EID 11

Dielectric Loss and Permittivity Measurements with GenRad Precision Capacitance Bridges

1. INTRODUCTION

Measurements on an electrical insulating material for ac losses and permittivity are, in effect, measurements of the capacitance and loss of a capacitor in which the material being measured forms the dielectric. With measuring systems such as the GenRad 1620 and 1621 available, instrumentation for capacitor measurements over the frequency range from 20 Hz to 100 kHz is quite simple. The problems lie in preparing the dielectrics and the electrodes, so that the resulting capacitors represent the properties of the materials to be measured. The GenRad instruments also help here since they are particularly well suited to the three-terminal fluid-displacement or "air-gap" methods that eliminate the need for attached electrodes.

The International Electrotechnical Commission (IEC) and the American Society for Testing and Materials (ASTM) have developed and published standard methods for the measurement of ac dielectric loss (dissipation factor) and permittivity (dielectric constant). These methods are described in the following documents:

IEC Publication 250 "Recommended Methods for the Determination of the Permittivity and Dielectric Dissipation Factor of Electrical Insulating Materials at Power, Audio, and Radio frequencies including Meter Wavelengths."

ASTM D150 "Standard Methods of Test for AC Loss Characteristics and Dielectric Constant (Permittivity) of Solid Electrical Insulating Materials."

ASTM D924 "Standard Method of Test for Power Factor and Dielectric Constant of Electrical Insulating Liquids."

The IEC Recommendations and ASTM Standards are substantially the same as far as basic procedures, equations, and the like are concerned. They were written for use by people highly skilled in testing electrical insulation. As such, they are not always readily understood by those who are considerably less experienced. These people will probably find it desirable to have both publications. Frequently one publication will help clarify a point that is obscure in the other. The IEC document has the added advantage for many that it is written in both French and English.

Impedance Measurement APPLICATION NOTE

GenRad

DEFINITIONS

Following are definitions of terms that are used in the characterization and measurement of dielectrics:

Relative Permittivity, ϵ_r: (Dielectric Constant, k')† The ratio of the capacitance, C_x, of a capacitor, in which the space between and around the electrodes is filled with the insulating material in question, to the capacitance, C_o, of the identical configuration of electrodes in vacuum:

$$\epsilon_r = \frac{C_x}{C_o}$$

The relative permittivity, ϵ_r, of *dry* air at normal atmospheric pressure is 1.00053. This is usually close enough to the value in a vacuum, 1.0000, to allow the capacitance, C_a, of the configuration of electrodes in air to be used instead of C_o to determine the relative permittivity, ϵ_r, with sufficient accuracy.

Permittivity, ϵ: The product of the insulating material's relative permittivity, ϵ_r, and the electric constant (or permittivity of vacuum), ϵ_o, in the measurement system. In the SI (International System of Units) system, the absolute permittivity is expressed in farads per meter (F/m); and the electric constant, ϵ_o, has the following value:

$$\epsilon_o = 8.854 \times 10^{-12}\ \text{F/m} \approx \frac{1}{36\pi} \times 10^{-9}\ \text{F/m}$$

Since picofarads and centimeters are usually used in calculating capacitance, the usual form of this equation is:

$$\epsilon_o = 0.08854\ \text{pF/cm}$$

Dielectric Loss Angle, δ,: The angle by which the phase difference between applied voltage and resulting current deviates from $\pi/2$ rad when the dielectric of the capacitor consists exclusively of the dielectric materials.

Dielectric Dissipation Factor, tan δ, (D)†: The tangent of the loss angle, δ. (Note: In some cases the term "loss tangent" is used in place of dielectric dissipation factor because the result of the measurement of the loss is reported as the tangent of the loss angle.)

Loss Index, ϵ_r'', (k'')†: The product of the material's dissipation factor (tan δ) and its relative permittivity:

$$\epsilon_r'' = \epsilon_r \tan\delta$$

Relative Complex Permittivity, ϵ_r^*: A combination of the relative permittivity and loss index.

$$\epsilon_r^* = \epsilon_r' - j\epsilon_r''$$

$$\epsilon_r' = \epsilon_r$$

where

$$\epsilon_r'' = \epsilon_r \tan\delta$$

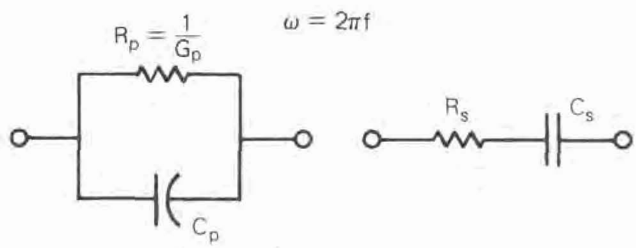
$$\tan\delta = \frac{\epsilon_r''}{\epsilon_r'}$$

†Equivalent nomenclature used in ASTM D150 in USA
‡Registered trademark of DuPont Co.

EQUIVALENT CIRCUITS

A capacitor with losses can be represented at any given frequency either by a capacitance, C_s, and a resistance, R_s, in series or by a capacitance, C_p, and a resistance, R_p, (or conductance G_p) in parallel.

Equivalent Parallel Circuit: Equivalent Series Circuit:



$$D = \tan\delta = \frac{1}{\omega C_p R_p} = \frac{G_p}{\omega C_p} \qquad D = \tan\delta = \omega C_s R_s$$

Figure 1. Series and Parallel Equivalent Circuits

While the parallel representation of an insulating material having a dielectric loss is usually the more proper representation, it is always possible and often desirable to represent a capacitor at a single frequency by a capacitance, C_s, in series with a resistance, R_s. If tan δ is small, less than 0.01, for all practical measurements $C_s = C_p$.

Following are some conversion relations between series and parallel components.

$$C_p = \frac{C_s}{1 + \tan^2\delta} \qquad C_p = \frac{C_s}{1 + D^2}$$

$$R_p = \frac{1}{G_p} = \frac{1 + \tan^2\delta}{\tan^2\delta} \qquad R_p = \frac{1}{G_p} = \frac{1 + D^2}{D^2} R_s$$

$$\omega C_s R_s = \frac{1}{\omega C_p R_p} = \tan\delta = D$$

The dielectric dissipation factor, tan δ or D, is the same for the series and parallel representations.

The GR 1615 Bridge (1620 System) will measure series capacitance and dissipation factor or parallel capacitance and conductance. The 1616 Bridge (1621 System) measures only parallel capacitance and conductance.

FACTORS AFFECTING DIELECTRIC PROPERTIES OF MATERIALS

Frequency: Most materials have dissipation factors and permittivities which vary significantly with frequency. Fused silica (quartz), polystyrene, polyethylene, and polytetrafluoroethylene (Teflon‡) are among the few whose characteristics vary only slightly with frequency.

Changes in permittivity and dissipation factor are produced by the dielectric-polarization and conductivity of the material. The most important changes are caused by dipole polarization due to polar molecules and interfacial polarization caused by inhomogeneities in the material, shown in the typical curves of Figure 2.

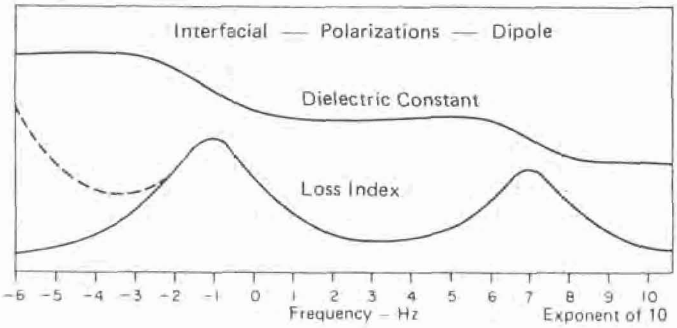


Figure 2. Variation of Dielectric Constant and Loss Index with Frequency

Temperature: The loss index usually shows a maximum at a frequency which varies with the temperature of the dielectric material. The temperature coefficients of dissipation factor and permittivity can be positive or negative depending on the position of the loss-index maximum with respect to the measuring temperature.

Moisture: The absorption of water or the formation of a water film on the surface of a dielectric material increases the degree of polarization, which raises the permittivity, the dissipation factor and the dc conductivity. It is therefore very important to condition the test specimens and control the moisture content, before and during testing, in order to obtain accurate measurements. (Note: The largest effects of humidity usually occur at frequencies below about 1 MHz and in the microwave region.)

