

c. Set the LEAKAGE CURRENT RANGE switch on a suitable range.

d. Read the leakage current on the meter; the full-scale reading is that set in the preceding step.

e. Throw the BIAS CHARGE-DISCHARGE switch to DISCHARGE before disconnection of the unknown.

### 3.3.3 CHARGING TIME.

The time required to charge a capacitor from a current-linked supply is:

$$\tau = \frac{CV}{I} \text{ (seconds, farads, volts, and amperes)}$$

The capacitance is the sum of the unknown capacitance and the internal power-supply by-pass capacitance. The current is the difference between the maximum power supply current, approximately 15 mA, and the leakage current in both capacitors. For low-energy-unknown capacitors, the charging time is that of the internal capacitor, which is about 4 seconds. For high-energy capacitors, the time constant may become much longer. If charging is too slow, an external supply of higher current rating should be used.

If the internal power supply has not been used in some time, the by-pass capacitors may become somewhat leaky, resulting in very slow charging until they are reformed. This is particularly noticeable on the higher voltage ranges. Note that if the total leakage of the unknown and by-pass capacitors exceeds the available current, the voltage will never reach its correct value.

The charging time also depends on the value of the ratio-arm resistor in series with the unknown, but this delay will not be noticed on the voltmeter which reads the total voltage applied to the bridge (see Figure 3-7). However, if the capacitance range switch is set to the correct capacitance range, this time constant is negligible.

### 3.3.4 METER RESPONSE.

The ammeter response is purposely slow in order to protect the meter from pinning when it passes excessive current (for example, when the bias is discharged with the ammeter in the circuit). The meter

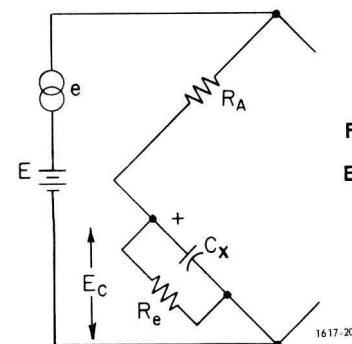


Figure 3-7. To change  $C_x$  to  $E_c$ ,  $E$  must be  $E_c (1 + \frac{R_A}{R_e})$ .

indication may become very slow, when very large capacitors with low leakage are measured, because the meter time constant is a function of the meter-range resistor and the unknown capacitor.

The voltage applied to the unknown during leakage-current measurements is slightly reduced by the ammeter voltage drop. This drop is proportional to the meter reading and is 0.2 V at full scale. This voltage change is of little consequence except at very low applied voltages. However, it does introduce a small transient in the ammeter which may indicate the current flow necessary to re-establish equilibrium.

### 3.4 VOLTAGE MEASUREMENT ACCURACY.

The voltmeter indicates 2-V to 600-V full scale in six ranges with an accuracy of  $\pm 3\%$ . The voltage measured is the voltage applied to the bridge input and, in most cases, this is the voltage across the unknown. However, when a very leaky capacitor is measured, the voltage drop in the ratio-arm resistor caused by the high-leakage current may result in the actual voltage on the capacitor being less than the voltage indicated (see Figure 3-7). In order to obtain the proper voltage in the capacitor, the voltmeter must be set to read  $E_c (1 + \frac{R_A}{R_e})$ . This difficulty is very rarely encountered if the capacitance switch is set to the correct range.

### 3.5 MAXIMUM DISCHARGE ENERGY.

Theoretically, the maximum energy on an unknown capacitor connected to the bridge could be 320,000 joules (800 V in 1 F). This energy would certainly destroy the discharge resistor and switch if internal-discharge circuits were used. Fortunately, nobody makes a capacitor of such capability. However, large capacitors are made for special purposes (such as welding) that can damage the discharge resistors, so that an energy limit is necessary. Therefore, the maximum voltage that should be discharged by the internal circuit is given in Table 3-1.

Also, if an external bias supply is used, the rate of charging and discharging may be high enough to overheat the discharge resistors, even though the limits of Table 3-1 are not exceeded. The average power dissipated should be limited to 5 watts.

Table 3-1

Maximum voltage for Internal Discharge	
Capacitance Range	Maximum Voltage
0 to 100 $\mu F$	800 V
0.1 to 1 mF	400 V
1 to 10 mF	100 V
10 to 100 mF	20 V
0.1 to 1 F	6 V

# Special Measurements—Section 4

## WARNING

It is possible to apply lethal voltage across a capacitor by means of this bridge. The energy stored in the unknown capacitor, and even in the internal capacitor, can be extremely dangerous to the operator; please follow the instructions carefully.

Never connect or disconnect anything at the UNKNOWN terminals unless the BIAS CHARGE-DISCHARGE switch is on DISCHARGE and the two warning lamps are off.

When no bias voltage is applied, set the VOLTAGE RANGE switch to 2 V, the BIAS ADJ to EXT and the BIAS CHARGE-DISCHARGE switch to DISCHARGE.

When operating the bridge at high voltage level, use every possible precaution to avoid contact with the UNKNOWN terminals, or the positive terminal of the capacitor under test.

### 4.1 USE OF AN EXTERNAL GENERATOR.

#### 4.1.1 CONNECTION.

The preferred connection for an external generator is at the EXT GEN terminals. The terminals are connected to the primary of the input transformer whose secondary winding is selected by the GEN LEVEL switch (Figure 4-1). If 5V, rms, is applied to the terminals, the voltage applied to the bridge will be as indicated by this switch. Note that the input to the bridge may be reversed by the function switch to check for stray coupling effects (refer to paragraph 4.4).

At low frequencies, more voltage may be applied to the bridge if the external generator is connected to the EXT BIAS terminals (Figure 4-2, see also paragraph 4.1.3). Use a shielded lead to avoid coupling to the unknown and, because the bridge is grounded, do not ground either side of the oscillator, to avoid ground loops.\* If, however, bias has to be applied, it can be done as shown in Figure 4-3.

The GR 1311 Audio Oscillator is recommended as an ideal external generator for driving the Type 1617.

#### 4.1.2 RANGE AND ACCURACY.

Table 4-1 indicates the nominal capacitance range of the Type 1617 Capacitance Bridge for better than 2% accuracy at different frequencies above 120 Hz.

The low end of the capacitance range is limited to 500 pF above 2 kHz, because of the frequency characteristic

\*With oscillators which have one side of the output tied to the case, do not use the third wire of the power cord, so as not to ground the case.

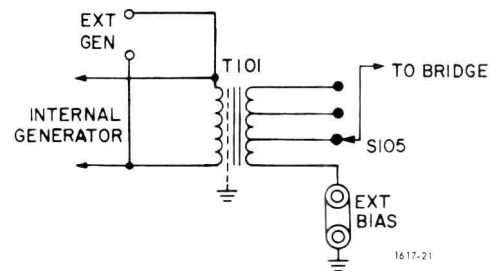


Figure 4-1. Location of the external generator connection (EXT GEN terminals).

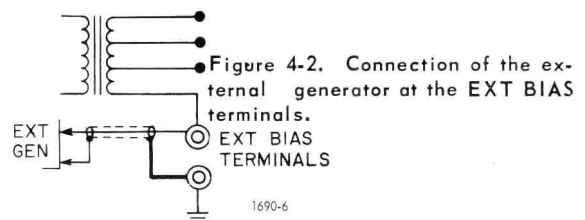


Figure 4-2. Connection of the external generator at the EXT BIAS terminals.

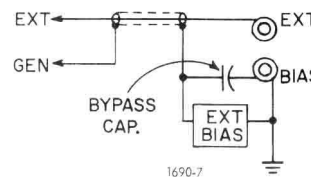


Figure 4-3. External generator and bias supply at the EXT BIAS terminals.

