



Standard Test Methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation¹

This standard is issued under the fixed designation D 150; 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 Department of Defense.

1. 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 that can be covered 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. The reader should also 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 and health practices and determine the applicability of regulatory limitations prior to use.* For specific hazard statements, see 7.2.6.1 and 10.2.1.

2. Referenced Documents

2.1 ASTM Standards:

- D 374 Test Methods for Thickness of Solid Electrical Insulation⁴
- D 618 Practice for Conditioning Plastics for Testing⁵
- D 1082 Test Method for Dissipation Factor and Permittivity (Dielectric Constant) of Mica⁴
- D 1531 Test Method for Relative Permittivity (Dielectric

- Constant) and Dissipation Factor by Fluid Displacement Procedures⁶
- D 1711 Terminology Relating to Electrical Insulation⁴
- D 5032 Practice for Maintaining Constant Relative Humidity by Means of Aqueous Glycerin Solutions⁶
- E 104 Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions⁷
- E 197 Specifications for Enclosures and Servicing Units for Tests Above and Below Room Temperature.⁸

3. Terminology

3.1 Definitions:

3.1.1 *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.

3.1.1.1 *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:

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

3.1.2 *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).

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

3.1.2.1 *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,

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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 Annual Book of ASTM Standards, Vol 10.01.

⁵ Annual Book of ASTM Standards, Vol 08.01.

⁶ Annual Book of ASTM Standards, Vol 10.02.

⁷ Annual Book of ASTM Standards, Vol 11.03.

⁸ Discontinued, see 1980 Annual Book of ASTM Standards, Parts 40 and 41.

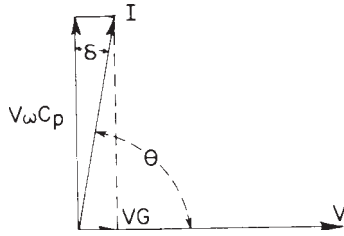


FIG. 1 Vector Diagram for Parallel Circuit

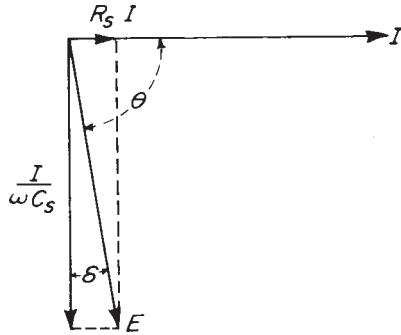


FIG. 2 Vector Diagram for Series Circuit

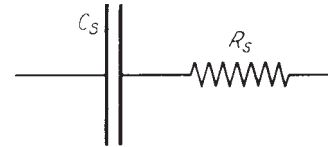


FIG. 4 Series Circuit

$$\kappa'' = \kappa' D$$

$$= \text{power loss}/(E^2 \times f \times \text{volume} \times \text{constant}) \quad (7)$$

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

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

3.1.5 phase angle, θ , n —the angle whose cotangent is the dissipation factor, $\text{arccot } \kappa''/\kappa'$ 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.

3.1.5.1 Discussion—*b*—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.

3.1.6 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.

3.1.6.1 Discussion—Power factor may be 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 may be found from the following:

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

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

3.1.7 relative permittivity (relative dielectric constant) (*SIC*) $\kappa'(\epsilon_r)$, 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:

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

3.1.7.1 Discussion—*a*—In common usage the word “relative” is frequently dropped.

3.1.7.2 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.)

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

3.1.7.4 Discussion—*d*—The series capacitance is larger than the parallel capacitance by less than 1% for a dissipation

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:

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

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

3.1.2.2 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).

3.1.3 loss angle (phase defect angle), (δ) , n —the angle whose tangent is the dissipation factor or $\text{arctan } \kappa''/\kappa'$ or whose cotangent is the phase angle.

3.1.3.1 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.