Field Strength: When interfacial polarization exists, the number of free ions increases with the field strength, and the magnitude and position of the loss-index maximum are altered. At higher frequencies, permittivity and dissipation factor are independent of field strength, as long as no partial discharge occurs in the dielectric.

FORM OF SPECIMEN

Solid Insulating Materials Sheet specimens are the form of material considered in the methods described in this note. Measurements on materials in tubular form are described elsewhere.‡

When high accuracy is required in measuring permittivity, the source of the greatest uncertainty is in the dimensions of the specimen, and particularly its thickness, which should therefore be large enough to allow its measurement with the required accuracy. The choice of thickness depends on the method of producing the specimen and the likely variation in thickness from point to point. For 1% accuracy, a thickness such as 1.5 mm is usually enough, although for greater accuracy it may be desirable to use a thicker specimen, for example 6 – 12 mm.

The thickness must be determined by measurements distributed systematically over the area of the specimen which is used in the electrical measurement, and should be uniform to within ±1% of the average thickness. When the electrodes extend to the edge of the specimen, the thickness can be determined by weighing, if the density of the material is known. The area chosen for the specimen should be large enough to provide a specimen capacitance which can be measured to the desired accuracy. With well-guarded and shielded equipment, there is no difficulty in measuring capacitances of 10 pF to a high degree of accuracy.

With the measuring system described in this note, solid dielectrics in sheet form are the required type of specimen. The samples can be either square or circular with a minimum dimension of 7.5 cm and a maximum dimension of 8.3 cm and a thickness up to 0.8 cm. No electrodes are required on the specimen since the Balsbaugh Model LD-3 Three-Terminal Research Cell (GR 1615-9005) has guarded electrodes.

Liquid Insulating Materials The LD-3 Cell is not suitable for most measurements on liquids except for those used in the fluid-displacement methods of measurements on solids. Cells suitable for measurements on liquids with the GR 1620 and 1621 Measuring Systems are described in IEC Publication 250. The Balsbaugh Type LRC-1 or 350 G Liquid Cell is suitable for this measurement.

In measurement on liquids, contamination of the specimen is very critical and cells for measurements on liquids must be thoroughly cleaned between measurements.

MEASUREMENT SYSTEM

A schematic of the measurement system is shown in Figure 3. The three-terminal connections of the GR 1620 and 1621 Measurement Systems make it easy to shield the specimens and to eliminate errors due to stray capacitances. The combination of the three-terminal measurement and the guard electrode on the LD-3 Research Cell makes possible the accurate knowledge of the dimensions of the area of the specimen being tested. The guard is also necessary in testing some materials at high humidities where surface leakage may be a problem.

Cell Description The LD-3 Research Cell is a three-terminal micrometer-electrode cell with plane, parallel electrodes for fluid or solid samples. The fixed, circular electrode, L, in Figure 4, has an inner section with a diameter of 6.350 ± .0025 cm separated by a .025 to .030 cm insulating gap from the guard ring around it. The other electrode, H, can be moved by a micrometer to adjust the separation, h_0, of the electrodes from 0 to 0.8 cm, and the separation can be read on the micrometer scale to .001 cm and estimated to .0002 cm.

The cell capacitance from L to H, when measured on a three-terminal bridge to eliminate the ground capacitances C_{LG} and C_{HG}, is simply that of a capacitor with parallel plates of area $A = \pi d^2/4$ and separation h_0.

$$C_{HL} = 0.08854 \frac{A}{h_0} \text{ pF} \qquad \text{(dimensions in cm)}$$

The effective diameter, d, is greater than that of the L electrode by approximately the width of the gap. CAUTION: Add the gap width, w, *not* 2 w, to the diameter of the electrode L to obtain its effective diameter.

Cell Assembly The cell as received is completely assembled except for the drain plug, overflow and micrometer. The Teflon drain plug should be installed in the hole in the bottom of the face plate and the overflow threaded into the tapped hole at the top of the cell. The micrometer is installed by setting it at about .01 cm and

‡Instruction book for GR 900-LB Slotted Line for measurements at frequencies above 100 MHz and IEC Publication 250, Para. 4.1.4.2

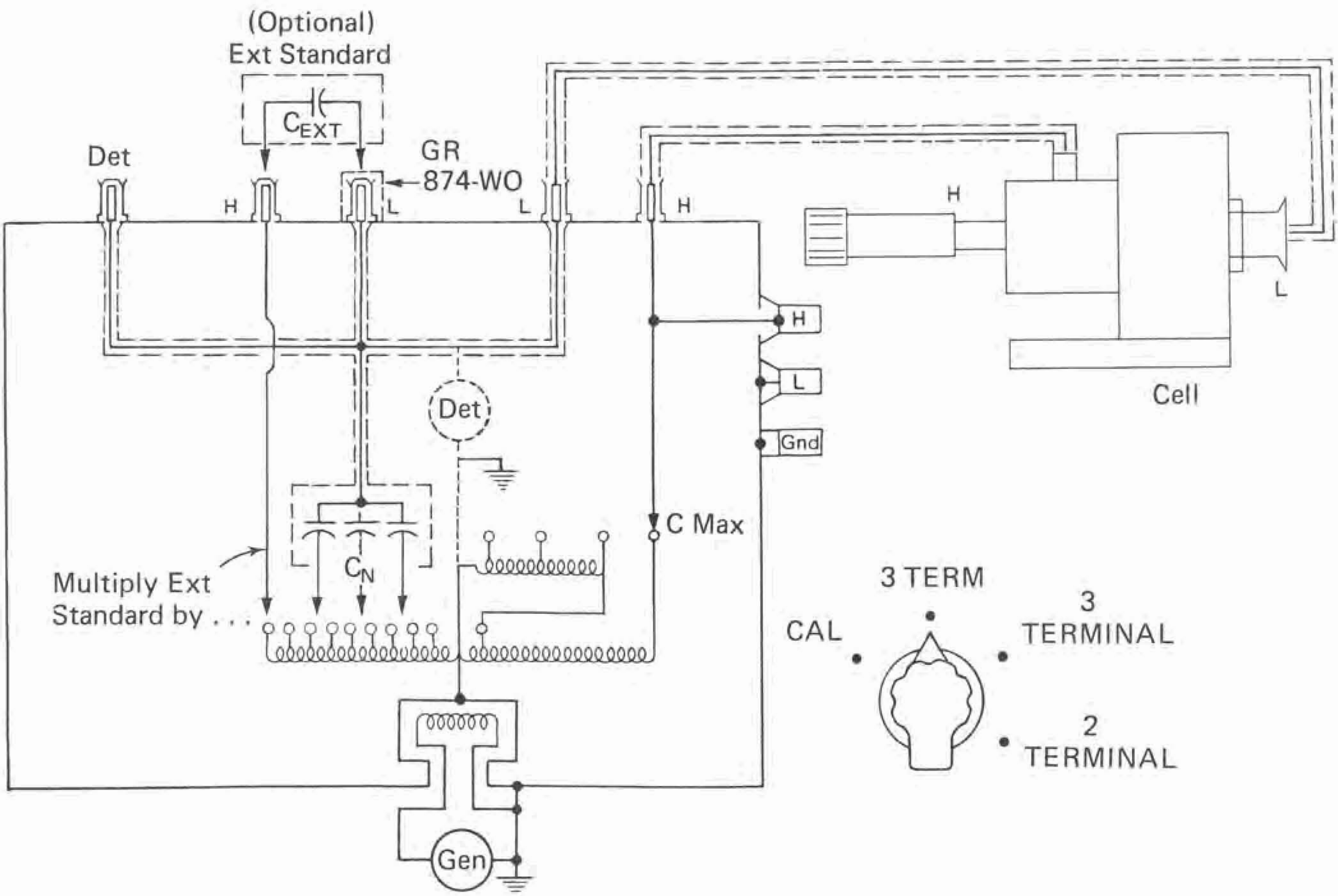


Figure 3. Bridge Circuit for 3-Terminal Coaxial Measurement of a Test Cell

pushing it into the hole at the rear of the cell until the electrodes come together. The resistance felt is from a spring which provides rearward movement of the movable electrode. Then tighten the micrometer locking set screw just enough to prevent the spring from pushing the micrometer out. Gradually turn the micrometer knob until a zero reading is obtained, and then further tighten the micrometer locking set screw. Tightening the set screw too much will score the shaft and make removal difficult.

