INTERNATIONAL

Designation: ~~D150 – 18~~ D150 – 22

Standard Test Methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation[1]

This standard is issued under the fixed designation D150; 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.

This standard has been approved for use by agencies of the U.S. Department of Defense.

1. ~~Scope~~ Scope*

1.1 These test methods cover the determination of relative permittivity, dissipation factor, loss index, power factor, phase angle, and loss angle of specimens of solid electrical insulating materials when the standards used are lumped impedances. The frequency range addressed extends from less than 1 Hz to several hundred megahertz.

NOTE 1—In common usage, the word relative is frequently dropped.

1.2 These test methods provide general information on a variety of electrodes, apparatus, and measurement techniques. A reader interested in issues associated with a specific material needs to consult ASTM standards or other documents directly applicable to the material to be tested.[2,3]

1.3 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.* For specific hazard statements, see 10.2.1.

1.4 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[4]

D374 Test Methods for Thickness of Solid Electrical Insulation (Metric) D0374_D0374M
D618 Practice for Conditioning Plastics for Testing
D1531 Test Methods for Relative Permittivity (Dielectric Constant) and Dissipation Factor by Fluid Displacement Procedures (Withdrawn 2012)[5]
D1711 Terminology Relating to Electrical Insulation

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[1] These test methods are under the jurisdiction of ASTM Committee D09 on Electrical and Electronic Insulating Materials and are the direct responsibility of Subcommittee D09.12 on Electrical Tests.

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[2] R. Bartnikas, Chapter 2, "Alternating-Current Loss and Permittivity Measurements," Engineering Dielectrics, Vol. IIB, Electrical Properties of Solid Insulating Materials, Measurement Techniques, R. Bartnikas, Editor, STP 926, ASTM, Philadelphia, 1987.

[3] R. Bartnikas, Chapter 1, "Dielectric Loss in Solids," Engineering Dielectrics, Vol IIA, Electrical Properties of Solid Insulating Materials: Molecular Structure and Electrical Behavior, R. Bartnikas and R. M. Eichorn, Editors, STP 783, ASTM Philadelphia, 1983.

[4] 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.

[5] The last approved version of this historical standard is referenced on www.astm.org.

***A Summary of Changes section appears at the end of this standard**

D5032 Practice for Maintaining Constant Relative Humidity by Means of Aqueous Glycerin Solutions
E104 Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions

3. Terminology

3.1 *Definitions:*

3.1.1 Use Terminology D1711 for definitions of terms used in these test methods and associated with electrical insulation materials.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *capacitance, C, n*—that property of a system of conductors and dielectrics which permits the storage of electrically separated charges when potential differences exist between the conductors.

~~3.2.1.1 *Discussion*—~~
~~Capacitance is the ratio of a quantity, *q*, of electricity to a potential difference, *V*. A capacitance value is always positive. The units are farads when the charge is expressed in coulombs and the potential in volts:~~

$$C = q/V \quad (1)$$

~~3.2.2 *dissipation factor, (D), (loss tangent), (tan δ), n*—the ratio of the loss index (κ") to the relative permittivity (κ') which is equal to the tangent of its loss angle (δ) or the cotangent of its phase angle (θ) (see Fig. 1 and Fig. 2).~~

$$D = \kappa''/\kappa' \quad (2)$$

~~3.2.2.1 *Discussion*—~~
~~*a:*~~

$$D = \tan\delta = \cot\theta = X_p/R_p = G/\omega C_p = 1/\omega C_p R_p \quad (3)$$

~~where:~~

~~G = equivalent ac conductance,~~
~~X_p = parallel reactance,~~
~~R_p = equivalent ac parallel resistance,~~
~~C_p = parallel capacitance, and~~
~~ω = $2\pi f$ (sinusoidal wave shape assumed).~~

~~The reciprocal of the dissipation factor is the quality factor, *Q*, sometimes called the storage factor. The dissipation factor, *D*, of the capacitor is the same for both the series and parallel representations as follows:~~

$$D = \omega R_s C_s = 1/\omega R_p C_p \quad (4)$$

~~The relationships between series and parallel components are as follows:~~

$$C_p = C_s/(1+D^2) \quad (5)$$

$$R_p/R_s = (1+D^2)/D^2 = 1+(1/D^2) = 1+Q^2 \quad (6)$$

~~3.2.2.2 *Discussion*—~~
~~*b: Series Representation*—While the parallel representation of an insulating material having a dielectric loss (Fig. 3) is usually the proper representation, it is always possible and occasionally desirable to represent a capacitor at a single frequency by a capacitance, C_s, in series with a resistance, R_s (Fig. 4 and Fig. 2).~~

~~3.2.3 *loss angle (phase defect angle), (δ), n*—the angle whose tangent is the dissipation factor or arctan *κ"/κ'* or whose cotangent is the phase angle.~~