3.1.4 loss index, $\kappa''(\epsilon_r)$, n —the magnitude of the imaginary part of the relative complex permittivity; it is the product of the relative permittivity and dissipation factor.

3.1.4.1 Discussion—*a*—It may be expressed as:

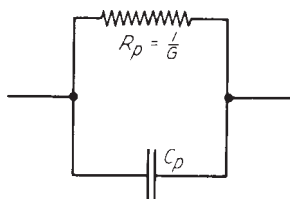


FIG. 3 Parallel Circuit

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.

3.1.7.5 *Discussion—e*—The permittivity of dry air at 23°C and standard pressure at 101.3 kPa is 1.000536 (1).⁹ Its divergence from unity, $\kappa' - 1$, 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

3.2 Other definitions may be found in Terminology D 1711.

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 (a) guidance for choices of electrodes, apparatus, and measurement approaches; and (b) 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	

4.2.4 Choice of Apparatus and Methods for Measuring Capacitance and A-C Loss

Frequency	Direct and Substitution Methods
Two-Terminal Measurements	Three-Terminal Measurements
Fluid Displacement Methods	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 may be physically as small as possible. Intermediate values of permit-

tivity 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 should 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, the quantity considered may also be 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 may be used 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, deterioration due to thermal aging may 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 may be much more significant.

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:

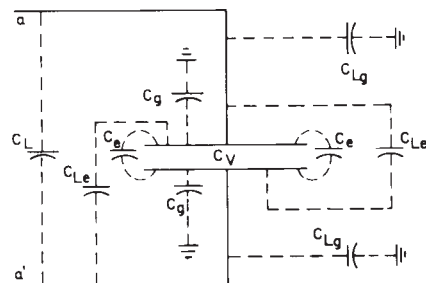


FIG. 5 Stray Capacitance, Unguarded Electrodes

⁹ The boldface numbers in parentheses refer to the list of references appended to these test methods.

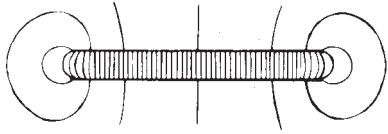


FIG. 6 Flux Lines Between Unguarded Electrodes

- 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 may be 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.

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: 	$C_v = \epsilon_0 \frac{A}{t} = 0.0088542 \frac{A}{t}$ $A = \frac{\pi}{4} (d_1 + B^A g)^2$	$C_e = 0$
Disk electrodes without guard-ring: Diameter of the electrodes = diameter of the specimen: 	$C_v = 0.0069541 \frac{d_1^2}{t}$	where $a \ll t$, $C_e = (0.0087 - 0.00252 \ln t)P$
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 permittivity, and $a \ll t$.
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 $a \ll t$.
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: 	$C_v = \frac{0.055632 l_1}{\ln \frac{d_2}{d_1}}$	$C_e = (0.0038 \kappa_x' - 0.00504 \ln t + 0.0136)P$ $P = \pi (d_1 + t)$ where κ_x' = an approximate value of the specimen permittivity.

^ASee Appendix X2 for corrections to guard gap.

TABLE 2 Calculation of Permittivity and Dissipation Factor, Noncontacting Electrodes