Electrical Connections The guard and low- or measuring-section electrode of the cell are connected internally to a GR874® coaxial connector on the face plate. The high lead is brought to the banana-plug receptacle extending from the shaft supporting the movable high electrode. The cell is connected to the bridge as shown in Figure 3. The low electrode is connected to the L (LOW) UNKNOWN terminal on the bridge by means of a GR 874-R22A Patch Cord and the high lead to the H (HIGH) UNKNOWN terminal by means of an 874-R34 Patch Cord. The terminal selector switch on the bridge is set in the three-terminal, shielded position for the measurements described in this note.

The bridge is connected to the generator and detector as outlined in the bridge instruction book. The connections of generator and detector to the bridge can be reversed to permit higher voltages to be applied to the unknown and to provide, in special cases, higher bridge sensitivity, as described in the instructions.

Calibration of Cell Before any precise dielectric measurements are attempted, other than by the two-fluid method, an accurate calibration of a cell should be made by measuring the cell capacitance with air dielectric, while the separation, h_o, is varied over its range. This will give the effective diameter, d, of the electrode and the relation between the micrometer reading, h_m, and the effective separation or spacing, h_o. If there is a micrometer error, h_{mo}, (usually caused by an error in the adjustment of the micrometer zero position), then

$$h_o = h_m + h_{mo}$$

The capacitance is $C_{HL} = \frac{s}{h_o} = \frac{s}{h_m + h_{mo}}$

where the constant

$$s = \epsilon_0 \epsilon_r A = 0.08854 \times 1.0005 \times \frac{\pi d^2}{4} = 0.06957\ d_{eff}^2\ \text{pF cm}$$

and $d_{eff} = 3.791\sqrt{s}$ cm

with air as the dielectric.

The micrometer reading, h_m, is then related to the capacitance by:

$$h_m = \frac{s}{C} - h_{mo}$$

and this is the equation of a straight line for h_m vs $\frac{1}{C}$ with slope s and intercept with the $\frac{1}{C}$ axis of $-h_{mo}$.

An example of the calibration of the cell that is used in the following examples is: The data for C vs h_m are shown below, as measured on the 1615 Bridge at 1 kHz, and with the test cell micrometer calibrated in inches but converted to centimeters.

Micrometer, h_m		Capacitance, C
inches	cm	pF
.0100	.0254	103.358
.0300	.0762	36.1694
.0500	.1270	21.9156
.0700	.1778	15.7202
.0900	.2286	12.2614
.1100	.2794	10.0446
.1300	.3302	8.5083
.1500	.3810	7.3790

The straight line that best fits these data can be found by using linear regression or least-squares methods of curve fitting (see any text on statistical methods), and pocket calculators make the calculations very easy. The results of such calculations on these data are:

$$s = 2.826 \text{ pF cm} \qquad h_{mo} = .0019 \text{ cm}$$

The separation, h_o, is therefore greater than the micrometer reading, h_m, by .0019 cm. The effective diameter, d_{eff}, is (with s in pF cm)

$$d_{eff} = 3.791\sqrt{s} = 3.791\sqrt{2.826} = 6.373 \text{ cm}$$

and the relation between C and the micrometer reading, h_m, is:

$$C = \frac{2.826}{(h_m + .0019)} \quad \text{pF}$$

The cell is, therefore, a calibrated variable capacitor and is often used as such in dielectric measurements.

When the calculations for curve fitting are not possible or not appropriate, a simple fit can be made with the straight line between the first and last data points, e.g., the points h_1 at .0254 and h_8 at .3810 cm above.

In this case:

$$s = \frac{h_8 - h_1}{\frac{1}{C_8} - \frac{1}{C_1}} = \frac{(.3810 - .0254)}{\frac{1}{7.379} - \frac{1}{103.358}} = 2.826 \quad \text{pF cm}$$

and, at .381 cm,

$$h_{mo} = \frac{s}{C} - h_m = \frac{2.826}{7.379} - 0.381 = .0020 \text{ cm}$$

The results obtained in this example are good, but to avoid errors from a bad measurement at the chosen points, the calculations should be repeated at other points or the data plotted to see how well the points fit a straight line.

Since the electrode diameter, d, and therefore the slope, s, can be expected to remain constant with time, a quick check for changes in the micrometer error, h_{mo}, can be made at any time for a cell with a calibrated value of s by measuring at some point, h_m, on the micrometer the corresponding C and calculating

$$h_{mo} = \frac{s}{C} - h_m.$$

MEASUREMENT METHODS

Measurement with Contacting Electrodes (a quick result, but use with caution) The definition of dielectric constant, $\epsilon_r = C_x/C_o$, suggests that ϵ_r can be determined by two measurements of capacitance: (1) C_1, the capacitance of a test cell with the unknown material as the dielectric, and (2) C_F, the capacitance of the same cell, with the same area and spacing, but with vacuum (or, usually, air with negligible error) as the dielectric between the electrodes. This simple method can be used to determine ϵ_r and tan δ (= D) with a minimum of calculation but not with great accuracy, e.g., within 10%.

As an example of the method, a sample of acrylic plastic sheet was measured in the test cell (Figure 4). The sample was a square 7.62 x 7.62 by 0.292 cm thick. The electrodes of the test cell were opened, the sample inserted between the electrodes, and the electrodes closed with the micrometer until the electrodes just touched the sample. NOTE: **Do not** force the electrodes against the sample by turning the micrometer with more than a very light finger pressure. Excessive pressure will change the micrometer calibration or damage the screw threads.

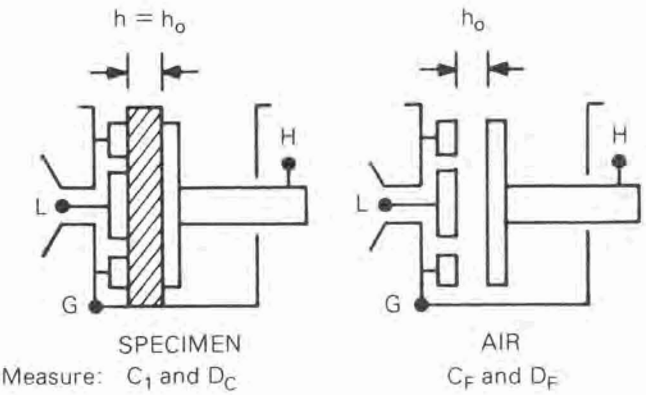


Figure 4. Measurement with Contacting Electrodes

With the specimen between the electrodes, the capacitance, C_1, and dissipation factor, D_C, are measured, and the micrometer reading, h_m, is recorded. For this specimen

$C_1 = 29.5441$ pF $\quad D_C = .0436 \quad h_m = .2941$ cm

The specimen was then removed from the cell, the micrometer readjusted to $h_m = .2941$ cm and the air C_F and D_F measured.

$C_F = 9.5422$ pF $\quad D_F = .00001 \quad h_m = .2941$ cm

The dielectric constant of the specimen is, neglecting the small difference between C_F in air and C_o in a vacuum,

$$\epsilon_r = C_1/C_F = 29.5441/9.5422 = 3.10$$

The dielectric dissipation factor, tan δ_X (= D_X) is .0436.

The dissipation factor D_X or tan δ_X of the specimen is, for most purposes, the measured $D_C = .0436$ of the cell with the specimen, because the loss in the empty cell and the phase errors in the bridge are both very small, e.g., $D_F = .00001$ at 1 kHz. The clear, dry, 3-terminal test cell can be used as a standard of low loss ($D = 0 \pm .00005$) to test the phase error in the bridge standards and ratio. This error in the 1615 and 1616 Bridges will be of the same order of magnitude as the uncertainty of cell loss at 1 kHz but can show a measurable increase at higher frequencies.

If the measured D_F of the air cell is a significant percent of the specimen D_C, set the cell air capacitance, C_F', by adjusting the micrometer to equal the measured C_1 with the sample and measure D_F' at this capacitance, $C_F' = C_1$, e.g., at 29.54 pF in the example. Then the correct $D_X = D_C - D_F'$. This assumes that any large D error comes from phase errors in the bridge transformer, which is the case for unknown capacitances less than 1000 pF. The bridge error can be negative as well as positive.