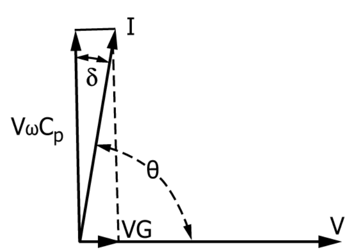


FIG. 1 Vector Diagram for Parallel Circuit

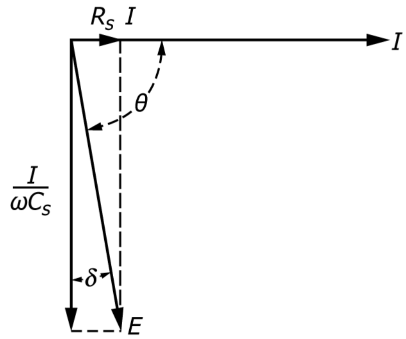


FIG. 2 Vector Diagram for Series Circuit

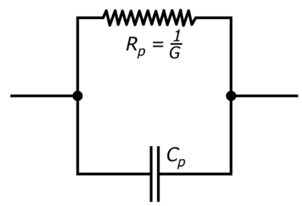


FIG. 3 Parallel Circuit

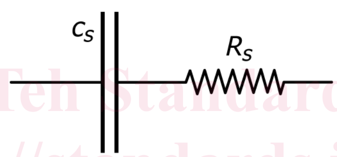


FIG. 4 Series Circuit

3.2.3.1 *Discussion*—

The relation of phase angle and loss angle is shown in Fig. 1 and Fig. 2. Loss angle is sometimes called the phase defect angle.

3.2.4 *loss index, κ'' (ε_r'') , n*—the magnitude of the imaginary part of the relative complex permittivity; it is the product of the relative permittivity and dissipation factor.

3.2.4.1 *Discussion*—

a—It is expressed as:

$$\kappa'' = \kappa' D \tag{7}$$

$$= \text{power loss}/(E^2 \times f \times \text{volume} \times \text{constant})$$

When the power loss is in watts, the applied voltage is in volts per centimeter, the frequency is in hertz, the volume is the cubic centimeters to which the voltage is applied, the constant has the value of 5.556×10^{-13}.

3.2.4.2 *Discussion*—

b—Loss index is the term agreed upon internationally. In the U.S.A. κ'' was formerly called the loss factor.

3.2.5 *phase angle, θ, n*—the angle whose cotangent is the dissipation factor, arccot κ''/κ' and is also the angular difference in the phase between the sinusoidal alternating voltage applied to a dielectric and the component of the resulting current having the same frequency as the voltage.

3.2.5.1 *Discussion*—

The relation of phase angle and loss angle is shown in Fig. 1 and Fig. 2. Loss angle is sometimes called the phase defect angle.

3.2.6 *power factor, PF,n*—the ratio of the power in watts, *W*, dissipated in a material to the product of the effective sinusoidal voltage, *V*, and current, *I*, in volt-amperes.

3.2.6.1 *Discussion*—

Power factor is expressed as the cosine of the phase angle θ (or the sine of the loss angle δ).

$$PF = W/VI = G/\sqrt{G^2 + (\omega C_p)^2} = \sin\delta = \cos\theta \tag{8}$$

When the dissipation factor is less than 0.1, the power factor differs from the dissipation factor by less than 0.5 %. Their exact relationship is found from the following:

$$PF = D/\sqrt{1+D^2} \quad (9)$$

$$D = PF/\sqrt{1-(PF)^2}$$

3.2.7 *relative permittivity (relative dielectric constant) (SIC) κ'(ε_r), n*—the real part of the relative complex permittivity. It is also the ratio of the equivalent parallel capacitance, C_p, of a given configuration of electrodes with a material as a dielectric to the capacitance, C_v, of the same configuration of electrodes with vacuum (or air for most practical purposes) as the dielectric:

$$\kappa' = C_p/C_v \quad (10)$$

3.2.7.1 *Discussion*—
a—In common usage the word "relative" is frequently dropped.

3.2.7.2 *Discussion*—
b—Experimentally, vacuum must be replaced by the material at all points where it makes a significant change in capacitance. The equivalent circuit of the dielectric is assumed to consist of C_p, a capacitance in parallel with conductance. (See Fig. 3.)

3.2.7.3 *Discussion*—
c—C_x is taken to be C_p, the equivalent parallel capacitance as shown in Fig. 3.

3.2.7.4 *Discussion*—
d—The series capacitance is larger than the parallel capacitance by less than 1 % for a dissipation factor of 0.1, and by less than 0.1 % for a dissipation factor of 0.03. If a measuring circuit yields results in terms of series components, the parallel capacitance must be calculated from Eq 5 before the corrections and permittivity are calculated.