Permittivity	Dissipation Factor	Identification of Symbols
<p>Micrometer electrodes in air (with guard ring):</p> $D_x = D_c + M\kappa_x' \Delta D$ $\kappa_x' = \frac{1}{1 - \frac{\Delta C t_0}{C_1 t}}$ <p>or, if t_0 is adjusted to a new value, t_0', such that $\Delta C = 0$</p> $\kappa_x' = \frac{t}{t - (t_0 - t_0')}$		
<p>Plane electrodes—fluid displacement:</p> $D_x = D_c + \Delta D M$ $\kappa_x' = \frac{\kappa_f'}{1 + D_x^2}$ $\left[\frac{(C_f + \Delta C)(1 + D_c^2)}{C_f + M[C_f - (C_f + \Delta C)(1 + D_c^2)]} \right] \cdot \left[\frac{(C_f + \Delta C)(1 + D_c^2)}{C_f + M[C_f - (C_f + \Delta C)(1 + D_c^2)]} \right]$ <p>When the dissipation factor of the specimen is less than about 0.1, the following equations can be used:</p> $\kappa_x' = \frac{\kappa_f' \Delta C t_0}{1 - \kappa_f' C_v + \Delta C t}$ $D_x = D_c + M \frac{\kappa_x'}{\kappa_f'} \Delta D$		
<p>CYLINDRICAL ELECTRODES (WITH GUARD RINGS)—FLUID DISPLACEMENT.</p> $\kappa_x' = \frac{\kappa_f'}{1 - \frac{\Delta C \log d_3/d_0}{C_1 \log d_2/d_1}}$ $D_x = D_c + \Delta D \frac{\kappa_x'}{\kappa_f'} \left\{ \log \frac{d_3}{d_0} - 1 \right\} \left\{ \log \frac{d_2}{d_1} \right\}$		
<p>Two-fluid method—plane electrodes (with guard ring):</p> $(D_x^2 + 1) \kappa_x' = \kappa_{f1}' + \frac{\Delta C_1 C_2 [(D_{f2}^2 + 1) \kappa_{f2}' - \kappa_{f1}']}{\Delta C_1 C_2 - \Delta C_2 C_1}$ $D_x = (D_x^2 + 1) \kappa_x' \left[\frac{\epsilon_0 A_2}{t_x} \left(\frac{D_{c2}}{C_2} - \frac{D_{f2}}{C_{f2}} \right) + \frac{D_{f2}}{\kappa_{f2}'} \right]$ $t_x = \frac{[C_2 C_{f2} \Delta C_1 - C_1 C_{f1} \Delta C_2] (D_{f2}^2 + 1) \epsilon_0 A_2 \kappa_{f1}' \kappa_{f2}'}{[\kappa_{f2}' (D_{f2}^2 + 1) - \kappa_{f1}'] C_1 C_2 C_{f1} C_{f2}}$		

ΔC = capacitance change when specimen is inserted (+ when capacitance increases),
 C_1 = capacitance with specimen in place,
 ΔD = increase in dissipation factor when specimen is inserted,
 D_c = dissipation factor with specimen in place.
 D_f = dissipation factor, fluid,
 t_0 = parallel-plate spacing mm,
 t = average thickness of specimen mm,
 M = $t_0/t - 1$,
 C_f = $\kappa_f' C_v$, capacitance with fluid alone,
 ϵ_0 = permittivity of a vacuum (0.0088542 pF/mm),
 A = area of the electrodes, mm² (the smaller if the two are unequal),
 κ_f' = permittivity of fluid at test temperature (= 1.00066 for air at 23°C, 50 % RH),
 C_v = vacuum capacitance of area considered ($\epsilon_0 A/t_0$, pF),
 d_0 = OD of inner electrode,
 d_1 = ID of specimen,
 d_2 = OD of specimen, and
 d_3 = ID of outer electrode
 g = guard gap, mm
 $d_{1,2, \text{ or } 3}$ = diameter, mm (see sketches)
 C_v = Vacuum capacitance
 B = $1 - 2\delta$ (see Appendix X2.1.3)
 (ed. note: ALSO eliminate the "''" after B (two places) and the footnote reference to Appendix X2).
 C_e = edge capacitance
 \ln = natural logarithm
 κ_x' = specimen permittivity (approximate value for Table 1 calculations)
 p = perimeter of measuring (low voltage) electrode, mm
 l = length of measuring (low voltage) electrode, mm
 NOTE— C and D in these equations are the values for the cell and may require calculations from the readings of the measuring circuit (as when using parallel substitution). Refer to Note 3.