For a test cell with a calibration of C vs h_m, the value of C_V could be calculated, instead of measured, from $C = m/(h_m + h_{mo})$. For this cell, the calculated $C_o = 9.5463$ for $h_m = .2941$. The difference between measured and calculated is mainly the error in setting or reading h_m.

More accurate measurements, in the following examples, show that the measured ϵ_r is low by 4%, the tan δ low by 7%. The reason is that in the measurement with the specimen between the electrodes there will always be a layer of air between the specimen and the electrodes. If the electrode spacing is $h_o (= h_m + h_{mo})$, and the thickness of the specimen h, the measured C is that of a capacitor of the specimen material with spacing h in series with an air capacitor with spacing $(h_o - h)$. The error in assuming no air layer $(h_o = h)$ increases in proportion to $(h_o - h)/h$ and, hence, the errors are large for thin specimens. The measured thickness of the acrylic specimen averages .2906 cm, so the air layer in this measurement was about .0035 cm. The method, however, is useful in determining quickly the magnitude of ϵ_r or tan δ.

Air-Gap Method Since a layer of air between specimen and electrodes cannot easily be avoided, a layer of known thickness can be used and the measured results can be corrected for its effects. This is the air-gap method.

Two measurements are made, as shown in Figure 5. The thickness of the sample is first measured at 5 or 10 points to determine an average value of h. The electrodes of the test cell are opened to .01 or .02 cm greater than h by setting the micrometer to an appropriate value of h_m. The capacitance and dissipation factor, C_F and D_F, are measured for this h_o with air as the dielectric. The specimen is then inserted between the electrodes, approximately in the center, and the new values, C_1 and D_C, measured.

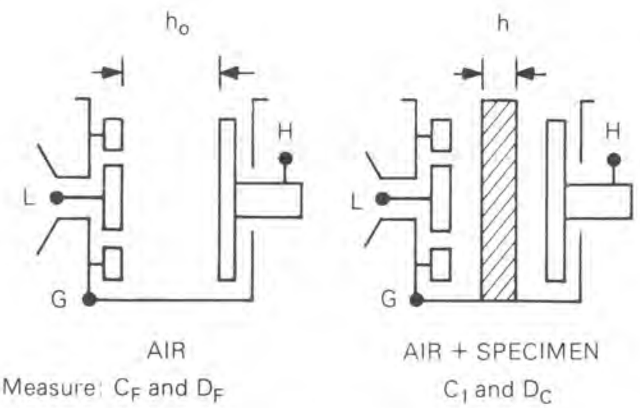


Figure 5. Air-Gap Method

For the sample acrylic sheet specimen used above, the measured average thickness was .2906 cm and the cell micrometer was set to .3175 cm. The bridge measurements were, at 1 kHz:

$$C_F = 8.8382 \qquad C_1 = 23.7742$$
$$D_F = .000010 \qquad D_C = .03500 = \tan\delta_C$$

The values of ϵ_r and tan δ can then be calculated from the equations

$$\epsilon_r = \frac{1}{1 - \frac{\Delta C}{C_1}\frac{h_o}{h}}$$

where $\Delta C = C_1 - C_F = 23.7742 - 8.8382 = 14.9360$

and, from the micrometer calibration:

$$h_o = h_m + h_{mo} = .3175 + .0019$$

and

$$\epsilon_r = 3.231$$

$$\tan\delta = D_X = D_C + \left(\frac{h_o}{h} - 1\right)\epsilon_r(D_C - D_F)$$

$$\tan\delta = D_X = .04623$$

The accuracy of these results depends mainly upon the accuracy with which the two thicknesses h and h_o can be measured.

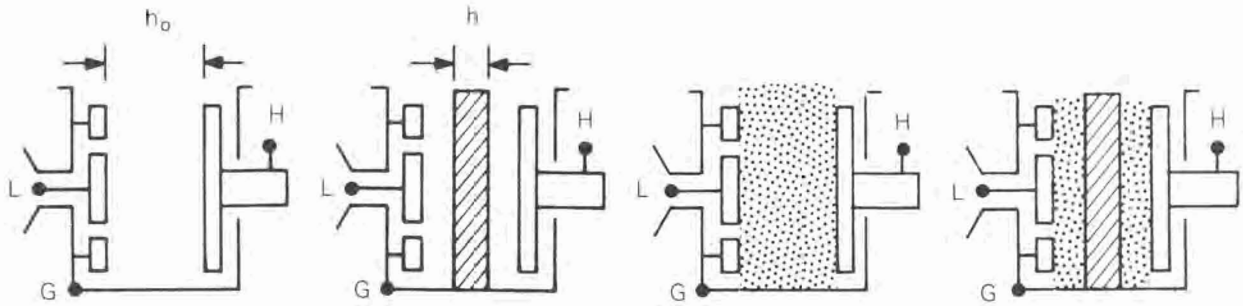
Two-Fluid Method For a specimen whose thickness is difficult to measure because it is thin or soft and for measurements of high accuracy, the ϵ_r can be determined without measurements of h and h_o by measuring the test cell with one fluid, usually air, and then the specimen plus air, as in the air-gap method, and then adding two more measurements of the same cell with a second fluid and with the specimen in that second fluid. This is the two-fluid method. Equations for calculating the permittivity and tan δ (D) of the dielectric material are shown in Figure 6.

The choice of the second fluid is determined primarily by the requirement that immersion in the fluid does not affect the specimen. For materials such as fused silica and polytetrafluoroethylene, organic liquids such as heptane or benzene are used. For plastics such as polyethylene and polymethylmethacrylate, non-sorbing liquids are required and low-viscosity silicones and fluorocarbons are commonly used. The silicone fluids (such as Dow Corning 200 fluid made by Dow Corning Corp., Midland, Michigan 48640, USA) are expensive and not readily available but are recommended because they are non-toxic, non-greasy, odorless, stable (e.g., from −57 to 204°C), and have an almost constant ϵ_r (2.3) from 60 Hz to 10 GHz and low tan δ or D (.00004) up to 100 MHz.

The same acrylic specimen used in the air-gap method was measured with a second fluid. The fluid was dimethyl siloxane (Dow Corning 200 Fluid), with a viscosity of 1 centistoke. The bridge measurements gave these values:

$$C_{F2} = 20.2916 \qquad C_2 = 27.5723$$
$$D_{F2} = .00026 \qquad D_{C2} = .04053$$

From these data and the four corresponding values previously measured for the air-gap method with the same h_o, the ϵ_r and D_X can be calculated and also the ϵ_r and D of the second fluid and the thickness, h, of the specimen in terms of the spacing h_o of the cell. The



MEASURED CAPACITANCE DISSIPATION FACTOR	FLUID 1 (AIR)		FLUID 1 + SPECIMEN	FLUID 2		FLUID 2 + SPECIMEN
	C_{F1} D_{F1}	$\Delta C_1 = C_1 - C_{F1}$ $\Delta D_1 = D_C - D_{F1}$	C_1 D_C	C_{F2} D_{F2}	$\Delta C_2 = C_2 - C_{F2}$ $\Delta D_2 = D_{C2} - D_{F2}$	C_2 D_{C2}

DIELECTRIC CONSTANT
OR RELATIVE PERMITTIVITY
ϵ_r

$$\epsilon_r = \epsilon_{F1} + \frac{C_2 \Delta C_1 (\epsilon_{F2} - \epsilon_{F1})}{C_2 \Delta C_1 - C_1 \Delta C_2}; \quad \frac{\epsilon_{F2}}{\epsilon_{F1}} = \frac{C_{F2}}{C_{F1}}$$

DISSIPATION FACTOR
D or TAN δ

$$D_X = D_{C2} + \frac{\epsilon_r C_V - C_2}{\Delta C_2} \Delta D_2; \quad C_V = \frac{C_{F1}}{\epsilon_{F1}}$$

OR, TO USE THE 8 MEASURED VALUES OF C AND D

$$\text{CALCULATE } A = \frac{1}{C_{F1}},\ S = \frac{1}{C_1},\ F = \frac{1}{C_{F2}},\ P = \frac{1}{C_2}$$