3.2.7.5 *Discussion*—
e—The permittivity of dry air at 23°C and standard pressure at 101.3 kPa is 1.000536 (**1**).[6] Its divergence from unity, κ' − 1, is inversely proportional to absolute temperature and directly proportional to atmospheric pressure. The increase in permittivity when the space is saturated with water vapor at 23°C is 0.00025 (**2, 3**), and varies approximately linearly with temperature expressed in degrees Celsius, from 10 to 27°C. For partial saturation the increase is proportional to the relative humidity

4. Summary of Test Method

4.1 Capacitance and ac resistance measurements are made on a specimen. Relative permittivity is the specimen capacitance divided by a calculated value for the vacuum capacitance (for the same electrode configuration), and is significantly dependent on resolution of error sources. Dissipation factor, generally independent of the specimen geometry, is also calculated from the measured values.

4.2 This method provides *(1)* guidance for choices of electrodes, apparatus, and measurement approaches; and *(2)* directions on how to avoid or correct for capacitance errors.

4.2.1 General Measurement Considerations:

Fringing and Stray Capacitance	Guarded Electrodes
Geometry of Specimens	Calculation of Vacuum Capacitance
Edge, Ground, and Gap Corrections	

4.2.2 Electrode Systems - Contacting Electrodes

Electrode Materials	Metal Foil
Conducting Paint	Fired-On Silver
Sprayed Metal	Evaporated Metal
Liquid Metal	Rigid Metal
Water	

4.2.3 Electrode Systems - Non-Contacting Electrodes

Fixed Electrodes	Micrometer Electrodes
Fluid Displacement Methods	

[6] The boldface numbers in parentheses refer to the list of references appended to these test methods.

4.2.4 Choice of Apparatus and Methods for Measuring Capacitance and AC Loss

Frequency
Two-Terminal Measurements
Fluid Displacement Methods
Direct and Substitution Methods
Three-Terminal Measurements
Accuracy considerations

5. Significance and Use

5.1 *Permittivity*—Insulating materials are used in general in two distinct ways, (*1*) to support and insulate components of an electrical network from each other and from ground, and (*2*) to function as the dielectric of a capacitor. For the first use, it is generally desirable to have the capacitance of the support as small as possible, consistent with acceptable mechanical, chemical, and heat-resisting properties. A low value of permittivity is thus desirable. For the second use, it is desirable to have a high value of permittivity, so that the capacitor is able to be physically as small as possible. Intermediate values of permittivity are sometimes used for grading stresses at the edge or end of a conductor to minimize ac corona. Factors affecting permittivity are discussed in Appendix X3.

5.2 *AC Loss*—For both cases (as electrical insulation and as capacitor dielectric) the ac loss generally needs to be small, both in order to reduce the heating of the material and to minimize its effect on the rest of the network. In high frequency applications, a low value of loss index is particularly desirable, since for a given value of loss index, the dielectric loss increases directly with frequency. In certain dielectric configurations such as are used in terminating bushings and cables for test, an increased loss, usually obtained from increased conductivity, is sometimes introduced to control the voltage gradient. In comparisons of materials having approximately the same permittivity or in the use of any material under such conditions that its permittivity remains essentially constant, it is potentially useful to consider also dissipation factor, power factor, phase angle, or loss angle. Factors affecting ac loss are discussed in Appendix X3.

5.3 *Correlation*—When adequate correlating data are available, dissipation factor or power factor are useful to indicate the characteristics of a material in other respects such as dielectric breakdown, moisture content, degree of cure, and deterioration from any cause. However, it is possible that deterioration due to thermal aging will not affect dissipation factor unless the material is subsequently exposed to moisture. While the initial value of dissipation factor is important, the change in dissipation factor with aging is often much more significant.

5.4 Capacitance is the ratio of a quantity, *q*, of electricity to a potential difference, *V*. A capacitance value is always positive. The units are farads when the charge is expressed in coulombs and the potential in volts:

$$C = q/V \tag{1}$$

5.5 Dissipation factor ((*D*), (loss tangent), (tan δ)) is the ratio of the loss index (κ") to the relative permittivity (κ') which is equal to the tangent of its loss angle (δ) or the cotangent of its phase angle (θ) (see Fig. 1 and Fig. 2).

$$D = \kappa''/\kappa' \tag{2}$$

5.5.1 It is calculated via Eq 3:

$$D = \tan\delta = \cot\theta = X_p/R_p = G/\omega C_p = 1/\omega C_p R_p \tag{3}$$

where:

G = equivalent ac conductance,
X_p = parallel reactance,
R_p = equivalent ac parallel resistance,
C_p = parallel capacitance, and
ω = $2\pi f$ (sinusoidal wave shape assumed).