NOTE—In the equation for the two-fluid method, subscripts 1 and 2 refer to the first and second fluids, respectively.
 NOTE—Values of C in the two-fluid equations are the equivalent series values.
 A_2 = effective area of guarded electrode with specimen in liquid, = $(d + B_g)^2 \pi/4$ (See Appendix X2 for corrections to guard gap).

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

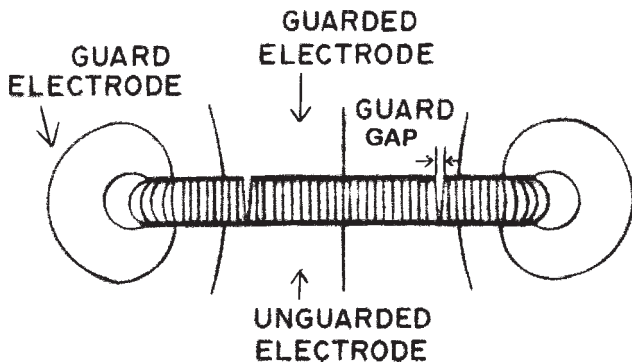


FIG. 7 Flux Lines Between Guarded Parallel Plate Electrodes

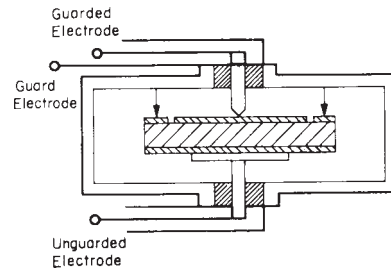


FIG. 8 Three-Terminal Cell for Solids

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 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, the ungrounded electrode should be surrounded by 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 which should, therefore, 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 may be 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 may not have the same magnitude. For the most accurate measurements on thin specimens, the fluid displacement method should be used (6.3.3). 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 should be uniform within $\pm 1\%$ 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 should 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. A thick specimen of low permittivity may necessitate a diameter of 100 mm or more 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) can be used to eliminate the effects of series resistance. A guarded specimen holder (Fig. 8) can be used 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, 18). Thus, the diameter of a circular electrode, each dimension of a rectangular electrode, or the length of a cylindrical electrode is increased by 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.

7. Electrode Systems ¹⁰

7.1 Contacting Electrodes—A specimen may be provided with its own electrodes, of one of the materials listed below. For two-terminal measurements the electrodes may extend either to the edge of the specimen or may be smaller than the specimen. In the latter case the two electrodes may be equal or unequal in size. If 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

¹⁰ Additional information on electrode systems can be found in Research Report RR: D09-1037 available from ASTM Headquarters.

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, 7). 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 may be unsatisfactory because of their series resistance. Micrometer electrodes should be used for the measurements.

7.2 Electrode Materials:

7.2.1 Metal Foil—Lead or tin foil from 0.0075 to 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 also may give trouble because of its stiffness. Such electrodes should be applied 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 should 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 may increase both permittivity and dissipation factor. It also may not be easy to obtain sharply defined electrode areas when the paint is brushed on, but this limitation usually can be overcome by spraying the paint and employing either clamp-on or pressure-sensitive masks. The conductivity of silver paint electrodes may be 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 can withstand, without change, a firing temperature of about 350°C. Its high conductivity makes such an electrode material satisfactory for use 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 may 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 Liquid Metal—Mercury electrodes may be used by floating the specimen on a pool of mercury and using confining rings with sharp edges for retaining the mercury for the guarded and guard electrodes, as shown in Fig. 9. A more convenient arrangement, when a considerable number of specimens must be tested, is the test fixture shown in Fig. 4 of Test Method D 1082. There is some health hazard present due to the toxicity of mercury vapor, especially at elevated temperatures, and suitable precautions should be taken during use. In measuring low-loss materials in the form of thin films such as mica splittings, contamination of the mercury may introduce considerable error, and it may be necessary to use clean mercury for each test. Wood's metal or other low-melting alloy can be used in a similar manner with a somewhat reduced health hazard.