THEN

$$\frac{\epsilon_r}{\epsilon_{F1}} = A \frac{A - S - F + P}{AP - SF}$$

$$\frac{h}{h_0} = \frac{A - S - F + P}{A - F}$$

$$D_X = D_C + \frac{A(S-P)}{AP - SF}(D_C - D_{F1})$$

OR

$$D_X = D_{C2} + \frac{F(S-P)}{AP - SF}(D_{C2} - D_{F2})$$

Figure 6. Two-Fluid Method

equations are given in Figure 6. The results of the calculations are:

$\epsilon_{F2} = 2.296$, with ϵ_{F1} of air assumed to be 1.0005
$\epsilon_X = 3.236$
$D_X = .04619$, calculated from D_C and D_{F1} .04630
$D_X = .04630$, calculated from D_{C2} and D_{F2} .04619 reversed

The calculated thickness is:

$h = 0.2906$ cm for $h_0 = 0.3194$ cm

Measurements on Liquids Permittivity and dissipation factor measurements on liquids are similar in principle to those on solids in that they are basically measurements on a capacitor in which the test specimen is the dielectric. They avoid the problem of making the electrode conform to the specimen since, with liquids, the specimen readily conforms to the electrodes. Contamination of the specimen is more critical, however, and much more care must be taken to avoid it. For this reason, the LD-3 Cell is not suitable for most measurements on liquids except for the ones used in the fluid-displacement methods of measurements on solids.

ASTM D924 shows several suitable three-terminal cells and one of these is shown in IEC Publication 250. Both standards give detailed instructions for cleaning the cells prior to use. Except for cleaning the cells, it is a simple matter to make measurements at room temperature and at the voltages normally used with the bridge.

As an example, a Balsbaugh Type 350G cell (which had been cleaned in accordance with ASTM D924) was connected to a 1615 bridge with the same patch cords used for the LD-3. The 874-R22A was connected to the guard and guarded electrode, and the ~~R34~~ R33 was plugged into the outer or unguarded electrode. The frequency was set at 1 kHz with 30 volts supplied to the bridge. The bridge was balanced first with the cell empty and then after the cell had been filled with the liquid under test. The following readings were taken:

$C_1 = 33.982$ pF	Capacitance of the cell with air as the dielectric.
$C_2 = 153.222$ pF	Capacitance of the cell with the liquid as the dielectric.
$D_1 = 0$	Dissipation factor with air as the dielectric.
$D_2 = 0.00121$	Dissipation factor with the liquid as a dielectric.

The permittivity ϵ_r of the liquid was:

$$\epsilon_r = \frac{C_2}{C_1} = \frac{153.222}{33.982} = 4.51$$

and the dissipation factor D was

$$D = D_2 - D_1 = 0.00121 - 0 = 0.00121$$

The largest use of liquid insulation is in apparatus for the electric power industry. It is used in transformers, cables, circuit breakers, capacitors and similar applications. Usually the tests are made at power frequency, a temperature of 100°C, and a voltage gradient of at least 5 V/mil (200 V/mm). Detailed instructions are given in ASTM D924 on the procedure for heating and testing the liquids at 100°C. The instruction manual for the 1615 gives directions for interchanging the generator and the detector connections in order to apply higher voltages to the bridge. The dissipation factor of insulating oils of petroleum origin is much higher at 100°C than at room temperature so measurements are possible in spite of the reduced sensitivity of the bridge.

1620-A Capacitance-Measuring Assembly

- **10^{-5} pF to 11.1 μF, 2- or 3-terminal**
- **0.01% accuracy, 1-ppm resolution**
- **lever balance, in-line readout**
- **reads dissipation factor or conductance**

The 1620-A is a self-contained assembly of the GR 1615-A Capacitance Bridge with appropriate oscillator and null detector for measurements at 11 frequencies between 20 Hz and 20 kHz. For applications requiring other or higher frequencies, to 100 kHz, the 1615-A bridge can be supplied separately and the oscillator and detector selected to meet your needs.

The 1620-A is intended for

- accurate and precise measurements of capacitance and dissipation factor
- measurement of circuit capacitances
- dielectric measurements
- intercomparison of capacitance standards differing in magnitude by as much as 1000:1

The 1615-A Capacitance Bridge brings to the measurement of capacitance, to the intercomparison of standards, and to the measurement of dielectric properties an unusual degree of accuracy, precision, range, and convenience.

High accuracy is achieved through the use of precisely wound transformer ratio arms and highly stable standards fabricated from Invar and hermetically sealed in dry nitrogen. For calibration these standards can be intercompared.

Two- or Three-Terminal Connection Accurate three-terminal measurements can be made even in the presence of capacitances to ground as large as 1 μF, as might be encountered with the unknown connected by means of long cables. The bridge has the necessary internal shielding to permit one terminal of the unknown capacitor to be directly grounded, so that true two-terminal and three-terminal measurements can both be made over the whole capacitance range.

Convenient Operation For both capacitance and dissipation factor, the balance controls are smoothly operating, lever-type switches. The readout is digital and the decimal point is automatically positioned. Each capacitance decade has a −1 position to facilitate rapid balancing.

The 1615 elementary diagram is also clearly delineated on the front panel of the bridge. Changes in connections and grounds are automatically indicated, as you switch the bridge terminals for different measurement conditions.

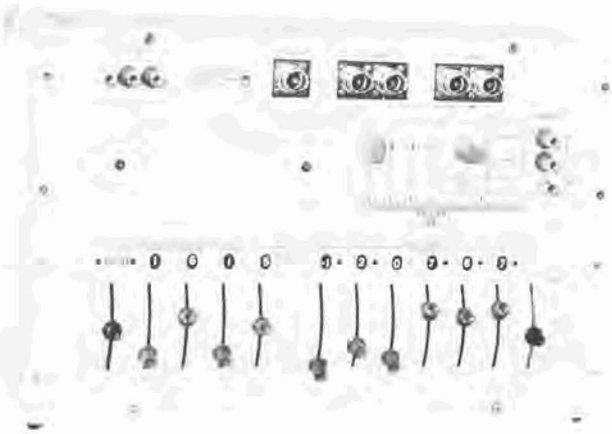
Extend Range to 11.1 μF With the 1615-P1 Range-Extension Capacitor, the 1615-A will measure to a maximum of 11.11110 μF. This capacitor plugs into front-panel bridge terminals and can be adjusted for calibration to the bridge standards.

SPECIFICATIONS

Performance: Refer to the 1615 Bridge.
Frequency: 50, 60, 100, 120, 200, 400, 500, 1000, 2000, 5000, and 10,000 Hz. For use below 100 Hz, 1620-AP (with preamplifier) should be used for resolution beyond 0.01% or 0.01 pF.
Generator: 1311-A Oscillator.
Detector: 1232-A Tuned Amplifier and Null Detector. 1232-P2 Preamplifier added in 1620-AP.
Power: 105 to 125 or 210 to 250 V, 50 to 400 Hz, 22 W for oscillator. Null detector and preamplifier operate from internal battery, 9 Burgess Type E4 cells or equivalent.
Mechanical: Bench cabinet. DIMENSIONS (wxhxd): 19.75x 19x11 in. (502x483x280 mm). WEIGHT: 59 lb (27 kg) net, 96 lb (44 kg) shipping.

Description	Catalog Number
Capacitance-Measuring Assembly	
1620-A, 115 V ⊛	**1620-9701**
1620-A, 230 V	**1620-9702**
1620-AP, with 1232-P2, 115 V	**1620-9829**
1620-AP, with 1232-P2, 230 V	**1620-9830**
Replacement Battery (9 used)	**8410-1372**

⊛ National stock number 4931-00-916-5952



1615-A Capacitance Bridge

The 1615-A is an accurate, high-precision bridge for the measurement and intercomparison of standard capacitors, circuit component capacitors, or dielectric materials. It is available with oscillator and detector in the 1620 assembly. Or, to take full advantage of its wide frequency range, the bridge can be ordered separately for use with oscillator and detector especially selected for your purposes.