Table 4-1

RANGE LIMITS At Different Frequencies (Less Than 2% Error)		
Frequency	Low Limit*	High Limit**
120 Hz	50 pF	1.1 F
200 Hz	50 pF	0.5 F
500 Hz	50 pF	80 mF
1 kHz	150 pF	20 mF
2 kHz	500 pF	5 mF
5 kHz	500 pF	800 $\mu$ F
10 kHz	500 pF	200 $\mu$ F

\*After zero correction.  
\*\*4-terminal measurement with twisted leads.

of the 10 M $\Omega$  ratio arm (R<sub>A</sub>). The high end is limited by the mutual inductance in the leads and between the terminals.

The low-frequency limit is approximately 20 Hz, at which point the meter starts to follow individual cycles. Full accuracy below 30 Hz is difficult to obtain on the lowest and highest ranges, because the limit on the input voltage (refer to paragraph 4.1.3) limits the sensitivity. At low frequencies, many low-powered oscillators will not drive the input inductance (approximately 50 mH) hard enough to give sufficient sensitivity. The D accuracy is  $\pm 0.001 \pm 0.01 C(\text{in F}) \pm 2\%$ , from 40 to 120 Hz, and  $[\pm 0.001 \pm 0.01 C(\text{in F})] \frac{f}{120} \pm 2\%$ , above 120 Hz.

#### 4.1.3 MAXIMUM AC VOLTAGE AND POWER.

The maximum voltage that should be applied to the EXT GEN terminals is  $\frac{1}{10} f_{\text{Hz}}$  or 10 V, rms, whichever is less. The maximum ac applied to the EXT BIAS terminals is 4 V, rms. Actually, more voltage (but less than 100 V) may be applied to the bridge when the C dial is set up-scale as long as the voltage on the UNKNOWN does not exceed 4 V (which would overdrive the guard amplifier).

Thus, the above fixed limits may be multiplied by:

$$\sqrt{1 + (0.0063 \times f \times C \text{ dial reading})^2}$$

The power input should be limited to 1 watt. (The output of the GR 1311 is limited to 1 watt.)

#### 4.1.4 MEASUREMENT PROCEDURE.

The procedure is the same as with the internal generator except that the function switch must be set to EXT GEN NORMAL or REVERSE, and the D reading must be multiplied by  $\frac{f}{120}$ . The generator level is adjusted on the external generator.

### 4.2 USE OF AN EXTERNAL MICROAMMETER.

The lowest range of the microammeter on the Type 1617 Capacitance Bridge is 60  $\mu$ A, full scale. Some

electrolytic capacitors (tantalum, in particular, and many other types) will require more sensitivity. This is easily accomplished by use of a sensitive external meter, such as the Type 1230 Electrometer (measures from  $\pm 1$  mA down to 0.3  $\mu$ A, or  $0.3 \times 10^{-12}$  A, full scale). The Weston 1946T (available in 5, 10 or 20- $\mu$ A, full-scale versions, with 2% accuracy) or the Westinghouse 371 (3% accuracy, 20  $\mu$ A full scale), are acceptable substitutes.

Connect the external meter in series with the unknown, with its negative terminal to the negative terminal of the bridge (Figure 4-4). It is now part of the unknown and has to be shorted out in a capacitance measurement to avoid error, or when charging the capacitor to avoid overload.

- Turn ac signal off when making leakage-current measurements by setting the METER switch to BIAS VOLTAGE.
- With the 4-terminal connection shown, note that the + meter terminal is grounded, so that the - terminal cannot be grounded. Also, in this connection keep the meter voltage drop below 0.1 V. (There are rectifiers between the two -1617 terminals).

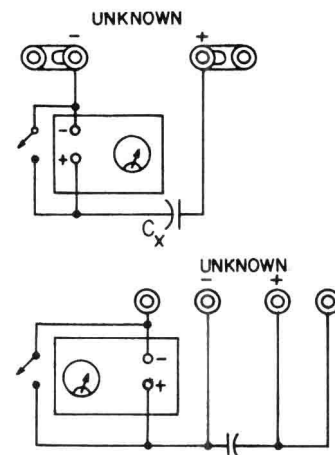


Figure 4-4. Use of an external ammeter for 2-terminal measurement, (top), 4-terminal measurement (bottom).

### 4.3 EXTERNAL BIAS SUPPLY (Table 3-1).

The internal bias supply will apply up to 600 V to the unknown; up to 800 V can be applied by use of an external dc supply. To apply external bias:

- Set the BIAS ADJ switch to EXTERNAL BIAS.
- Remove the shorting link from the EXT BIAS terminals and connect the power supply to these terminals.

c. To preserve the sensitivity of the bridge, the effective ac impedance of the supply has to be very low, and this is ensured by placing a bypass capacitor as shown in Figure 4-5. This capacitor should be at least of the same order of magnitude as the unknown.

## WARNING

The bypass capacitor has the same bias voltage across it as the unknown. Make sure the dc supply is off and the BIAS CHARGE-DISCHARGE switch is on DISCHARGE before disconnecting or connecting it.

The measurement procedure, once the external dc supply is connected, is the same as with the internal bias supply. The energy available from the external bias supply should be limited to 1 W so that if the unknown is shorted, the bridge ratio-arm resistor will not be damaged.

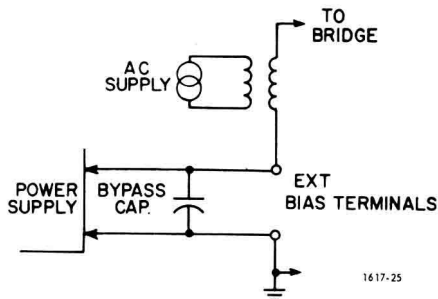


Figure 4-5. Connection of the external bias supply.

## 4.4 USE OF THE NORMAL/REVERSE POSITIONS.

Because the bridge test signal is synchronous with the power line, 120-Hz hum pickup will cause a bridge error. The NORMAL/REVERSE positions of the function switch allow the test signal to be reversed (Figure 4-6) with respect to the power line, so that the presence of pickup can be ascertained.

Should the D or C readings differ between balances on the NORMAL and REVERSE position, the best answer is the average of the two readings. This difficulty is most likely to occur on the lowest or highest ranges. Use the maximum possible signal level to reduce the effect.

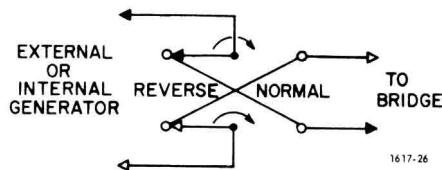


Figure 4-6. The reversing switch.

## 4.5 OTHER APPLICATIONS.

### 4.5.1 REMOTE MEASUREMENTS.

When long leads are used, the two principal sources of error are the lead impedance (it can be several ohms)

and the stray capacitance. For D accuracy, four-lead connections are necessary, and to reduce the stray capacitances, the positive lead should be shielded and the shield guarded.

When both errors may be important, a five-terminal measurement can be made (Figure 4-7).

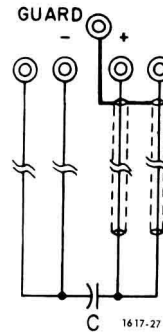


Figure 4-7. A 5-terminal connection.