7.2.6.1 Warning— *Mercury metal-vapor poisoning has long been recognized as a hazard in the industry. The exposure limits are set by government agencies and are usually based upon recommendations made by the American Conference of Governmental Industrial Hygienists.¹¹ The concentration of mercury vapor over spills from broken thermometers, barometers, and other instruments using mercury can easily exceed*

¹¹ American Conference of Governmental Hygienists, Building D-7, 6500 Glenway Ave., Cincinnati, OH 45211.

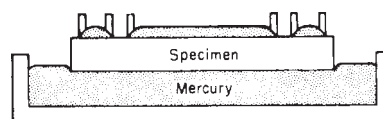


FIG. 9 Guarded Specimen with Mercury Electrodes

these exposure limits. Mercury, being a liquid with high surface tension and quite heavy, will disperse into small droplets and seep into cracks and crevices in the floor. This increased area of exposure adds significantly to the mercury vapor concentration in the air. The use of a commercially available emergency spill kit is recommended whenever a spill occurs. Mercury vapor concentration is easily monitored using commercially available sniffers. Make spot checks periodically around operations where mercury is exposed to the atmosphere. Make thorough checks after spills.

7.2.7 Rigid Metal—For smooth, thick, or slightly compressible specimens, rigid electrodes under high pressure can sometimes be used, 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. The dimensions of a specimen may continue to change for as long as 24 h after the application of pressure.

7.2.8 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—Specimens of sufficiently low surface conductivity can be measured without applied electrodes by inserting them in a prefabricated electrode system, in which there is an intentional airgap on one or both sides of the specimen. The electrode system should be rigidly assembled and should preferably include 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, if the electrode system is filled with a liquid, these limitations may be removed (see 7.3.3).

7.3.2 Micrometer Electrodes—The micrometer-electrode system, as shown in Fig. 10, was developed (8) 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 made 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, and connection capacitance. In this respect it is advantageous to use it over the entire frequency range. A disadvantage is that the capacitance calibration is not as accurate as that of a conventional multiplate variable capacitor, and also it is not direct reading. At frequencies below 1 MHz, where the effect of series inductance and resistance in the leads is negligible, the capacitance calibration of the micrometer electrodes can be replaced by that of a standard capacitor, either in parallel with the micrometer-electrode system or in the adjacent capacitance arm of the bridge. The change in capacitance with the specimen in and out is measured in terms of this capacitor. A source of minor error in a micrometer-electrode system is that the edge capacitance of the electrodes, which is included in their calibration, is slightly changed by the presence of a dielectric having the same diameter as the electrodes. This error can be practically eliminated by making the diameter of the specimen less than that of the electrodes by twice its thickness (3). When no electrodes are attached to the specimen, surface conductivity may cause serious errors in dissipation factor measurements of low loss material. When the bridge used for measurement has a guard circuit, it is advantageous to use guarded micrometer electrodes. The effects of fringing, etc., are almost completely eliminated. When the electrodes and holder are well made, no capacitance calibration is necessary as the capacitance can be calculated from the electrode spacing and the diameter. The micrometer itself will require calibration, however. It is not practicable to use electrodes on the specimen when using guarded micrometer electrodes unless the specimen is smaller in diameter than the guarded electrode.

7.3.3 Fluid Displacement Methods—When the immersion medium is a liquid, and no guard is used, the parallel-plate system preferably shall be constructed so that the insulated high potential plate is supported between, parallel to, and equidistant from two parallel low-potential or grounded plates, the latter being the opposite inside walls of the test cell designed to hold the liquid. This construction makes the electrode system essentially self-shielding, but normally requires duplicate test specimens. Provision must be made for precise temperature measurement of the liquid (9, 10). Cells should be constructed of brass and gold plated. The high-potential electrode shall be removable for cleaning. The faces must be as nearly optically flat and plane parallel as possible.