1615-P1

1615-P2

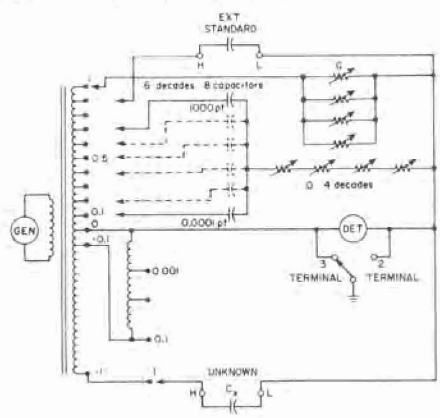
SPECIFICATIONS

RANGES	ACCURACY
Capacitance, 10 aF to 1.11110 μF (10^{-17} to 10^{-6} farad) in 6 ranges, direct-reading, 6-figure resolution; least count 10^{-17} F (10 aF). With Range-Extension Capacitor, upper limit is 11.11110 μF.	At 1 kHz, ±(0.01% + 0.00003 pF). At higher frequencies and with high capacitance, additional error is $[\pm 3 \times 10^{-5}\% + 2\,(C_{\mu F}) \times 10^{-3}\% \pm 3 \times 10^{-7}\,\mathrm{pF}] \times (f_{kHz})^2$. At lower frequencies and with low capacitance, accuracy may be limited by bridge sensitivity. Comparison accuracy, unknown to external standard, 1 ppm.
Dissipation Factor, D, At 1 kHz, 0.000001 to 1, 4-figure resolution; least count, 0.000001 (10^{-6}); range varies directly with frequency.	$\pm[0.1\%$ of measured value $+ 10^{-5}(1 + f_{kHz} + 5 f_{kHz} C_{\mu F})]$
Conductance, G, 10^{-6} μ℧ to 100 μ℧, 2 ranges +, 2 ranges −, 4-figure resolution, least count 10^{-6} μ℧, independent of frequency; range varies with C range.	$\pm[1\%$ of measured value $+ 10^{-5}$ μ℧ $+ 6 \times 10^{-2} f_{kHz} C_{\mu F} \times (1 + f_{kHz} + 5 f_{kHz} C_{\mu F})$ μ℧$]$

Standards: 1000, 100, 10, 1, 0.1, 0.01, 0.001, 0.0001 pF. Temperature coefficient of capacitance is less than 5 ppm/°C for the 1000-, 100-, and 10-pF standards, slightly greater for the smaller units.

Frequency: Approx 50 Hz to 10 kHz. Useful with reduced accuracy to 100 kHz. Below 100 Hz, resolution better than 0.01% or 0.01 pF requires preamplifier or special detector.

Generator: GR 1310 or 1311-A oscillator recommended. Max safe generator voltage ($30 \times f_{kHz}$) volts, 300 V max. If generator and detector connections are interchanged, 150 to 500 V can be applied, depending on switch settings.



Elementary schematic diagram.

Detector: GR 1232-A Tuned Amplifier and Null Detector recommended. For increased sensitivity needed to measure low-loss small capacitors (on lowest C and D ranges simultaneously) at frequencies below 1 kHz, use 1232-AP or 1238 (with 1311 oscillator).

Supplied: 874-WO Open-Circuit Termination, 874-R22A Patch Cord, 274-NL Patch Cord.

Available: Type 1615-P1 RANGE-EXTENSION CAPACITOR; 1615-P2 COAXIAL ADAPTOR converts 2-terminal binding-post connection on 1615 bridge to GR900® Precision Coaxial Connector for highly repeatable connections and enables measurements with adaptor to be direct-reading by compensating for terminal capacitance.

Mechanical: Rack-bench cabinet. DIMENSIONS (wxhxd): Bench, 19x12.75x10.5 in. (483x324x267 mm); rack, 19x12.25x8.5 in. (483x311x217 mm); 1615-P1 (dia x h): 3.06x4.87 in. (78x124 mm). WEIGHT: 39 lb (18 kg) net, 58 lb (27 kg) shipping.

Description	Catalog Number
1615-A Capacitance Bridge	
Bench Model ✠	**1615-9801**
Rack Model	**1615-9811**
1615-P1 Range-Extension Capacitor	**1615-9601**
1615-P2 Coaxial Adaptor, GR900 to binding posts	**1615-9602**

✠ National stock numbers 6625-00-470-8446; 6625-00-005-7274

1621 Precision Capacitance-Measurement System

- **10^{-7} pF to 10 μF**
  12-digit readout, 10-ppm basic accuracy
- **10^{-10} $\mu\mho$ to 1000 $\mu\mho$**
  5-digit readout, 0.1% basic accuracy
- **10 Hz to 100 kHz**
- **3-terminal measurements**
  with 2- or 3-terminal connection
- **comparison measurements**
- **simple lever balance with in-line readout**

The whole of precision The 1621 represents the first major improvement in nearly a decade in ultra-precise laboratory capacitance intercomparisons and dielectric measurements. It is a completely self-contained system capable of capacitance measurements in increments as small as 0.1 aF (10^{-7} pF) and conductance measurements in increments as small as 100 a$\mho$ (10^{-10} $\mu\mho$; equivalent to a shunt resistance of 10^{10} MΩ). Measurements are three terminal, with 2- or 3-terminal connection, and provision is also made for the connection of an external standard for comparison measurements.

Such capability and precision are usually accompanied by restricted frequency and complex operation. The 1621, however, avoids these difficulties. Little degradation of performance occurs from 10 Hz to 10 kHz and operation to 100 kHz is possible. Balances are achieved by in-line readout lever switches — easily adjusted and read correctly. All digits of capacitance and conductance, as well as pertinent multipliers, are also provided by BCD-coded contact closures, available at rear-panel connectors for use by printers or data-processing equipment.

Three integrated units The 1621 is an assembly of three integrated instruments: A precision ratio-arm bridge, a highly stable oscillator, and an extremely sensitive detector. Most of the bridge's internal standards are enclosed in an insulated housing to reduce the effects of ambient temperature changes; unused standards are disconnected to reduce shunt capacitance at the detector input. The oscillator provides up to 125 V or 5 A for sufficient signal to be detected even with unbalances as small as one part in 10^8 of 10 pF. The detector contains three meters to help you speed the balance: One displays the magnitude and the other two simultaneously display the in-phase and quadrature components of any unbalance.

SPECIFICATIONS

(See 1616 for performance specifications)

Frequency: 10 Hz to 100 kHz.

Supplied: 1616 Precision Capacitance Bridge, 1316 Oscillator, 1238 Detector, all necessary interconnection cables, and power cord.

Available: 1408 REFERENCE STANDARD CAPACITORS (10 pF and 100 pF) for calibration.

Power: 100 to 125 and 200 to 250 V, 50 to 60 Hz, 51 W.

Mechanical: Bench or rack models. DIMENSIONS (wxhxd): Bench, 19.75x24.25x15 in. (502x616x381 mm); rack, 19x 20.91x11.44 in. (483x531x291 mm). WEIGHT: Bench, 105 lb (48 kg) net, 140 lb (64 kg) shipping; rack, 90 lb (41 kg) net, 125 lb (57 kg) shipping.

Description	Catalog Number
1621 Precision Capacitance-Measurement System	
Bench Model, 60-Hz	**1621-9701**
Rack Model, 60-Hz	**1621-9702**
Bench Model, 50-Hz	**1621-9703**
Rack Model, 50-Hz	**1621-9704**

1616 Precision Capacitance Bridge

- 10^{-7} pF to 10 μF — 12-digit readout
- 10^{-10} $\mu\mho$ to 1000 $\mu\mho$ — 5-digit readout
- 10 Hz to 100 kHz
- up to 150-V input from oscillator
- 3-terminal measurements
- coaxial measurements

The heart of precision The 1616 is the heart of the 1621 Capacitance-Measuring Assembly. The bridge is also available separately for use where oscillator and detector are on hand or in applications in which they must be specialized for a unique need.

The 1616 employs a transformer ratio-arm bridge with which unbalances as small as 0.1 aF (10^{-7} pF) and 100 a$\mho$ (10^{-10} $\mu\mho$) can be resolved. Detection of such small unbalances is aided by ratio-transformer voltage capabilities up to 160 volts at 1 kHz and by range switching that disconnects the unused internal standards in order to reduce shunt capacitance across the detector input.