### 4.5.2 INDUCTANCE MEASUREMENT.

**Series Substitution Method.** Inductance can be determined from the measurement of the net effective capacitance of the unknown inductor in series with a known capacitor of suitable value. The series capacitor must be small enough so that the net reactance of the combination is capacitive, and it must be large enough so that a significant change in effective capacitance results. Proceed as follows:

- Connect the inductor and the capacitor in series (Figure 4-8) to the bridge.
- Short circuit the inductor and balance the bridge. Observe the C and D readings. Call them  $C_1$  and  $D_1$ .
- Remove the short circuit and rebalance the bridge. Call the new readings  $C_2$  and  $D_2$ .
- Compute the series inductance ( $L_s$ ) and the series resistance ( $R_s$ ) from:

$$L_s = \frac{C_2 - C_1}{\omega^2 C_1 C_2} \quad R_s = \frac{D_2 C_1 - D_1 C_2}{\omega C_1 C_2}$$

with the C's in farads and the D's in absolute values.

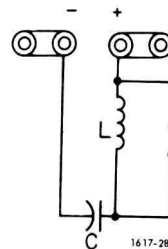


Figure 4-8. Inductance measurement by the series-substitution method.

**Parallel substitution Method.** For measurements using the parallel substitution method, proceed as follows:



- a. Connect the unknown inductor and the capacitor in parallel (Figure 4-9).
- b. Disconnect the high lead of the inductor and balance the bridge. Observe the C and D readings. Call them  $C_1$  and  $D_1$ .
- c. Connect the inductor and rebalance the bridge. Call the new reading  $C_2$  and  $D_2$ .
- d. Convert  $C_1$  and  $C_2$  To  $C_1'$  and  $C_2'$ , the effective parallel value, with

$$C' = \frac{C}{1 + D^2}$$

- e. Compute the parallel inductance ( $L_p$ ) and resistance ( $R_p$ ) from

$$L_p = \frac{1}{\omega^2 (C_1' - C_2')} \quad R_p = \frac{1}{\omega (D_2 C_2' - D_1 C_1')}$$

with the C's in farads and the D's in absolute values.

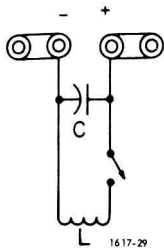


Figure 4-9. Inductance measurement by the parallel-substitution method.

#### 4.5.3 SERIES AND PARALLEL COMPONENTS.

An impedance that is neither a pure reactance nor a pure resistance may be represented, at any specific frequency, by either a series or a parallel combination of resistance and reactance. The values of resistance and reactance used in the equivalent circuit depend on whether a series or a parallel combination is used. The equivalent circuits are shown in Figure 4-10.

The relationships between the circuit elements are:

$$Z = R_s + \frac{1}{j\omega C_s} = \frac{R_p}{R_p + \frac{1}{j\omega C_p}} = \frac{D^2 R_p + \frac{1}{j\omega C_p}}{1 + D^2}$$

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

$$C_s = (1 + D^2) C_p; \quad C_p = \frac{1}{1 + D^2} C_s$$

$$R_s = \frac{D^2}{1 + D^2} R_p; \quad R_p = \frac{1 + D^2}{D^2} R_s$$

$$R_s = \frac{D}{\omega C_s}; \quad R_p = \frac{1}{\omega C_p D}$$

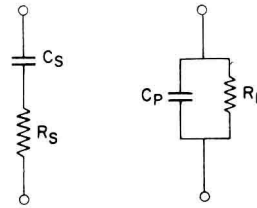


Figure 4-10. Series and parallel equivalent circuits.

#### 4.5.4 DIELECTRIC SAMPLES MEASUREMENT.

The dielectric constant and dissipation factor of an insulating material can be determined from the measurement of the capacitance and dissipation factor of an elementary capacitor, with the material used as the insulating medium between metallic electrodes of suitable dimensions.

**Two-Electrode Method.** A simple two-electrode method is sufficient for most purposes. The procedure is as follows:

- a. If possible, choose a sample of such shape and dimensions as to yield a capacitance of 100 pF or more. The calculation of dielectric constant is simplified if the thickness and area are easily measured and calculated, such as a disk or rectangle. If measurements are to be made at various frequencies, it is best to use sizes and shapes as specified in ASTM-D-150 (available from American Society for Testing Materials, 260 Race Street, Philadelphia, Pennsylvania).
- b. Measure and record the dimensions of the sample, and clean it thoroughly. (A mixture of half grain alcohol and half ether is recommended, unless either is a solvent for the material.)
- c. When the sample is dry, apply a very thin film of refined petrolatum to one surface. Place a thin metal-foil electrode, preferably less than 1 mil thick, and larger than the sample, on this surface.
- d. Press the electrode in place with a pad of cloth or squeegee roller and rub out any air bubbles, so that the foil is in intimate contact with the surface. Then trim the foil to the same size as the sample.
- e. Apply the other electrode to the sample as described in steps c and d.

#### NOTE

An alternate method of forming electrodes is to brush a good silver paint (such as Dupont No. 4132 Silver Paste) on the sample and to dry it overnight at 60°C. Such an electrode is porous to moisture, so that the dielectric can be conditioned at any desired relative humidity without removing the electrode.

f. Measure capacitance as described in paragraph 3.2.

g. Compute dielectric constant (to a first approximation) as follows:

$$K = \frac{4.45 tC}{A}$$

where K is dielectric constant

t is thickness of the sample, in inches

C is measured capacitance, in pF

A is area of the electrodes, in square inches.

For a complete discussion of the effects of stray electric field at the edges of the electrodes, and the effect of the capacitance of the high electrode to ground, refer to ASTM D-150.

**Three Electrodes Method.** The guard arrangement (Figure 4-11) provides an electrical equivalent to a 3-terminal capacitance, and is measured as such.

#### 4.5.5 LIQUID INSULATION MEASUREMENT.

Liquid insulation, such as transformer oil, requires some type of cell for measurement of capacitance and dissipation factor. The cell in its simplest form can be a multiple-plate air capacitor immersed in the liquid, or a grounded cylindrical can with a slightly smaller insulated cylindrical electrode. Such cells do not allow the accurate calculation of dielectric constant, nor do they maintain a constant voltage gradient of the liquid. These difficulties are overcome by the use of a three-electrode cell, such as described in ASTM D-150. Such a cell is electrically equivalent to Figure 4-11 and permits a 3-terminal measurement.

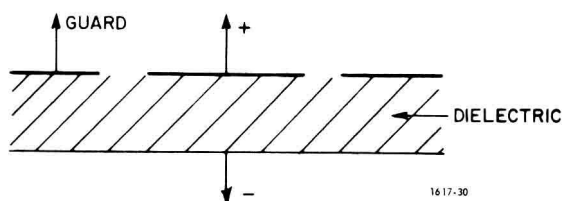


Figure 4-11. Guard-electrode arrangement to measure dielectric samples.

#### 4.5.6 TRANSFORMER INSULATION MEASUREMENT.

The insulation in a transformer, together with the primary and the secondary windings and the transformer

case, form a 3-terminal network (Figure 4-12). Usually the three capacitances are of the same order of magnitude, and any one of them can be measured directly by the bridge, if it is connected between the UNKNOWN terminals and the other two capacitances are connected to the GUARD terminal.

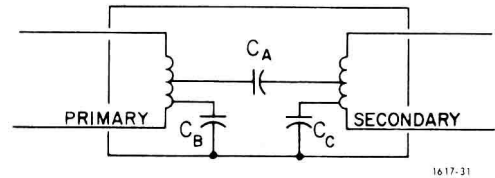


Figure 4-12. Capacitances existing in a transformer.

#### 4.5.7 TEST JIGS.

The Type 1650-P1 Test Jig (refer to the appendix) is available from General Radio for faster measurements, it allows rapid 2- and 3-terminal measurement. Connections to the bridge are made through two Type 274-DB plugs and a clip lead to connect the guard. Special jigs can be made for different shapes of capacitors, or for 4-terminal measurements (paragraph 5.7.3). The principles discussed in paragraph 3.1.4 and 3.1.5 should be taken into account in the design of such a jig.