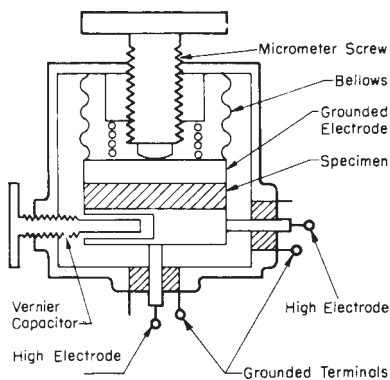


FIG. 10 Micrometer-Electrode System

A suitable liquid cell for measurements up to 1 MHz is shown in Fig. 4 of Test Method D 1531. Changes in the dimensions of this cell may be made to provide for testing sheet specimens of various thicknesses or sizes, but, such changes should not reduce the capacitance of the cell filled with the standard liquid to less than 100 pF. For measurements at frequencies from 1 to about 50 MHz, the cell dimensions must be greatly reduced, and the leads must be as short and direct as possible. The capacitance of the cell with liquid shall not exceed 30 or 40 pF for measurements at 50 MHz. Experience has shown that a capacitance of 10 pF can be used up to 100 MHz without loss of accuracy. Guarded parallel-plate electrodes have the advantage that single specimens can be measured with full accuracy. Also a prior knowledge of the permittivity of the liquid is not required as it can be measured directly (11). If the cell is constructed with a micrometer electrode, specimens having widely different thicknesses can be measured with high accuracy since the electrodes can be adjusted to a spacing only slightly greater than the thickness of the specimen. If the permittivity of the fluid approximates that of the specimen, the effect of errors in determination of specimen thicknesses are minimized. The use of a nearly matching liquid and a micrometer cell permits high accuracy in measuring even very thin film.

7.3.3.1 All necessity for determining specimen thickness and electrode spacing is eliminated if successive measurements are made in two fluids of known permittivity (12, 13, 18). This method is not restricted to any frequency range; however, it is best to limit use of liquid immersion methods to frequencies for which the dissipation factor of the liquid is less than 0.01 (preferably less than 0.0001 for low-loss specimens).

7.3.3.2 When using the two-fluid method it is important that both measurements be made on the same area of the specimen as the thickness may not be the same at all points. To ensure that the same area is tested both times and to facilitate the handling of thin films, specimen holders are convenient. The holder can be a U-shaped piece that will slide into grooves in the electrode cell. It is also necessary to control the temperature to at least 0.1°C. The cell may be provided with cooling coils for this purpose (13).

8. Choice of Apparatus and Methods for Measuring Capacitance and AC Loss

8.1 *Frequency Range*—Methods for measuring capacitance and ac loss can be divided into three groups: null methods, resonance methods, and deflection methods. The choice of a method for any particular case will depend primarily on the operating frequency. The resistive- or inductive-ratio-arm capacitance bridge in its various forms can be used over the frequency range from less than 1 Hz to a few megahertz. For frequencies below 1 Hz, special methods and instruments are required. Parallel-T networks are used at the higher frequencies from 500 kHz to 30 MHz, since they partake of some of the characteristics of resonant circuits. Resonance methods are used over a frequency range from 50 kHz to several hundred megahertz. The deflection method, using commercial indicating meters, is employed only at power-line frequencies from 25 to 60 Hz, where the higher voltages required can easily be obtained.

8.2 *Direct and Substitution Methods*—In any direct method, the values of capacitance and ac loss are in terms of all the circuit elements used in the method, and are therefore subject to all their errors. Much greater accuracy can be obtained by a substitution method in which readings are taken with the unknown capacitor both connected and disconnected. The errors in those circuit elements that are unchanged are in general eliminated; however, a connection error remains (Note 4).