For thermal stability in precision intercomparisons, eight of the twelve internal capacitance standards are mounted in an insulated compartment to reduce the effects of ambient temperature changes. Misreading the values at balance is virtually impossible due to direct-reading lever switches that control the balance for both capacitance and conductance. Panel layout is unusually neat — only the unknown capacitor and, if desired, an external standard for comparison measurements are connected to the front panel; the oscillator and detector are connected to the rear as are the BCD data-output channels.

SPECIFICATIONS

Capacitance measurement, 3-terminal: DECADES: 12. RANGE: 0.1 aF to 1 μF (10^{-19} to 10^{-6} F). ACCURACY:* ±10 ppm, when most-significant decade is 1, 10, or 100 pF per step; otherwise, and at other frequencies, accuracy is ±[50 ppm + (0.5 + 20 $C_{\mu F}$) $(f_{kHz})^2$ ppm + (f_{kHz}) aF].

Capacitance, 2-terminal: Same as above, except as follows. RANGE: One additional decade, to 10 μF (10^{-19} to 10^{-5} F).

Conductance measurement, 3-terminal: DECADES: 5 (virtually extended to 11 by G multiplier). RANGE: 100 a$\mho$ to 100 $\mu\mho$ (10^{-16} to 10^{-4} $\mho$). ACCURACY:* ±(0.1% + 1 step in least significant decade). There is a small reduction in conductance accuracy at frequencies other than 1 kHz. RESIDUAL C (across conductance standards): ±(< 0.03 pF).

Conductance, 2-terminal: Same as above, except as follows: RANGE: One additional decade, to 1000 $\mu\mho$ (10^{-16} to 10^{-3} $\mho$).

Multipliers: FOR 3-TERM: X1, X10; FOR 2-TERM: X1, X10, X100; affect both C and G. FOR CONDUCTANCE ONLY: X1, X10^{-1}, . . . X10^{-6} (7 positions). Effects of these multipliers are included in the specified ranges.

Frequency: 10 Hz to 100 kHz.

Standards: CAPACITANCE: Air dielectric with TC < +20 ppm/°C and D <10 ppm for 8 lowest decades; Invar†, air dielectric with TC of +3 ±1 ppm/°C and D <10 ppm for 3 middle decades; mica dielectric with TC of 20 ±10 ppm/°C and D <200 ppm for 2 highest decades. ADJUSTMENTS for all capacitance standards available through key-locked door on panel. THERMAL LAG: C standards for first 8 decades mounted in an insulated compartment with a thermal time constant of 6 h (time required for compartment interior to reach 63% of ambient change). CONDUCTANCE: Metal-film resistors in T networks with small phase angles.

Comparison: Terminals provided to connect external standard for comparison measurements; 13-position panel switch multiplies standard by −0.1, 0 . . . +1.

Input: The smaller of 160 f_{kHz} or 350 V rms can be applied to the bridge transformer at the GENERATOR terminal without waveform distortion; 500 V rms max, depending on conductance range, when GENERATOR and DETECTOR connections are interchanged.

Interface: GR900® locking coaxial connector on panel to connect 2-terminal unknowns, 2 gold-plated GR874® locking coaxial connectors on panel to connect 3-terminal unknowns and 2 to connect external standard. DATA OUTPUT: 50-pin and 36-pin type 57 connectors on rear provide connection to 8-4-2-1 weighted BCD contacts (rated at 28 V, 1 A) on each switch for capacitance and conductance values respectively. OSCILLATOR and DETECTOR: Connect to rear BNC connectors.

Required: OSCILLATOR: GR 1316 recommended. DETECTOR: GR 1238 recommended. The 1616 Bridge is available with this oscillator and detector as the 1621 Capacitance-Measuring Assembly.

Available: 1316 OSCILLATOR, 1268 DETECTOR, a broad line of capacitance and resistance standards, and coaxial cables for connection of unknowns and standards.

Mechanical: Bench or rack model. DIMENSIONS (wxhxd): Bench, 19.75x13.81x12.88 in. (502x351x327 mm); rack, 19x 12.22x10.56 in. (483x310x268 mm). WEIGHT: Bench, 57 lb (26 kg) net, 69 lb (32 kg) shipping; rack, 49 lb (23 kg) net, 61 lb (28 kg) shipping.

Description	Catalog Number
1616 Precision Capacitance Bridge	
Bench Model	**1616-9700**
Rack Model	**1616-9701**

*Accuracy stated as fraction of measured value, for these conditions: frequency, 1 kHz, except as noted; temperature, 23° ± 1°C; humidity, < 50% RH.

† Registered trademark of the Carpenter Steel Co.

1316 Oscillator

- **10 Hz to 100 kHz**
- **up to 125 V or 5-A output**
- **output level adjustable and metered**
- **in-phase and quadrature reference outputs**
- **in-line readout dials**
- **current-limited output — short circuits OK**

Convenience and performance Set four controls and the 1316 provides any frequency from 10 Hz to 100 kHz with 1% accuracy and with little chance of an improper setting — the dials provide in-line readout, including decimal point and frequency units. Set two more controls, and the 1316 provides up to 1.6 watts of output power (125 V open circuit or 5 A short circuit), low distortion, and accurate metering.

These features alone would qualify the 1316 as an excellent general-purpose oscillator but it offers more: Output constant within ±2%, excellent stability (only 0.005% drift over a 12-hour period), and a synchronizing feature that allows the oscillator to be locked to an external standard for even greater accuracy and stability.

Excellent bridge oscillator The 1316 is a high-performance bridge oscillator specifically intended for use with the 1238 Detector and the 1616 Precision Capacitance Bridge. The oscillator supplies 2 references (in quadrature) for the 2-phase phase-sensitive detector, which enables you to make independent and ultra-precise balances of the conductance (real part) and capacitance (imaginary part) of capacitive devices.

The 1316 contains a Wien-bridge oscillator isolated from the load by a low-distortion transformer-coupled power amplifier. The oscillator circuit includes a provision to introduce a synchronizing signal for phase locking or to extract a signal, independent of the output setting, to operate a counter or to synchronize an oscilloscope.

SPECIFICATIONS

Frequency: 10 Hz to 100 kHz in 4 decade ranges. Controlled by one 11-position and one 10-position switch for the most-significant digits and a continuously adjustable dial with detented zero position for the third digit; in-line readout with decimal point and frequency units.

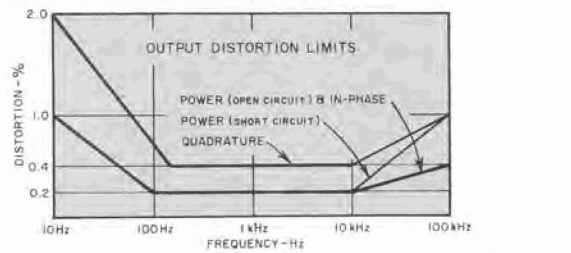
Accuracy: ±1% of setting with continuously adjustable dial at zero detent position. DRIFT (typical at 1 kHz): Warmup 0.1%, short-term (10 min) 0.001%, long-term (12 h) 0.005%. RESETTABILITY: Within 0.005%.

Power Output: CONTROLLED by 5-position switch and uncalibrated vernier. MONITORED by meter with ±3% accuracy. AVAILABLE at rear BNC connector.

	Output Range				
	1.5 V	5 V	15 V	50 V	150 V
Open circuit E, rms	≥ 1.25 V	≥ 4 V	≥ 12.5 V	≥ 40 V	≥ 125 V
Distortion	< 0.2% from 100 Hz to 10 kHz				
Hum	0.003% of max output				
Response	output constant within ±2% from 10 Hz to 100 kHz*				
Short Circuit I	5 A	1.6 A	0.5 A	0.16 A	0.05 A
Distortion	< 0.2% from 100 Hz to 10 kHz				
Impedance	0.25 Ω	2.5 Ω	25 Ω	250 Ω	2.5 kΩ
Power	1.6 W max into matched load				

*±5% for outputs >30 V rms at frequencies >50 kHz.

Reference Outputs: Quadrature output lags in-phase output by 90°. Each available at rear BNC connectors.