#### 4.5.8 LIMIT TESTING.

The Type 1617 bridge may be set up to provide a go-no-go indication useful for component testing. The panel meter is used as the indicator. Proceed as follows:

- a. Balance the bridge with one of the components to be tested (one within tolerance).
- b. Offset the C dial from the balance position by the desired tolerance.
- c. Adjust the SENSITIVITY control for a center-scale meter deflection.
- d. Set the C dial to the nominal value of the component.
- e. Connect each component to the bridge. If the meter deflection is between zero and center scale, the component is within limits.

# Principles of Operation—Section 5

## 5.1 BRIDGE CIRCUITS.

### 5.1.1 GENERAL.

The circuit of the Type 1617 Capacitance Bridge is basically the familiar series-capacitance-comparison type used in most general-purpose capacitance bridges. The capacitance,  $C$ , of the unknown is proportional to  $R_N$  and its dissipation factor,  $D$ , to  $R_S$  (Figure 5-1).

### 5.1.2 LOW CAPACITANCE.

On the lowest five capacitance ranges (up to  $10 \mu\text{F}$ ), the circuit used is the simple one shown in Figure 5-1; (the guard circuit is connected for 3-terminal measurements). The bridge circuit is oriented so that a grounded dc supply will apply a voltage to the unknown capacitor through the ratio-arm resistor  $R_A$ . Reasonable lead resistances and inductances cause negligible errors; for example, a  $0.1\text{-}\Omega$  lead resistance introduces a  $D$  error of less than 0.001 in the measurement of a  $10 \mu\text{F}$  capacitor.

### 5.1.3 LEAD EFFECTS ON HIGH CAPACITANCE MEASUREMENTS.

One farad is only  $1.3 \text{ m}\Omega$  at 120 Hz and the same  $0.1\text{-}\Omega$  lead resistance will now result in a  $D$  reading of 70.

Figure 5-2 shows  $R_A$  and  $C_X$  as 4-terminal components; the lead resistances are also drawn and their individual effects can be evaluated. First,  $r_1$  and  $r_8$  are

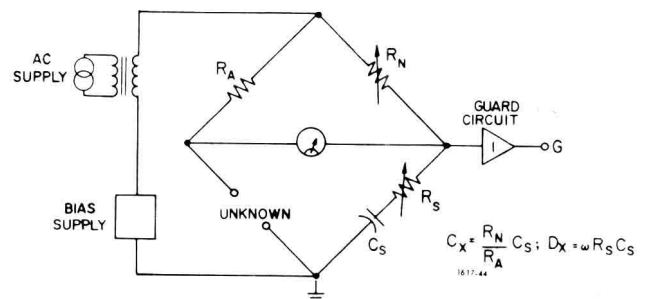


Figure 5-1. The RC bridge used on the five lower capacitance ranges.

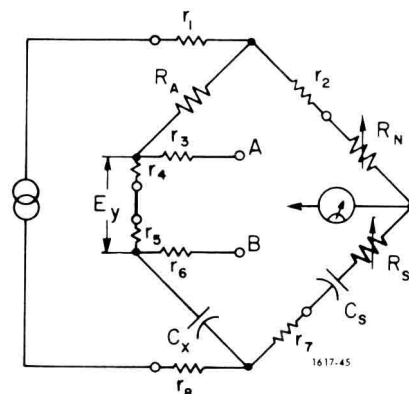


Figure 5-2. The RC bridge circuit where the unknown and the ratio arm resistor are represented as 4-terminal components.

in series with the generator and only reduce the effective applied voltage but do not change the null condition. Then  $r_2$  and  $r_7$  are in series respectively with  $R_N$  and  $R_S-C_S$ , which have relatively high impedance and, therefore, are little affected;  $r_3$  and  $r_6$  are in series with the detector. The remaining  $r_4$  and  $r_5$  (and their connection) present the main error. Their total impedance may be much higher than the impedance of either  $C_X$  or  $R_A$ , making the voltage drop across them an important part of the applied voltage.

Tying the detector to point A, places the lead resistance in the  $C_X$  arm and introduces an enormous D error; tying it to point B adds the lead resistance to  $R_A$ , and the C measurement is erroneous. Moreover, the lead inductance, if placed in series with a very large  $C_X$ , would cause a capacitance error even at 120 Hz. Obviously some means of greatly reducing the error is required.

A seemingly natural way to compensate the leads effects would be to divide the voltage from A to B, in the ratio of  $R_A$  to the unknown or  $R_N$  to the  $R_S-C_S$  combination, therefore applying the principle of the Kelvin double bridge (long used for dc resistance measurement) to an ac bridge. This would be done by connecting another pair of arms, similar to the  $R_N$  and  $C_S-R_S$  arms, from A to B and connecting the detector to the junction of these arms (Figure 5-3).

Corresponding variable components would be ganged to maintain the same ratio in both sets of arms. If the ratios between both pairs of arms were exactly the same, there would be no error, however large the lead impedances might be. Unfortunately, the ability to track with a wirewound rheostat is limited at best by its resolution. In general, tracking to much better than 1% is difficult. When measuring 1 F, 20 mΩ of lead resistance and a tracking accuracy of 1% still produce a C error of over 2%.

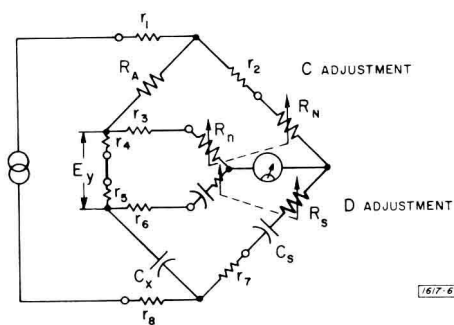


Figure 5-3. A four-terminal capacitance bridge using the Kelvin double-bridge principle. For ac measurement on a complex impedance, two ganged adjustments are necessary.

#### 5.1.4 THE BRIDGE CIRCUIT FOR HIGH CAPACITANCE.

A unique feature of the Type 1617 Capacitance Bridge is the compensation arrangement used to measure high-valued (low-impedance) capacitors, as shown in Figure 5-4.

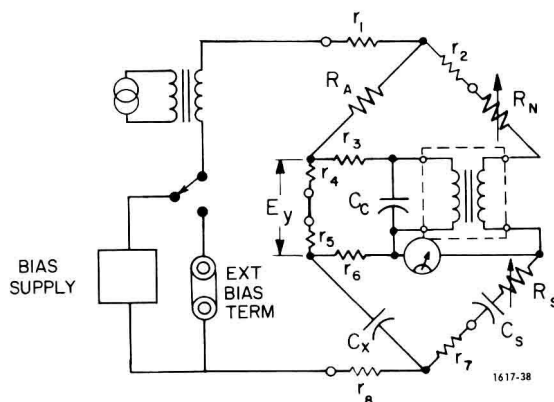


Figure 5-4. The basic circuit of the Type 1617 bridge where a voltage equal to the error voltage,  $E_y$ , is placed in the opposite side of the bridge by a tightly coupled transformer.

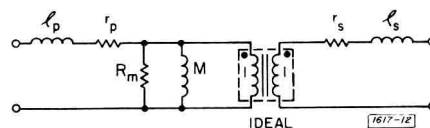


Figure 5-5. Equivalent circuit of the transformer.