The reciprocal of the dissipation factor is the quality factor, *Q*, sometimes called the storage factor. The dissipation factor, *D*, of the capacitor is the same for both the series and parallel representations as follows:

$$D = \omega R_s C_s = 1/\omega R_p C_p \tag{4}$$

The relationships between series and parallel components are as follows:

$$C_p = C_s/(1+D^2) \tag{5}$$

$$R_p/R_s = (1+D^2)/D^2 = 1+(1/D^2) = 1+Q^2 \quad (6)$$

5.5.2 *Series Representation*—While the parallel representation of an insulating material having a dielectric loss (Fig. 3) is usually the proper representation, it is always possible and occasionally desirable to represent a capacitor at a single frequency by a capacitance, C_s, in series with a resistance, R_s (Fig. 4 and Fig. 2).

5.6 Loss angle ((phase defect angle), (δ)) is the angle whose tangent is the dissipation factor or arctan κ''/κ' or whose cotangent is the phase angle.

5.6.1 The relation of phase angle and loss angle is shown in Fig. 1 and Fig. 2. Loss angle is sometimes called the phase defect angle.

5.7 Loss index (κ" (ε_r")) is the magnitude of the imaginary part of the relative complex permittivity; it is the product of the relative permittivity and dissipation factor.

5.7.1 The loss index is expressed as:

$$\kappa'' = \kappa' D \quad (7)$$

$$= \text{power loss}/(E^2 \times f \times \text{volume} \times \text{constant})$$

.

When the power loss is in watts, the applied voltage is in volts per centimeter, the frequency is in hertz, the volume is the cubic centimeters to which the voltage is applied, the constant has the value of 5.556×10^{-13}.

NOTE 2—Loss index is the term agreed upon internationally. In the United States, κ" was formerly called the loss factor.

5.8 Phase angle (θ) is the angle whose cotangent is the dissipation factor, arccot κ"/κ' and is also the angular difference in the phase between the sinusoidal alternating voltage applied to a dielectric and the component of the resulting current having the same frequency as the voltage.

5.8.1 The relation of phase angle and loss angle is shown in Fig. 1 and Fig. 2. Loss angle is sometimes called the phase defect angle.

5.9 Power factor (*PF*) is the ratio of the power in watts, *W*, dissipated in a material to the product of the effective sinusoidal voltage, *V*, and current, *I*, in volt-amperes.

5.9.1 Power factor is expressed as the cosine of the phase angle θ (or the sine of the loss angle δ).

$$PF = W/VI = G/\sqrt{G^2+(\omega C_p)^2} = \sin\delta = \cos\theta \quad (8)$$

When the dissipation factor is less than 0.1, the power factor differs from the dissipation factor by less than 0.5 %. Their exact relationship is found from the following:

$$PF = D/\sqrt{1+D^2} \quad (9)$$

$$D = PF/\sqrt{1-(PF)^2}$$

5.10 Relative permittivity ((relative dielectric constant) (SIC) κ'(ε_r)) is the real part of the relative complex permittivity. It is also the ratio of the equivalent parallel capacitance, C_p, of a given configuration of electrodes with a material as a dielectric to the capacitance, C_v, of the same configuration of electrodes with vacuum (or air for most practical purposes) as the dielectric:

$$\kappa' = C_p/C_v \quad (10)$$

NOTE 3—In common usage the word "relative" is frequently dropped.

NOTE 4—Experimentally, vacuum must be replaced by the material at all points where it makes a significant change in capacitance. The equivalent circuit of the dielectric is assumed to consist of C_p, a capacitance in parallel with conductance. (See Fig. 3.)

NOTE 5—C_x is taken to be C_p, the equivalent parallel capacitance as shown in Fig. 3.

NOTE 6—The series capacitance is larger than the parallel capacitance by less than 1 % for a dissipation factor of 0.1, and by less than 0.1 % for a dissipation factor of 0.03. If a measuring circuit yields results in terms of series components, the parallel capacitance must be calculated from Eq 5 before the corrections and permittivity are calculated.

NOTE 7—The permittivity of dry air at 23 °C and standard pressure at 101.3 kPa is 1.000536 (1).[6] Its divergence from unity, κ' – 1, is inversely proportional to absolute temperature and directly proportional to atmospheric pressure. The increase in permittivity when the space is saturated with water vapor at 23 °C is 0.00025 (2, 3), and varies approximately linearly with temperature expressed in degrees Celsius, from 10 °C to 27 °C. For partial saturation the increase is proportional to the relative humidity.

6. General Measurement Considerations

6.1 *Fringing and Stray Capacitance*—These test methods are based upon measuring the specimen capacitance between electrodes, and measuring or calculating the vacuum capacitance (or air capacitance for most practical purposes) in the same electrode system. For unguarded two-electrode measurements, the determination of these two values required to compute the permittivity, κ_x' is complicated by the presence of undesired fringing and stray capacitances which get included in the measurement readings. Fringing and stray capacitances are illustrated by Figs. 5 and 6 for the case of two unguarded parallel plate electrodes between which the specimen is to be placed for measurement. In addition to the desired direct interelectrode capacitance, C_v, the system as seen at terminals a-a' includes the following:

C_e = fringing or edge capacitance,
C_g = capacitance to ground of the outside face of each electrode,
C_L = capacitance between connecting leads,
C_{Lg} = capacitance of the leads to ground, and
C_{Le} = capacitance between the leads and the electrodes.