		In-Phase	Quadrature
Output, open-circuit		1.25 ± 0.25 V rms	
Distortion,	100 Hz to 10 kHz	< 0.2%	< 0.4%
Response,	10 Hz to 10 kHz	±2%	
	10 kHz to 100 kHz	±4%	
Minimum Load		47 kΩ	

Synchronization: INPUT: Frequency can be locked to external signal; lock range, ±1%/V rms input up to 10 V; frequency controls function as phase adjustment. OUTPUT: ≥0.3 V rms behind 27 kΩ; useful to sync oscilloscope or to drive a counter or another oscillator. Single rear BNC connector serves as both input and output terminal.

Power: 100 to 125 and 200 to 250 V, 50 to 60 Hz, 36 W.

Mechanical: Bench or rack mount. DIMENSIONS (wxhxd): Bench, 19.75x5x13.06 in. (502x127x332 mm); rack, 19x 3.47x11.44 in. (483x88x291 mm). WEIGHT: Bench, 26 lb (12 kg) net, 32 lb (15 kg) shipping; rack, 21 lb (10 kg) net, 27 lb (12 kg) shipping.

Description	Catalog Number
1316 Oscillator	
Bench Model	**1316-9700**
Rack Model	**1316-9701**

1238 Detector

- 10 Hz to 100 kHz
- 100-nV full-scale sensitivity
- magnitude, in-phase, and quadrature meters for rapid bridge balances
- excellent bridge detector

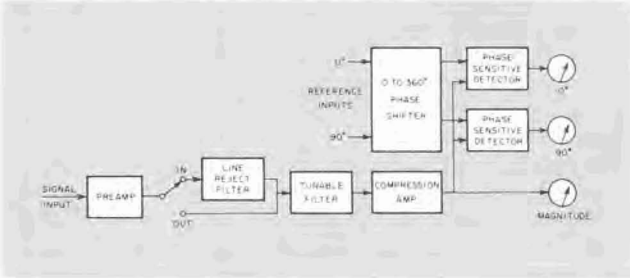
Designed for the difficult If you've ever had to extract a small signal from noise or to resolve a signal into its in-phase and quadrature components, you can appreciate the advantages of the 1238. With its high gain — 130 dB — and meters not only for magnitude of the input signal but for the in-phase and quadrature components as well, the 1238 lends itself handily to the most exacting applications.

This high-performance detector is attractive in other respects also, including 1-GΩ input impedance for minimum loading, overload protection against signals up to 200 V, and flat or tuned frequency response (with or without line-frequency rejection) to tailor the detector to your signal no matter how "tainted" it might be.

Excellent bridge detector In combination with a special oscillator, GR 1316, that supplies the necessary quadrature reference channels, this detector is superb for sensitive audio-frequency detection. The combination is specifically intended for use with the 1616 Precision Capacitance Bridge, enabling resolutions of one part in 10^8 of 10 pF. Refer to the 1621 Precision Capacitance-Measurement System.

The 1238 Detector consists of a high-impedance low-noise preamplifier, a tuned amplifier, a compression amplifier, and two phase-sensitive detectors. Three panel meters provide the indications: one displays the magnitude of the input signal and two others simultaneously display its in-phase and quadrature components. The reference signals can be rotated continuously from 0 through 360° to ensure that the phase meters respond independently to the components of significance to you, for the most rapid bridge balances or signal analysis.

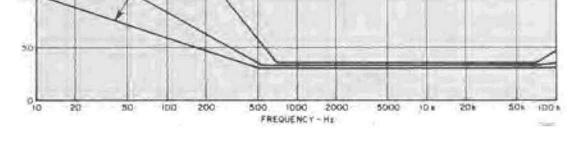
The effects of noise, hum, or any other input-signal contaminants are normally reduced or eliminated from your measurements by means of a tunable filter, line-rejection filter, and selectable time constants in the phase-sensitive detector circuits — all controlled from the front panel by the simple push of a button or turn of a knob.



SPECIFICATIONS

Frequency: 10 Hz to 100 kHz, flat or tuned. FLAT: ±5 dB from 10 Hz to 100 kHz. TUNED: Set by 4 in-line readout dials with ±5% of reading accuracy, 2 to 4% bandwidth, and second harmonic ≥30 dB down from peak. LINE-REJECTION FILTER: Reduces line level by ≥40 dB while signal is down 6 to 10 dB at 10 Hz from line frequency; filter can be switched out.

Signal Input from bridge or other source: Applied to rear BNC connector. SENSITIVITY: Also see curve; 100 nV rms typical for full-scale deflection at most frequencies, compression can be switched in to reduce full-scale sensitivity by 20 dB. IMPEDANCE: 1 GΩ∥20 pF. MAXIMUM INPUT: 200 V rms. VOLTAGE GAIN: ≈105 dB in flat mode, ≈130 dB in tuned mode, set by 12-position switch. SPOT NOISE VOLTAGE:



<30 nV × $\sqrt{\text{bandwidth}_{Hz}}$ at 1 kHz with input impedance of 70 MΩ∥500 pF. MONITORED by magnitude, in-phase, and quadrature meters; phase-sensitive detectors contain time-constant variable from 0.1 to 10 s in 5 steps.

Reference Inputs from oscillator: Applied to rear BNC connectors. Two ≥1-V rms reference signals required, with 90° phase difference between them. PHASE SHIFTER rotates both references continuously from 0 to 360° and two verniers rotate each reference individually ≈10°.

Outputs: MAIN AMPLIFIER: 4 V rms (approx 2.3 V for full scale on Magnitude meter) available at rear BNC connector. MAGNITUDE: 6 V dc for full scale deflection; PHASE DETECTORS: Up to 1 V dc each for full scale deflection (depending on Sensitivity setting); available at rear 5-pin type 126 jack.

Environment: TEMPERATURE: 0 to +55°C operating, −40 to +75°C storage. BENCH HANDLING: 4 in. or 45° (MIL-810A-VI). SHOCK: 30 G, 11 ms (MIL-T-4807A-4.5-3A).

Required: Oscillator with 0 and 90° outputs; the 1316 Oscillator is recommended.

Power: 100 to 125 and 200 to 250 V, 50 to 60 Hz, 15 W.

Mechanical: Bench or rack models. DIMENSIONS (wxhxd): Bench, 19.56x6.66x12.94 in. (497x169x329 mm); rack, 19x5.22x13.06 in. (483x133x332 mm). WEIGHT: Bench, 27 lb (13 kg) net, 40 lb (19 kg) shipping; rack, 21 lb (10 kg) net, 34 lb (16 kg) shipping.

Description	Catalog Number
1238 Detector	
60-Hz Bench Model	**1238-9700**
60-Hz Rack Model	**1238-9701**
50-Hz Bench Model	**1238-9703**
50-Hz Rack Model	**1238-9704**

Three-Terminal Research Cell
MODEL LD-3

For Measurement of
- **Dielectric constant**
- **Dissipation factor**
- **Permittivity**
- **Loss factor**

On Such Materials as
- **Synthetic Films**
- **Elastomers**
- **Fibrous Materials**
- **Plastics**
- **Laminates**

Description

The LD-3 is a liquid-tight, three-terminal cell with a 6.35 cm diameter guarded electrode, variable in spacing from 0 to 0.8 cm. Electrodes are constructed of stainless steel, with a housing of plated brass and Teflon*-type insulation. It can be operated at temperatures up to 200° C and at frequencies up to 1 MHz.

Advantages

The LD-3 cell is a versatile piece of test equipment, which may be used to perform dielectric measurements by the micrometer electrode method, the air gap method, the liquid displacement method or the two-fluid method. Since it is a three-terminal cell, fringing effects are minimized. Single specimens of varying thicknesses can be measured with full accuracy since the electrode spacing is adjustable. When used as a liquid displacement cell, the dielectric constant of the immersion fluid can be determined directly in the cell, and, as with all liquid displacement measurements, dependence on accurate knowledge of the sample thickness is greatly reduced. If the two-fluid method is employed, extreme accuracy is obtainable since thickness determinations on the specimen are unnecessary.

The unit is suitable for a wide variety of measurement situations. It can be used as a three-terminal micrometer electrode system, in which the sample is clamped between the electrodes, and the electrode spacing, capacitance and dissipation factor are recorded. Upon removal of the sample, the electrodes are positioned closer together to rebalance the bridge and the new spacing is recorded. The electrical parameters of the sample can then be computed.

*Teflon is a registered trademark of the Du Pont Co.