The creation of a voltage equal to  $E_y$  between the  $R_N$  arm and the  $R_S-C_S$  arm solves the problem, because the lead error is compensated by the symmetry of the circuit. This is achieved by insertion of a 1:1 transformer. Unfortunately, the transformer, bifilar wound on a high permeability core, is not perfect, as shown by the equivalent circuit of Figure 5-5.  $C_c$  is a capacitor placed to "resonate out" some of the effect of the mutual inductance. The coupling coefficient of the transformer differs from unity by only a few parts per million.

The bridge-balance equation yields the following:

$$C_x = \frac{R_N}{R_A} C_S \left[ 1 + \frac{r_p + r_s + r_3}{R_N} - \frac{(r_4 + r_5) l_p}{R_A M} + \frac{(r_4 + r_5) r_6 C_X (1 - \omega^2 M C_c)}{M} - \frac{(r_4 + r_5) (r_3 + r_p)}{R_M R_A} - D_x \right]$$

$$\left( \frac{(r_4 + r_5) (r_3 + r_6) (1 - \omega^2 M C_c)}{R_A \omega M} - \frac{(r_4 + r_5) \omega l_p}{R_A R_M} + \frac{\omega(l_p + l_s)}{R_N} \right)$$

This form is quite impracticable, but a little examination will simplify the equation greatly. The first error term is taken into account in the calibration of  $R_N$ . By construction, the transformer has very small leakage inductance, making the second, sixth, and seventh terms negligible. The addition of  $C_C$  reduces the error in the third and fifth terms. The equation becomes:

$$C_x = \frac{R_N}{R_A} C_S \left\{ 1 + \frac{r_4 + r_5}{R_A} \left[ \frac{r_6 C_x (1 - \omega^2 M C_C) R_A}{M} - \frac{r_3 + r_p}{R_M} - \frac{D_x (r_3 + r_6) (1 - \omega^2 M C_C)}{\omega M} \right] \right\}$$

Note that the important error terms are not constant but are functions of the changing  $R_A$  and  $C_X$ , which makes complete compensation impossible.

The use of this scheme gives extremely good results; measurement of 1F, with  $r_4 + r_5 = r_6 = 20 \text{ m}\Omega$ , gives an error of approximately 0.1%. Therefore, the specification (1% for C) makes allowance for connecting leads of considerable length when large remotely located capacitors are measured.

## 5.2 GUARD CIRCUIT.

Whenever stray capacitances are an important percentage of the capacitance of the unknown, shielding is necessary to prevent error. The addition of a shield to prevent stray capacitances across the unknown results in an appreciable capacitance created by the shield itself, and a guard point is required to keep these capacitances from affecting the measurement. The guard circuit of the Type 1617 Capacitance Bridge, therefore, advantageously permits remote and 3-terminal measurements (refer to paragraph 3.1.4). It is also useful in that it prevents the internal shields from introducing other stray capacitances.

The junction of the  $R_N$  and  $R_S$ - $C_S$  arms (point A, Figure 5-6) is usually used as guard point in RC bridges. The capacitance from A to the + UNKNOWN terminal shunts the detector and causes no error. The capacitance from A to ground shunts the  $R_S$ - $C_S$  arm but is comparatively so small that it can be neglected. However, the Type 1617 can apply 600 V across the unknown, therefore across the  $R_S$ - $C_S$  arm, placing the guard point at a potential of 600 V, a rather undesirable situation.

To avoid this dangerous situation, a unity-gain amplifier is connected between this passive guard point and the actual guard terminal, G, as shown in Figure 5-6. The output of the amplifier is clamped to ground by a rectifier, so that G is never at a high potential,

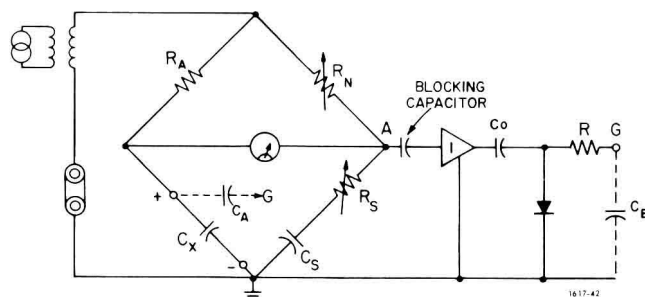


Figure 5-6. The guard circuit with respect to the bridge.

even in case of an accidental short from the guard to the + UNKNOWN terminal.

The performance of the guard circuit is measured by its gain and output impedance. The capacitance from the + UNKNOWN terminal to G ( $C_A$ ) in effect shunts the unknown, but with a value reduced by a factor of 1-K. The gain, K, of the unity amplifier is approximately 0.999, so that 1000 pF to GUARD is equivalent to approximately 1 pF across  $C_X$ . Capacitance from G to ground ( $C_B$ ) has no effect by itself, but it does reduce the effectiveness of the GUARD because of the limited output impedance of the amplifier. The effective capacitance shunting the unknown is approximately:

$$C_A \left( 1 - K \frac{C_o}{C_o + C_B} \right) \approx C_A (1 - K) + \frac{C_A C_B}{C_o}$$

where  $C_o$  is the output capacitance of the guard circuit (10  $\mu\text{F}$ ).

The resistor in series with the guard protects the grounding rectifier from excessive current and has a lower impedance than the 10  $\mu\text{F}$  output capacitor at 120 Hz.

A shorted GUARD terminal does not damage the guard circuit, but impairs the accuracy of the bridge.

## 5.3 THE INTERNAL GENERATOR.

The generator can be considered a selective filter operating on the rectified line voltage, or an oscillator synchronized to the line. The former is probably more accurate because the circuit would not oscillate when powered by a supply having low ripple.

The filter circuit is a simple Wien-bridge feedback arrangement, with two arms formed by the RC-Wien network, and the other two by the level-adjustment divider. The line voltage is full-wave rectified, to supply a signal rich in the 120-Hz component, and the filter capacitor is purposefully small so that a great amount of this signal reaches the input stage by means of the bias resistor (R217).

The compound (Darlington) output stage drives the primary of the input transformer at a level of about 5 V, rms. This transformer isolates the generator circuit from the capacitance bridge, which may have 600 Vdc

applied to it. It also provides several output voltages by means of secondary taps selected by the GEN LEVEL switch.

#### 5.4 INTERNAL DETECTOR.

The detector for this bridge is ungrounded and yet powered by the line, even though the bridge signal is a line harmonic. This makes the limitation of hum pickup both critical and difficult. Extensive shielding and guarding, both in the transformer and the leads, keeps the pickup negligible and controls the stray capacitances to ground.

The detector circuit is a straight-forward selective-amplifier circuit. The input stage has a high input impedance to avoid loading the bridge on the lower ranges (when it presents a very high impedance to the detector). The selective stage is made "flat" by ungrounding the twin-T selective circuit, when the function switch is in the EXT GEN position. The output stages form an amplifier capable of high compression, accomplished by a diode network in the feedback voltage divider. This compression gives a "semi-logarithmic" characteristic to the meter response, allowing balances over a wide dynamic range without repeated adjustments of the DETECTOR SENSITIVITY potentiometer (R443). No connection to the detector output is available on the panel of the Type 1617 Capacitance Bridge because it is very rarely necessary. However, the use of a shielded transformer (GR Type 578-A or -B) connected to the detector board (Figure 5-7) will make this output readily usable if it is required.

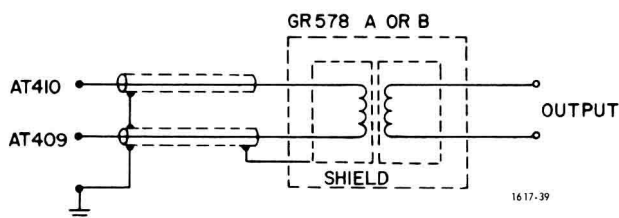


Figure 5-7. Connections to the detector etched board to make the detector output available.