Only the desired capacitance, C_v, is independent of the outside environment, all the others being dependent to a degree on the proximity of other objects. It is necessary to distinguish between two possible measuring conditions to determine the effects of the undesired capacitances. When one measuring electrode is grounded, as is often the case, all of the capacitances described are in parallel with the desired C_v- with the exception of the ground capacitance of the grounded electrode and its lead. If C_v is placed within a chamber with walls at guard potential, and the leads to the chamber are guarded, the capacitance to ground no longer appears, and the capacitance seen at a-a' includes C_v and C_e only. For a given electrode arrangement, the edge capacitance, C_e, can be calculated with reasonable accuracy when the dielectric is air. When a specimen is placed between the electrodes, the value of the edge capacitance can change requiring the use of an edge capacitance correction using the information from Table 1. Empirical corrections have been derived for various conditions, and these are given in Table 1 (for the case of thin electrodes such as foil). In routine work, where best accuracy is not required it is convenient to use unshielded, two-electrode systems and make the approximate corrections. Since area (and hence C_v) increases of the square diameter while perimeter (and hence C_e) increases linearly with diameter, the percentage error in permittivity due to neglecting the edge correction decreases with increasing specimen diameter. However, for exacting measurements it is necessary to use guarded electrodes.

6.2 *Guarded Electrodes*—The fringing and stray capacitance at the edge of the guarded electrode is practically eliminated by the addition of a guard electrode as shown in Fig. 7 and Fig. 8. If the test specimen and guard electrode extend beyond the guarded electrode by at least twice the thickness of the specimen and the guard gap is very small, the field distribution in the guarded area will be identical with that existing when vacuum is the dielectric, and the ratio of these two direct capacitances is the permittivity. Furthermore, the field between the active electrodes is defined and the vacuum capacitance can be calculated with the accuracy limited only by the accuracy with which the dimensions are known. For these reasons the guarded electrode (three-terminal) method is to be used as the referee method unless otherwise agreed upon. Fig. 8 shows a schematic representation of a completely guarded and shielded electrode system. Although the guard is commonly grounded, the arrangement shown permits grounding

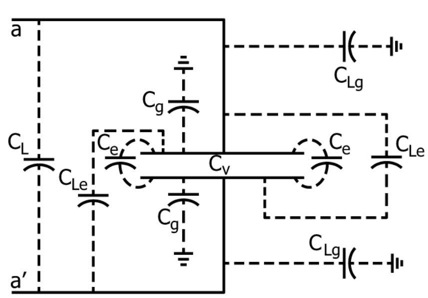


FIG. 5 Stray Capacitance, Unguarded Electrodes

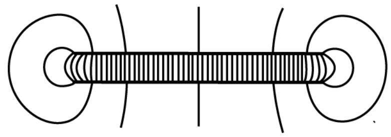


FIG. 6 Flux Lines Between Unguarded Electrodes

either measuring electrode or none of the electrodes to accommodate the particular three-terminal measuring system being used. If the guard is connected to ground, or to a guard terminal on the measuring circuit, the measured capacitance is the direct capacitance between the two measuring electrodes. If, however, one of the measuring electrodes is grounded, the capacitance to ground of the ungrounded electrode and leads is in parallel with the desired direct capacitance. To eliminate this source of error, surround the ungrounded electrode with a shield connected to guard as shown in Fig. 8. In addition to guarded methods, which are not always convenient or practical and which are limited to frequencies less than a few megahertz, techniques using special cells and procedures have been devised that yield, with two-terminal measurements, accuracies comparable to those obtained with guarded measurements. Such methods described here include shielded micrometer electrodes (7.3.2) and fluid displacement methods (7.3.3).