8.3 *Two- and Three-Terminal Measurements*—The choice between three-terminal and two-terminal measurements is generally one between accuracy and convenience. The use of a guard electrode on the dielectric specimen nearly eliminates the effect of edge and ground capacitance, as explained in 6.2. The provision of a guard terminal eliminates some of the errors introduced by the circuit elements. On the other hand, the extra circuit elements and shielding usually required to provide the guard terminal add considerably to the size of the measuring equipment, and the number of adjustments required to obtain the final result may be increased many times. Guard circuits for resistive-ratio-arm capacitance bridges are rarely used at frequencies above 1 MHz. Inductive-ratio-arm bridges provide a guard terminal without requiring extra circuits or adjustments. Parallel-T networks and resonant circuits are not provided with guard circuits. In the deflection method a guard can be provided merely by extra shielding. The use of a two-terminal micrometer-electrode system provides many of the advantages of three-terminal measurements by nearly eliminating the effect of edge and ground capacitances but may increase the number of observations or balancing adjustments. Its use also eliminates the errors caused by series inductance and resistance in the connecting leads at the higher frequencies. It can be used over the entire frequency range to several hundred megahertz. When a guard is used, the possibility exists that the measured dissipation factor may be less than the true value. This is caused by resistance in the guard circuit at points between the guard point of the measuring circuit and the guard electrode. This may arise from high contact resistance, lead resistance, or from high resistance in the guard electrode itself. In extreme cases the dissipation factor may appear to be negative. This condition is most likely to exist when the dissipation factor without the guard is higher than normal due to surface leakage. Any point capacitively coupled to the measuring electrodes and resistively coupled to the guard point can be a source of difficulty. The common guard resistance produces an equivalent negative dissipation factor proportional to $C_h C_l R_g$, where C_h and C_l are guard-to-electrode capacitances and R_g is the guard resistance (14).

8.4 *Fluid Displacement Methods*—The fluid displacement method may be employed using either three-terminal or self-shielded, two-terminal cells. With the three-terminal cell the permittivity of the fluids used may be determined directly. The self-shielded, two-terminal cell provides many of the advantages of the three-terminal cell by nearly eliminating the effects of edge and ground capacitance, and it may be used with measuring circuits having no provision for a guard. If it is equipped with an integral micrometer electrode, the effects on

the capacitance of series inductance in the connective leads at the higher frequencies may be eliminated.

8.5 Accuracy—The methods outlined in 8.1 contemplate an accuracy in the determination of permittivity of $\pm 1\%$ and of dissipation factor of $\pm (5\% + 0.0005)$. These accuracies depend upon at least three factors: the accuracy of the observations for capacitance and dissipation factor, the accuracy of the corrections to these quantities caused by the electrode arrangement used, and the accuracy of the calculation of the direct interelectrode vacuum capacitance. Under favorable conditions and at the lower frequencies, capacitance can be measured with an accuracy of $\pm (0.1\% + 0.02 \text{ pF})$ and dissipation factor with an accuracy of $\pm (2\% + 0.00005)$. At the higher frequencies these limits may increase for capacitance to $\pm (0.5\% + 0.1 \text{ pF})$ and for dissipation factor to $\pm (2\% + 0.0002)$. Measurements of dielectric specimens provided with a guard electrode are subject only to the error in capacitance and in the calculation of the direct interelectrode vacuum capacitance. The error caused by too wide a gap between the guarded and the guard electrodes will generally amount to several tenths percent, and the correction can be calculated to a few percent. The error in measuring the thickness of the specimen can amount to a few tenths percent for an average thickness of 2 mm, on the assumption that it can be measured to ± 0.005 mm. The diameter of a circular specimen can be measured to an accuracy of $\pm 0.1\%$, but enters as the square. Combining these errors, the direct interelectrode vacuum capacitance can be determined to an accuracy of $\pm 0.5\%$. Specimens with contact electrodes, measured with micrometer electrodes, have no corrections other than that for direct interelectrode capacitance, provided they are sufficiently smaller in diameter than the micrometer electrodes. When two-terminal specimens are measured in any other manner, the calculation of edge capacitance and determination of ground capacitance will involve considerable error, since each may be from 2 to 40% of the specimen capacitance. With the present knowledge of these capacitances, there may be a 10% error in calculating the edge capacitance and a 25% error in evaluating the ground capacitance. Hence the total error involved may be from several tenths to 10% or more. However, when neither electrode is grounded, the ground capacitance error is minimized (6.1). With micrometer electrodes, it is possible to measure dissipation factor of the order of 0.03 to within ± 0.0003 and dissipation factor of the order of 0.0002 to within ± 0.00005 of the true values. The range of dissipation factor is normally 0.0001 to 0.1 but may be extended above 0.1. Between 10 and 20 MHz it is possible to detect a dissipation factor of 0.00002. Permittivity from 2 to 5 may be determined to $\pm 2\%$. The accuracy is limited by the accuracy of the measurements required in the calculation of direct interelectrode vacuum capacitance and by errors in the micrometer-electrode system.