#### 5.5 THE BIAS VOLTAGE SUPPLY.

The bias-voltage supply is connected in series with the input transformer and bridge as shown in Figure 5-8, so that the full dc is applied to the capacitor being measured. The ac signal is applied to the bridge in series with the dc supply, which therefore must present a low ac impedance at its output to avoid a serious reduction of the ac voltage applied to the bridge when large capacitors are measured. This requirement is met by placing a capacitor at the output of the dc supply to present a low impedance to the ac signal. This capacitor must be able to charge to the full bias voltage. A dif-

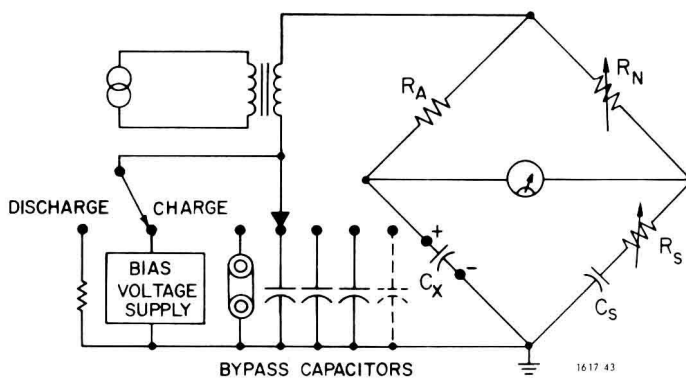


Figure 5-8. The bias-voltage supply and its battery of bypass capacitors.

ferent capacitor, offering the lowest impedance at the required voltage, is switched in as the bias voltage range is changed (giving optimum conditions at all times).

The high-voltage supply itself is a series-regulator circuit, using a high-voltage vacuum tube as the series element and transistors for additional loop gain. The supply is adjustable both continuously and in steps. The continuous adjustment is accomplished with an adjustable reference sampled by one side of the differential input stage. The other input samples the voltage across a fixed resistor in series with the switched range resistors.

On the 2-V range, the sampling resistor (R214) is tied directly to ground and the adjustment span is set for 2 V, maximum, by means of R208. Thus, 1 mA flows in the sampling resistor for a full-scale setting. This condition is still met when resistors are placed between the sampling resistor and ground, making the maximum output voltage (in volts) for each range equal to the value of the total resistance (in kilohms) added, plus 2 V.

It should be noted that all the regulator circuitry may be off ground by the full bias voltage and, therefore, the bias should be set to a low voltage range when this circuit is to be serviced.

#### 5.6 ORTHONULL.<sup>®</sup>

Orthonull is a mechanical device that improves the bridge balance convergence when high-D capacitors are measured. Ordinarily, balances with such components are tedious and often impossible, due to the "sliding null" resulting from the interdependence of the two adjustments. Rapid balances are possible with Orthonull, which does not affect the electrical balance conditions but which does help avoid false nulls, improving bridge accuracy for high-D measurements. The unbalance voltage of the bridge, that is the voltage existing across the detector before balance is achieved, can be expressed as follows:

$$E_O = E_{in} \frac{Z_2 Z_4 - Z_1 Z_3}{(Z_1 + Z_2)(Z_3 + Z_4)} = E_{in} \frac{Z_2 - \frac{Z_1 Z_3}{Z_4}}{(Z_1 + Z_2)(1 + \frac{Z_3}{Z_4})}$$

where  $Z_1, Z_2, Z_3, Z_4$  are the impedances of the four arms.

For the bridge of Figure 5-1:

$$E_O = \frac{R_X + \frac{1}{j\omega C_X} - \frac{R_A R_S}{R_N} + \frac{1}{j\omega C_S R_N}}{\text{Denominator}}$$

We will assume that the denominator is more or less constant in the region of the null. The numerator is the difference between the unknown impedance  $R_X + \frac{1}{j\omega C_X}$  and what can be called the "bridge impedance". The bridge output is proportional to this difference, which is the distance between them on the complete plane. To balance the bridge, the bridge impedance is varied by adjustment of  $R_N$  (the C dial) and  $R_S$  (the D dial), until it equals the unknown impedance. An adjustment of  $R_S$  varies only the real part of the bridge impedance, whereas the adjustment of  $R_N$  varies both parts, and is therefore a multiplier of the bridge impedance. Thus, adjustment of  $R_S$  moves the bridge impedance horizontally on the complex plane, while adjustment of  $R_N$  moves it radially (see Figure 5-9). Each control is adjusted for a minimum voltage.

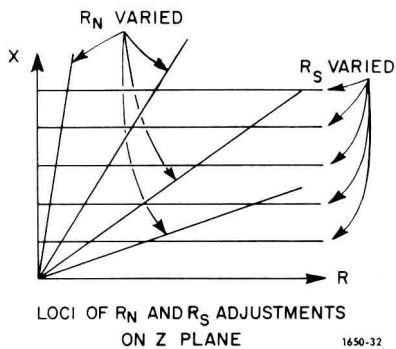


Figure 5-9. Loci of  $R_N$  and  $R_S$  adjustments on the Z plane.

When  $X \gg R$  (i.e., when  $D$  is low) these two adjustments are almost orthogonal, and rapid convergence is possible. When  $D$  is high, however, the adjustment becomes more parallel and convergence is slow, causing a "sliding null", as shown in Figure 5-10, where  $D = 2$ . With higher  $D$ 's, convergence is even slower.

The Orthonull device makes the two adjustments orthogonal by nonreciprocally ganging  $R_N$  and  $R_S$ . From the equation, it is apparent that if  $R_S/R_N$  remained constant as  $R_N$  was varied, only the imaginary part of the bridge impedance would change. But when

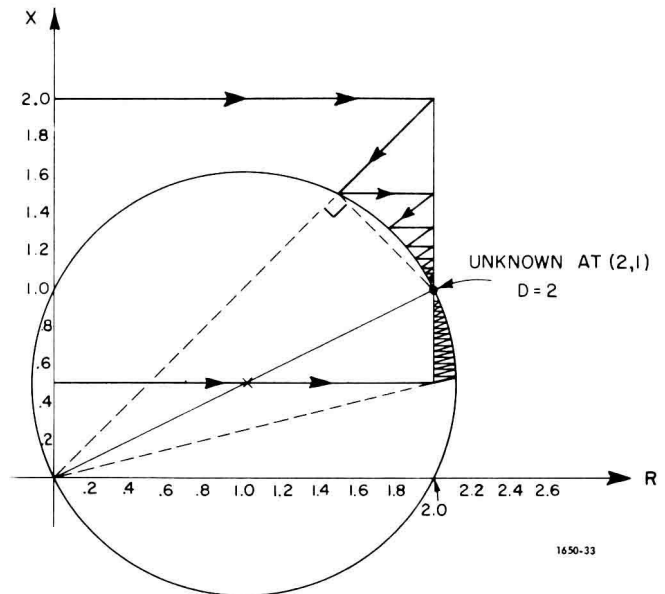


Figure 5-10. Loci of "sliding null" balances.

$R_S$  is adjusted,  $R_N$  must not move, to vary only the real part. The solution is a simple friction clutch to permit nonreciprocal action. Both the inherent difference in friction of the two rheostats and the pulley ratio favor torque transmission in the desired direction.