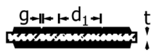
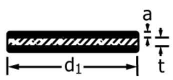
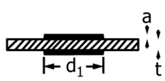
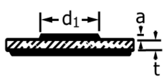
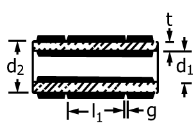
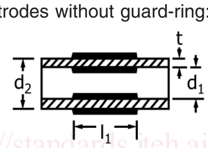
6.3 *Geometry of Specimens*—For determining the permittivity and dissipation factor of a material, sheet specimens are preferable. Cylindrical specimens can also be used, but generally with lesser accuracy. The source of the greatest uncertainty in permittivity is in the determination of the dimensions of the specimen, and particularly that of its thickness. Therefore, the thickness shall be large enough to allow its measurement with the required accuracy. The chosen thickness will depend on the method of producing the specimen and the likely variation from point to point. For 1 % accuracy a thickness of 1.5 mm (0.06 in.) is usually sufficient, although for greater accuracy it is desirable to use a thicker specimen. Another source of error, when foil or rigid electrodes are used, is in the unavoidable gap between the electrodes and the specimen. For thin specimens the error in permittivity can be as much as 25 %. A similar error occurs in dissipation factor, although when foil electrodes are applied with a grease, the two errors are not likely to have the same magnitude. For the most accurate measurements on thin specimens, use the fluid displacement method ~~(6.3.3).~~(7.3.3). This method reduces or completely eliminates the need for electrodes on the specimen. The thickness must be determined by measurements distributed systematically over the area of the specimen that is used in the electrical measurement and shall be uniform within ±1 % of the average thickness. If the whole area of the specimen will be covered by the electrodes, and if the density of the material is known, the average thickness can be determined by weighing. The diameter chosen for the specimen shall be such as to provide a specimen capacitance that can be measured to the desired accuracy. With well-guarded and screened apparatus there need be no difficulty in measuring specimens having capacitances of 10 pF to a resolution of 1 part in 1000. If a thick specimen of low permittivity is to be tested, it is likely that a diameter of 100 mm or more will be needed to obtain the desired capacitance accuracy. In the measurement of small values of dissipation factor, the essential points are that no appreciable dissipation factor shall be contributed by the series resistance of the electrodes and that in the measuring network no large capacitance shall be connected in parallel with that of the specimen. The first of these points favors thick specimens; the second suggests thin specimens of large area. Micrometer electrode methods ~~(6.3.2)~~(7.3.2) can be used to eliminate the effects of series resistance. Use a guarded specimen holder (Fig. 8) to minimize extraneous capacitances.

6.4 *Calculation of Vacuum Capacitance*—The practical shapes for which capacitance can be most accurately calculated are flat parallel plates and coaxial cylinders, the equations for which are given in Table 1. These equations are based on a uniform field between the measuring electrodes, with no fringing at the edges. Capacitance calculated on this basis is known as the direct interelectrode capacitance.

6.5 *Edge, Ground, and Gap Corrections*—The equations for calculating edge capacitance, given in Table 1, are empirical, based on published work **(4)** (see 8.5). They are expressed in terms of picofarads per centimetre of perimeter and are thus independent of the shape of the electrodes. It is recognized that they are dimensionally incorrect, but they are found to give better approximations to the true edge capacitance than any other equations that have been proposed. Ground capacitance cannot be calculated by any equations presently known. When measurements must be made that include capacitance to ground, it is recommended that the value be determined experimentally for the particular setup used. The difference between the capacitance measured in the two-terminal arrangement and the capacitance calculated from the permittivity and the dimensions of the specimen is the ground capacitance plus the edge capacitance. The edge capacitance can be calculated using one of the equations of Table 1. As long as the same physical arrangement of leads and electrodes is maintained, the ground capacitance will remain constant, and the experimentally determined value can be used as a correction to subsequently measured values of capacitance. The effective area of a guarded electrode is greater than its actual area by approximately half the area of the guard gap (**5, 6, 7**). Thus, the diameter of a circular electrode, each dimension of a rectangular electrode, or the length of a cylindrical electrode is increased by

TABLE 1 Calculations of Vacuum Capacitance and Edge Corrections (see 8.5)

Note 1—See Table 2 for Identification of Symbols used.

Type of Electrode	Direct Inter-Electrode Capacitance in Vacuum, pF	Correction for Stray Field at an Edge, pF
Disk electrodes with guard-ring: 	$C_v = \varepsilon_0 \frac{A}{t} = 0.0088542 \frac{A}{t}$ $A = \frac{\pi}{4}(d_1 + B^A g)^2$	$C_e = 0$
Disk electrodes without guard-ring: Diameter of the electrodes = diameter of the specimen: 		where a << *t*, $C_e = (0.0087 - 0.00252 \ln t)\ P$
Equal electrodes smaller than the specimen: 	$C_v = 0.0069541 \frac{d_1^{\ 2}}{t}$	$C_e = (0.0019\ \kappa_x' - 0.00252 \ln t + 0.0068)P$ where: κ_x' = an approximate value of the specimen permit tivity, and a << *t*.
Unequal electrodes: 		$C_e = (0.0041\ \kappa_x' - 0.00334 \ln t + 0.0122)P$ where: κ_x' = an approximate value of the specimen permittivity, and a << *t*.
Cylindrical electrodes with guard-ring: 	$C_v = \frac{0.055632\ (l_1 + B^A g)}{\ln \frac{d_2}{d_1}}$	$C_e = 0$
Cylindrical electrodes without guard-ring: 	$C_v = \frac{0.055632\ l_1}{\ln \frac{d_2}{d_1}}$	If $\frac{t}{t + d_1} < \frac{1}{10}$ $C_e = (0.0038\ \kappa_x' - 0.00504 \ln t + 0.0136)P$ $P = \pi\ (d_1 + t)$ where κ_x' = an approximate value of the specimen permittivity.