9. Sampling

9.1 See materials specifications for instructions on sampling.

10. Procedure

10.1 Preparation of Specimens:

10.1.1 General—Cut or mold the test specimens to a suitable shape and thickness determined by the material specification being followed or by the accuracy of measurement required, the test method, and the frequency at which the measurements are to be made. Measure the thickness in accordance with the standard method required by the material being tested. If there is no standard for a particular material, then measure thickness in accordance with Test Methods D 374. The actual points of measurement shall be uniformly distributed over the area to be covered by the measuring electrodes. Apply suitable measuring electrodes to the specimens (Section 7) (unless the fluid displacement method will be used), the choice as to size and number depending mainly on whether three-terminal or two-terminal measurements are to be made and, if the latter, whether or not a micrometer-electrode system will be used (7.3). The material chosen for the specimen electrodes will depend both on convenience of application and on whether or not the specimen must be conditioned at high temperature and high relative humidity (Section 7). Obtain the dimensions of the electrodes (of the smaller if they are unequal) preferably by a traveling microscope, or by measuring with a steel scale graduated to 0.25 mm and a microscope of sufficient power to allow the scale to be read to the nearest 0.05 mm. Measure the diameter of a circular electrode, or the dimensions of a rectangular electrode, at several points to obtain an average.

10.1.2 Micrometer Electrodes—The area of the specimen may be equal to or less than the area of the electrodes, but no part of the specimen shall extend beyond the electrode edges. The edges of the specimens shall be smooth and perpendicular to the plane of the sheet and shall also be sharply defined so that the dimensions in the plane of the sheet may be determined to the nearest 0.025 mm. The thickness may have any value from 0.025 mm or less to about 6 mm or greater, depending upon the maximum usable plate spacing of the parallel-plate electrode system. The specimens shall be as flat and uniform in thickness as possible, and free of voids, inclusions of foreign matter, wrinkles, and other defects. It has been found that very thin specimens may be tested more conveniently and accurately by using a composite of several or a large number of thicknesses. The average thickness of each specimen shall be determined as nearly as possible to within ± 0.0025 mm. In certain cases, notably for thin films and the like but usually excluding porous materials, it may be preferable to determine the average thickness by calculation from the known or measured density of the material, the area of the specimen face, and the mass of the specimen (or specimens, when tested in multiple thicknesses of the sheet), obtained by accurate weighing on an analytical balance.

10.1.3 Fluid Displacement—When the immersion medium is a liquid, the specimen may be larger than the electrodes if the permittivity of the standard liquid is within about 1% of that of the specimen (see Test Method D 1531). Also, duplicate specimens will normally be required for a cell of the type described in 7.3.3, although it is possible to test a single specimen at a time in such cells. In any case, the thickness of the specimen preferably should not be less than about 80% of