The ratio  $R_S/R_N$  must be constant for variation in  $R_N$  for any initial settings of  $R_N$  and  $R_S$ , since  $R_S$  may be moved independently of  $R_N$ . This requires rheostats with exponential characteristics (and logarithmic dials). The  $D$  rheostat is a 54-dB exponential potentiometer. The  $C$  rheostat is exponential in the dial range from 1 to 11, and linear below 1. Thus, for correct Orthonull action, the  $C$  dial must always be set in the range above 1.

The advantage of Orthonull is illustrated in Figure 5-11, which is a plot of the number of adjustments necessary for a balance. Not only does the Orthonull reduce the number of balances, but it permits 1% measurements that would otherwise be impossible with  $D$ 's above 3, due to the finite resolution of the  $D$  rheostat. This finite resolution causes the meter indication to vary in jumps when Orthonull is used at  $D$ 's above 3. However, by selection of the best null, 1% accuracy is possible with  $D$ 's of more than 5 and 20% with  $D$ 's of 10.

## 5.7 THREE-AND-FOUR-TERMINAL MEASUREMENTS.

### 5.7.1 GENERAL.

Stray impedances - the plague of precise metrology - are of two kinds: shunt and series impedances. Fortunately, in the case of capacitance measurements, they are rarely both important at the same time. The

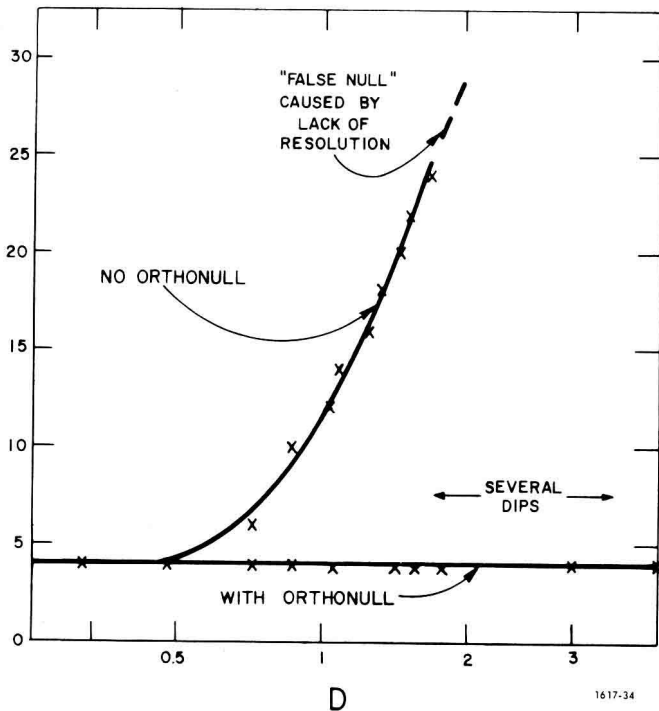


Figure 5-11. Number of adjustments to obtain balance versus  $D$ .

shunt impedances introduce error in low-capacitance measurements and are corrected by 3-terminal measurements. The series impedances are important in the measurement of high capacitance (low impedance) and necessitate 4-terminal measurements.

### 5.7.2 THREE-TERMINAL MEASUREMENTS.

The shielding of a low-valued capacitor prevents the direct shunting of the unknown by a stray capacitance. However, the shield is, in effect, a third terminal and there may be appreciable capacitance from the terminals of the unknown to the shield (Figure 5-12).

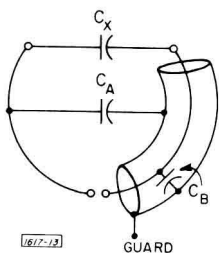


Figure 5-12. Measurement of a capacitor  $C_x$  with a shielded lead and the resulting stray capacitances. The shield prevents stray capacitance from being set up directly across the unknown.

The object is to eliminate  $C_A$  and  $C_B$  from the direct measurements of  $C_x$ . This can be accomplished by measurement of short-circuit transfer admittance,  $I_o/E_{in}$ , of the circuit of Figure 5-13.

If the source and the ammeter have zero impedance, the measurement is independent of  $C_A$  and  $C_B$  and:

$$y_{21} = I_o/E_{in} = j\omega C_x$$

The Type 1617 Capacitance Bridge uses an active guard circuit to achieve the same result (refer to paragraph 5.2).

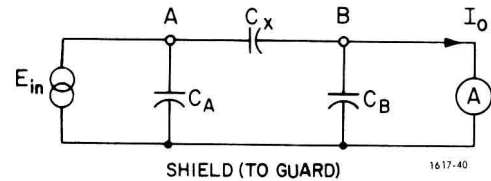


Figure 5-13. Elimination of the effect of the stray capacitances  $C_A$  and  $C_B$  by a short-circuit transfer-admittance measurement.

### 5.7.3 FOUR-TERMINAL MEASUREMENTS.

A high-valued capacitor is little affected by a shunt stray capacitance but, because of its low impedance, it is very much affected by a series stray impedance (such as lead resistance). Here, a measurement of transfer impedance,  $E_o/I_{in}$ , will eliminate the effect of the leads (Figure 5-14) if both the source and the voltmeter have infinite impedances;  $E_o/I_{in} = Z_{21}$  is exactly the impedance from  $A$  to  $A'$ , i.e.,  $1/j\omega C_x$ . This method shows quite clearly why in a 4-terminal component, two terminals ( $C, C'$ ) are usually labelled the "current" terminals and two, ( $P, P'$ ) the "potential" terminals.

The Type 1617 uses a similar, if not exactly identical method of measurement. Its two outer connectors can be considered "current terminals" and the inner connectors "potential terminals".

It is interesting to note that there are some applications where both series and shunt stray impedances affect the unknown enough to require that both 3- and 4-terminal techniques be used at the same time. Examples are: very high precision measurements on standard capacitors of medium value, high-frequency measurements on capacitors and measurements on remotely located components (refer to paragraph 4.5.1).

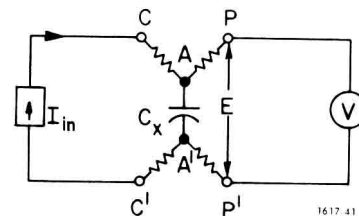


Figure 5-14. Elimination of the lead impedance by a transfer-impedance measurement.

<sup>1</sup>R.D. Cutkosky, "Four Terminal Pair Networks as Precision Pair Networks," IEEE Transactions on Communication and Electronics, #70, January 1962, page 19.

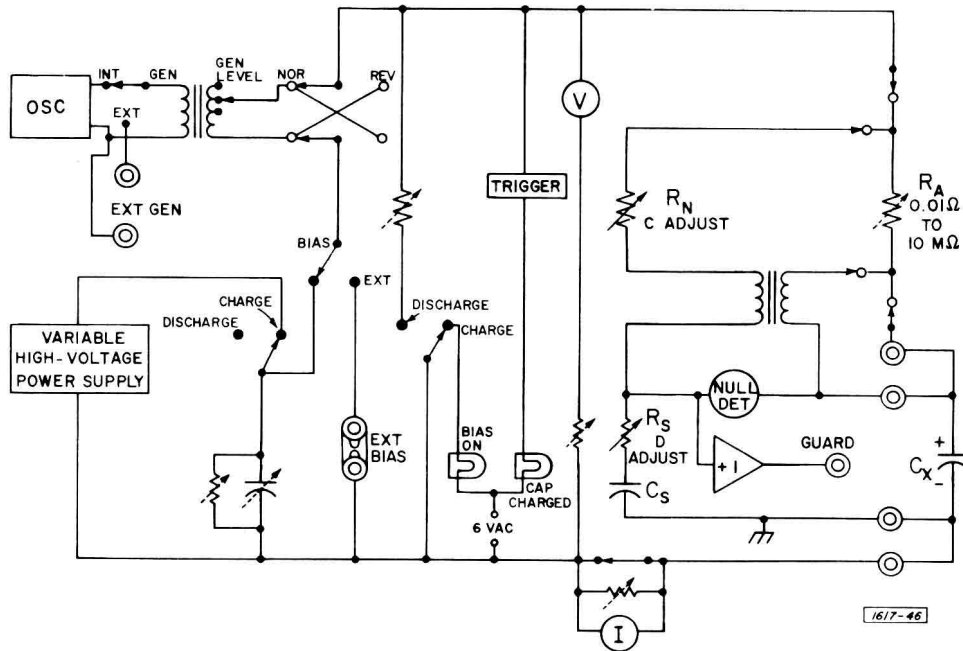


Figure 5-15. Simplified schematic of Type 1617 Capacitance Bridge showing three measurement modes: null, voltage, and current.