[A] See Appendix X2 for corrections to guard gap.

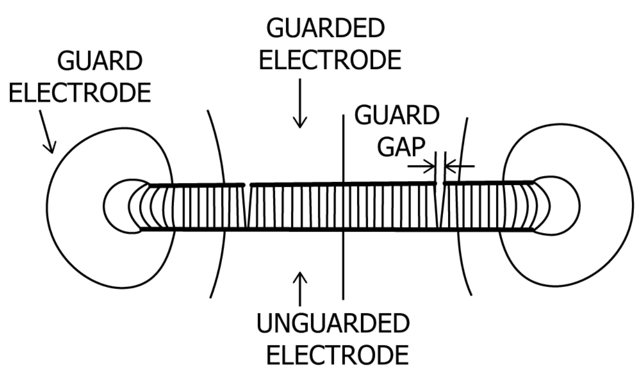


FIG. 7 Flux Lines Between Guarded Parallel Plate Electrodes

the width of this gap. When the ratio of gap width, *g*, to specimen thickness, *t*, is appreciable, the increase in the effective dimension of the guarded electrode is somewhat less than the gap width. Details of computation for this case are given in Appendix X2.

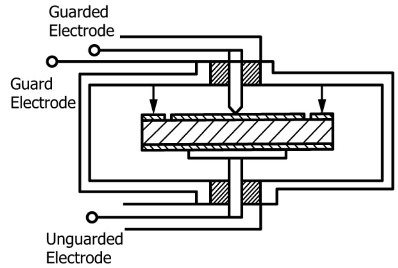


FIG. 8 Three-Terminal Cell for Solids

7. Electrode Systems[7]

7.1 *Contacting Electrodes*—It is acceptable for a specimen to be provided with its own electrodes, of one of the materials listed below. For two-terminal measurements, the electrodes shall either extend to the edge of the specimen or be smaller than the specimen. In the latter case, it is acceptable for the two electrodes to be equal or unequal in size. If they are equal in size and smaller than the specimen, the edge of the specimen must extend beyond the electrodes by at least twice the specimen thickness. The choice between these three sizes of electrodes will depend on convenience of application of the electrodes, and on the type of measurement adopted. The edge correction (see Table 1) is smallest for the case of electrodes extending to the edge of the specimen and largest for unequal electrodes. When the electrodes extend to the edge of the specimen, these edges must be sharp. Such electrodes must be used, if attached electrodes are used at all, when a micrometer electrode system is employed. When equal-size electrodes smaller than the specimen are used, it is difficult to center them unless the specimen is translucent or an aligning fixture is employed. For three-terminal measurements, the width of the guard electrode shall be at least twice the thickness of the specimen (**6, 8**). The gap width shall be as small as practical (0.5 mm is possible). For measurement of dissipation factor at the higher frequencies, electrodes of this type are likely to be unsatisfactory because of their series resistance. Use micrometer electrodes for the measurements.

7.2 *Electrode Materials:*

7.2.1 *Metal Foil*—Lead or tin foil from ~~0.0075~~0.0075 mm to ~~0.025 mm~~ 0.025 mm thick applied with a minimum quantity of refined petrolatum, silicone grease, silicone oil, or other suitable low-loss adhesive is generally used as the electrode material. Aluminum foil has also been used, but it is not recommended because of its stiffness and the probability of high contact resistance due to the oxidized surface. Lead foil is also likely to give trouble because of its stiffness. Apply such electrodes under a smoothing pressure sufficient to eliminate all wrinkles and to work excess adhesive toward the edge of the foil. One very effective method is to use a narrow roller, and to roll outward on the surface until no visible imprint can be made on the foil. With care the adhesive film can be reduced to 0.0025 mm. As this film is in series with the specimen, it will always cause the measured permittivity to be too low and probably the dissipation factor to be too high. These errors usually become excessive for specimens of thickness less than 0.125 mm. The error in dissipation factor is negligible for such thin specimens only when the dissipation factor of the film is nearly the same as that of the specimen. When the electrode is to extend to the edge, it shall be made larger than the specimen and then cut to the edge with a small, finely ground blade. A guarded and guard electrode can be made from an electrode that covers the entire surface, by cutting out a narrow strip (0.5 mm is possible) by means of a compass equipped with a narrow cutting edge.

