes the apparent magnetic flux density to be lower than actual and reduces accuracy. Calculate E_f for all values of magnetic flux density to be tested and enter into the data sheet.

10.3 *Specific Core Loss:*

10.3.1 To obtain the specific core loss of the specimen in watts per unit mass, it is necessary to subtract all secondary circuit power included in the wattmeter indication before dividing by the active mass of the specimen. The specific core loss at a particular magnetic flux density and frequency is:

$$P_{c(B:f)} = (W - E_2^2/R)/m_1, \quad W/kg \quad (23)$$

10.3.2 In the 25-cm Epstein frame, it is assumed that 0.94 m is the effective magnetic path length with specimens 0.28 m or longer. For the purpose of computing core loss, the active mass is assumed to be:

$$m_1 = l_1 m/(4l) = 0.94m/(4l) = 0.235\ m/l,\ \text{kg} \quad (24)$$

10.4 *Form Factor Correction*—See 9.4.

10.5 *Specific Exciting Power:*

10.5.1 The specific exciting power at a particular flux density and frequency is calculated from the rms current in the primary of the test frame and the rms voltage induced in the secondary as follows:

$$P_{z(B:f)} = E_2 I/m_1, \text{V} - \text{A/kg} \quad (25)$$

10.5.2 In the 25-cm Epstein frame, it is assumed that 0.94 m is the effective magnetic path length with specimens 0.28 m or longer. For the purpose of computing exciting power, the active mass is assumed to be:

$$m_1 = l_1 m/(4l) = 0.94m/(4l) = 0.235\ m/l,\ \text{kg} \quad (26)$$

10.6 *Exciting Current and Magnetic Field Strength:*

10.6.1 Exciting current is assumed to be the rms value I unless otherwise specified.

The magnetic field strength H determined from I is based upon the assumption that the peak of the current is $\sqrt{2}\,I$. In fact, this is not true because the current waveform is generally distorted and nonsinusoidal for sine voltage waveforms. This is due to the nonlinear characteristics of magnetic materials other than air. However, this is accepted practice. Hence:

$$H_z\,(\text{impedance magnetic field strength}) = \sqrt{2}N_1 I/l_1,\ \text{A/m} \quad (27)$$

where N_1 is number of turns in the test frame primary.

10.6.2 *Peak Exciting Current*—The measured peak current is given by:

$$I_P = I_{p-p}/2,\ A\ or \quad (28)$$
$$I_P = E_p/r,\ A\ or$$
$$I_P = E_{p-p}/2r,\ A$$

Hence:

$$H_p\,(\text{peak magnetic field strength}) = N_1 I_p/l_1,\ \text{A/m} \quad (29)$$

10.6.3 *Inductance Exciting Current (Optional)*—The inductive or reactive component of the exciting current, I_L, is usually determined from the measured value of reactive power, P_q in vars, where:

$$I_L = P_q/E_2,\ A \quad (30)$$

Hence:

$$H_L(\text{inductance magnetic field strength}) = \sqrt{2}N_1 I_L/l_1,\ \text{A/m} \quad (31)$$

10.7 *Relative Permeability:*

10.7.1 Several different types of ac permeability may be calculated using data collected from tests described in this test method. These different permeabilities are based upon several different definitions of magnetic field strength. The general form of the equation for relative permeability is:

$$\mu = B/(H\ \Gamma_m) \quad (32)$$

where $B = B_i + H_p\Gamma_m$. For convenience in calculating peak permeability, the intrinsic induction, B_i, may be used instead of the normal induction, B, for most testing. This entails no loss of accuracy until $H_p\Gamma_m$ becomes appreciable in magnitude relative to B_i. If greater accuracy is required, B should be used.

10.7.2 *Impedance Relative Permeability:*

$$\mu_z = B/(H_z\ \Gamma_m) \quad (33)$$

10.7.3 *Peak Relative Permeability:*

$$\mu_p = B/(H_p\ \Gamma_m) \quad (34)$$

10.7.4 *Inductance Relative Permeability:*

$$\mu_L = B/(H_L\ \Gamma_m) \quad (35)$$

10.8 *Incremental dc (Biasing) and Magnetic Field Strength:*

$$H_b(\text{dc magnetic field strength}) = N_{dc} I_{dc}/l_1,\ \text{A/m} \quad (36)$$

where:

N_{dc} = dc winding turns of the test frame and
I_{dc} = dc bias current (measured).