## 5.8 GENERAL.

The interrelationship of the several circuits that make up the Type 1617 Capacitance Bridge will become

more apparent by reference to Figure 5-15, a simplified schematic description of the complete instrument. Comprehensive circuit details are presented in the full schematic drawings shown in Section 6.

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# Service and Maintenance—Section 6

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## WARNING

High voltages, constituting potentially lethal shock hazards, exist in the circuitry inside the case of this bridge.

If troubleshooting is necessary, it should be performed by qualified personnel familiar with the hazards inherent in high-voltage circuits.

### 6.1 WARRANTY.

We warrant that each new instrument manufactured and sold by us is free from defects in material and workmanship, and that, properly used, it will perform in full accordance with applicable specifications.

### 6.2 SERVICE.

The warranty stated above attests the quality of materials and workmanship in our products. When difficulties do occur, our service engineers will assist in any way possible. If the difficulty cannot be eliminated by use of the following service instructions, please write or phone our Service Department (see rear cover), giving full information of the trouble and of steps taken to remedy it. Be sure to mention the serial and type numbers of the instrument.

Before returning an instrument to General Radio for service, please write to our Service Department or nearest District Office, requesting a "Returned Material Tag". Use of this tag will ensure proper handling and identification. For instruments not covered by the warranty, a purchase order should be forwarded to avoid unnecessary delay.

### 6.3 TROUBLE ANALYSIS.

#### 6.3.1 PRELIMINARY CHECKS.

If satisfactory balances are difficult or impossible to obtain, make the following external checks first.

1. Is the instrument connected to the line?
2. Is the power on?
3. Is the unknown connected correctly?
4. Are all the panel controls set properly?
5. Are all the shorting links in place? For 2- and 3-terminal measurements, link the two positive terminals and link the two negative terminals. The link on the EXT BIAS terminals should always be connected if the terminals are not in use.
6. Is the unknown what it is thought to be? Try measuring a known component.
7. Is the D so high that Orthonull should be used?
8. Is the SENSITIVITY control on?

#### 6.3.2 TROUBLE ANALYSIS.

The Type 1617 Capacitance Bridge is self-contained and incorporates six major circuits, the generator, the detector, the guard and trigger, the bias supply, the meter and the bridge; one or several of these may become defective.

A component is connected and balance is attempted.

1. NOISY OR ERRATIC BALANCE. This may be due to surface contamination of the wirewound C and D control rheostats. Contamination can form if the bridge is left idle for an extended period and can be eliminated by rotating the controls several times.

## 2. WRONG VOLTAGE INDICATION.

If the bias was applied and it appears that a wrong result is obtained, a d-c voltmeter across the unknown will read the actual value of the dc bias applied. If this is not what was intended, or shown by the meter, the internal supply is faulty, proceed to paragraph 6.4.3 (see also paragraph 3.4).

3. CAPACITANCE MEASUREMENT ERROR. If the measurement was guarded (3-terminal) and it appears that the guard does not accomplish its purpose, proceed to paragraph 6.4.4. The proper functioning of the guard when measuring a small capacitor ( $<0.01 \mu\text{F}$ ) is checked by connecting a capacitor (around 1000 pF) from the guard to the positive terminal. If the reading is not appreciably changed, the guard is operative. Loss of proper guard action can cause errors in the highest as well as the lowest C ranges. Check guard if error appears on those ranges (see above).

Finally, if the balance obtained is known to be erroneous, some bridge circuit component is faulty, (refer to paragraph 6.4.6).

4. NO DEFLECTION. A process of elimination will localize the trouble.

a. Connect an external generator (120 Hz giving 5 V, rms); the Types 1310 or 1311 oscillators are well suited for the purpose. If balance is obtainable, the internal generator is faulty (refer to paragraph 6.4.1). If nothing happens, proceed below.

b. Detector and Meter Check—Keep the external generator connected and set controls as follows:

MULTIPLIER switch to 100 pF.

C Dial to 10.

D Dial to 1.

GEN LEVEL MAX VOLTS to 0.2.

DETECTOR SENSITIVITY fully clockwise.

c. Disconnect the link at the two positive UNKNOWN terminals, thus isolating the detector input and connect an oscillator between AT401\* and AT402. A signal from this oscillator of approximately 0.5 V at 120 Hz should drive the meter full scale. This meter should peak at 120 Hz  $\pm 2\%$ .

If the check is negative, either the detector or the meter is faulty. Connect an external indicator (earphones, scope . . .) to the detector output (refer to paragraph 5.4 and Figure 5-7) and again look for this signal. If it is there, the meter is faulty; if it is not the detector is to be repaired. Proceed to paragraph 6.4.2.

\*The anchor terminals (AT) are the most accessible test points, they are on one side of the etched boards (see Figures 6-7 through 6-9). The AT is usually omitted on the board. All anchor terminals with the same first digit (4 in AT401) are on the same board.

5. EXCESSIVE DISCHARGE TIME. On the high-voltage ranges, high-capacitance ranges, and combinations of high capacitance/high voltage, where lethal charges may be present at the UNKNOWN terminals, the circuit is designed so as to discharge the capacitor being measured very quickly. Therefore, when the BIAS CHARGE-DISCHARGE control is switched to DISCHARGE, the CAPACITOR CHARGED lamp should go out almost immediately.

When measuring high-value capacitors at low voltage, it may take up to several seconds to drop the bias voltage below 1 volt and therefore have the lamp go out, but this is not a dangerous condition.

If the time required for discharge is excessive, it may indicate a burned-out discharge resistor (R178 through R181), or a faulty discharge switch (S106).

## 6.4 DETAIL TROUBLE ANALYSIS (Figure 6-1).

### 6.4.1 GENERATOR.

Set the function switch to INT 120 C, the MULTIPLIER switch to 1  $\mu\text{F}$ , and connect a scope across R115 (on switch S102). The waveform (120 Hz) should be free of distortion and have an amplitude equal to the setting of the GEN LEVEL MAX VOLTS switch (S105). If the level is incorrect adjust R222. (Too high a level causes waveform distortion). If some, but not all three, voltages are obtained, check switch S105 for proper contact and check the secondary taps of T101 for open-circuit indications. If the correct ac output cannot be obtained, check the dc levels within the generator circuit (Table 6-6) and the ac voltages at transformer output T501 (Table 6-1).

Table 6-1

Transformer Secondary Voltages (T501) With 115 V Into The Primary (Figures 6-2 and 6-10)	
Pins	Voltage (rms)
5-6	9.6 V
7-8	4.8 V
8-9	15.3 V
10-11	110 V
11-12	155 V
13-14	110 V
14-15	6.0 V
17-18	15.0 V

### 6.4.2 DETECTOR.

With 0.5 mV applied (paragraph 6.3.2), Table 6-2 shows typical waveforms and amplitudes. Check the dc voltages as in Table 6-6.