7.2.2 *Conducting Paint*—Certain types of high-conductivity silver paints, either air-drying or low-temperature-baking varieties, are commercially available for use as electrode material. They are sufficiently porous to permit diffusion of moisture through them and thereby allow the test specimen to condition after application of the electrodes. This is particularly useful in studying humidity effects. The paint has the disadvantage of not being ready for use immediately after application. It usually requires an overnight air-drying or low-temperature baking to remove all traces of solvent, which otherwise has the potential to increase both permittivity and dissipation factor. It is often also not easy to obtain sharply defined electrode areas when the paint is brushed on, but it is possible to overcome by spraying the paint and employing either clamp-on or pressure-sensitive masks. The conductivity of silver paint electrodes is often low enough to give trouble at the higher frequencies. It is essential that the solvent of the paint does not affect the specimen permanently.

7.2.3 *Fired-On Silver*—Fired-on silver electrodes are suitable only for glass and other ceramics that are able to withstand, without change, a firing temperature of about ~~350°C.~~350 °C. Its high conductivity makes such an electrode material satisfactory for use

[7] Additional information on electrode systems can be found in Research Report RR:D09-1037 available from ASTM Headquarters.

on low-loss materials such as fused silica, even at the highest frequencies, and its ability to conform to a rough surface makes it satisfactory for use with high-permittivity materials, such as the titanates.

7.2.4 *Sprayed Metal*—A low-melting-point metal applied with a spray gun provides a spongy film for use as electrode material which, because of its grainy structure, has roughly the same electrical conductivity and the same moisture porosity as conducting paints. Suitable masks must be used to obtain sharp edges. It conforms readily to a rough surface, such as cloth, but does not penetrate very small holes in a thin film and produce short circuits. Its adhesion to some surfaces is poor, especially after exposure to high humidity or water immersion. Advantages over conducting paint are freedom from effects of solvents, and readiness for use immediately after application.

7.2.5 *Evaporated Metal*—Evaporated metal used as an electrode material has the potential to have inadequate conductivity because of its extreme thinness, and must be backed with electroplated copper or sheet metal. Its adhesion is adequate, and by itself it is sufficiently porous to moisture. The necessity for using a vacuum system in evaporating the metal is a disadvantage.

7.2.6 *Rigid Metal*—For smooth, thick, or slightly compressible specimens, it is permissible to use rigid electrodes under high pressure, especially for routine work. Electrodes 10 mm in diameter, under a pressure of 18.0 MPa have been found useful for measurements on plastic materials, even those as thin as 0.025 mm. Electrodes 50 mm in diameter, under pressure, have also been used successfully for thicker materials. However, it is difficult to avoid an air film when using solid electrodes, and the effect of such a film becomes greater as the permittivity of the material being tested increases and its thickness decreases. The uncertainty in the determination of thickness also increases as the thickness decreases. It is possible that the dimensions of a specimen will continue to change for as long as 24 h after the application of pressure.

7.2.7 *Water*—Water can be used as one electrode for testing insulated wire and cable when the measurements are made at low frequency (up to 1000 Hz, approximately). Care must be taken to ensure that electrical leakage at the ends of the specimen is negligible.

7.3 *Non-Contacting Electrodes:*

7.3.1 *Fixed Electrodes*—It is possible to measure specimens of sufficiently low surface conductivity, without applied electrodes, by inserting them in a prefabricated electrode system, in which there is an intentional air gap on one or both sides of the specimen. Assemble the electrode system rigidly and ensure that it includes a guard electrode. For the same accuracy, a more accurate determination of the electrode spacing and the thickness of the specimen is required than if direct contact electrodes are used. However, these limitations are likely to be removed if the electrode system is filled with a liquid (see 7.3.3).

7.3.2 *Micrometer Electrodes*—The micrometer-electrode system, as shown in Fig. 9, was developed **(9)** to eliminate the errors caused by the series inductance and resistance of the connecting leads and of the measuring capacitor at high frequencies. A built-in vernier capacitor is also provided for use in the susceptance variation method. It accomplishes this by maintaining these inductances and resistances relatively constant, regardless of whether the test specimen is in or out of the circuit. The specimen, which is either the same size as, or smaller than, the electrodes, is clamped between the electrodes. Unless the surfaces of the specimen are lapped or ground very flat, metal foil or its equivalent must be applied to the specimen before it is placed in the electrode system. If electrodes are applied, they also must be smooth and flat. Upon removal of the specimen, the electrode system can be adjusted to have the same capacitance by moving the micrometer electrodes closer together. When the micrometer-electrode system is carefully calibrated for capacitance changes, its use eliminates the corrections for edge capacitance, ground capacitance,

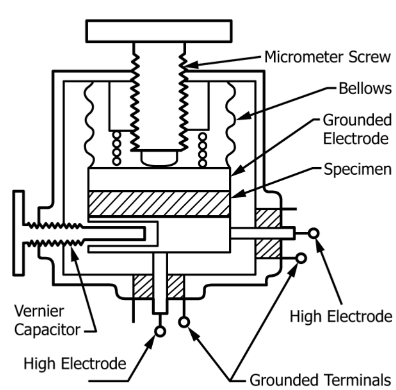


FIG. 9 Micrometer-Electroder System