When the dc magnetic field strength H_b is present, the values of core loss, exciting current, and so forth measured and their derived properties, specific core loss, specific exciting power, and relative permeability are all considered to be incremental values, for example, $P_{\Delta c}$, I_Δ, $P_{\Delta q}$, $P_{\Delta c}(B{:}f)$, $P_{\Delta z}(B{:}f)$, and $\mu_{\Delta z}$. These are measured and calculated as though the dc bias were not present.

11. Precision and Bias of Measurement

11.1 *Estimated Reproducibility Between Laboratories:*

11.1.1 At low frequencies and moderate magnetic flux densities: core loss ±3 %, relative permeability ±5 %.

11.1.2 At low frequencies and high magnetic flux densities: core loss ±4 %, relative permeability ±5 %.

11.1.3 At 5000 Hz: core loss ±4 %, relative permeability ±5 %.

11.1.4 At 10 000 Hz: core loss ±5 %, relative permeability ±5 %.

11.2 Note that the above are estimates of the between-laboratory reproducibility for tests according to this test method. The within-laboratory repeatability should be much better than the above values.

11.3 *Bias*—At date of this revision, no accepted reference material and data covering the scope of this test method is available. Therefore, no statement of bias can be made.

12. Keywords

12.1 alternating-current; ammeter; core loss; customary units; Epstein; exciting power; flux voltage; form factor; incremental magnetization; magnetic flux density; magnetic; magnetic material; magnetic test; permeability; voltmeter; wattmeter

ANNEXES

(Mandatory Information)

A1. RECOMMENDED STANDARD TEST MAGNETIC FLUX DENSITIES AND TEST FREQUENCIES

A1.1 *Recommended Standard Test Points*—Unless otherwise specified, the test frequency shall be 400 Hz. If test values at higher frequencies are required, preference should be given to test frequencies listed in Table A1.1. Standard test magnetic flux densities for the various standard test frequencies are also shown.

TABLE A1.1 Recommended Test Magnetic Flux Densities for Standard Test Frequencies

Frequency, Hz	Magnetic Flux Density	
	kG	T
400	10 or 15	1.0 or 1.5
800	5 or 10	0.5 or 1.0
1000	5 or 10	0.5 or 1.0
1600	2 or 5	0.2 or 0.5
3200	2 or 5	0.2 or 0.5
5000	1 or 2	0.1 or 0.2
10 000	0.5 or 1	0.05 or 0.1

A2. EXAMPLE OF LOSS SEPARATION CALCULATION USING THE "TWO FORM FACTOR METHOD"

A2.1 In the following equations, "core loss" designates either net core loss as measured or specific core loss in either customary or SI units. It is necessary, of course, to be consistent in the quantities.

A2.2 The "Two Form Factor" method assumes that the corrected core loss at either form factor will be the same, thus:

$$P_1(100)/(h+eK_1) = P_2(100)/(h+eK_2)$$

where:

P_1 = observed core loss (specific core loss) at distortion Level 1,
P_2 = observed core loss (specific core loss) at distortion Level 2,
K_1 = $(E_{1r}/E_f)^2$,
K_2 = $(E_{2r}/E_f)^2$

E_{1r} and E_{2r} are the rms values of the secondary voltage at distortion Levels 1 and 2, respectively.

E_f = flux voltage at the specified flux density,
e = percent eddy-current loss,
h = percent hysteresis loss, and also
e = 100 – h.

Substituting in the above equation and solving for e, yields:

$e = 100(P_2 - P_1)/[P_1(K_2 - 1) - P_2(K_1 - 1)]$

NOTE A2.1—Although there are several methods mentioned in literature, the "Two Form Factor" and "Two Frequency" methods are commonly used. The "Two Form Factor" method is preferred because the measurements made at each form factor value are those encountered in this test method. It also is easy to achieve two different levels of form factor with most test equipment.