

◆ PRECISION INSTRUMENTS FOR TEST AND MEASUREMENT ◆

1615 Capacitance Bridge

**1620 Capacitance
Measuring System**

User and Service Manual

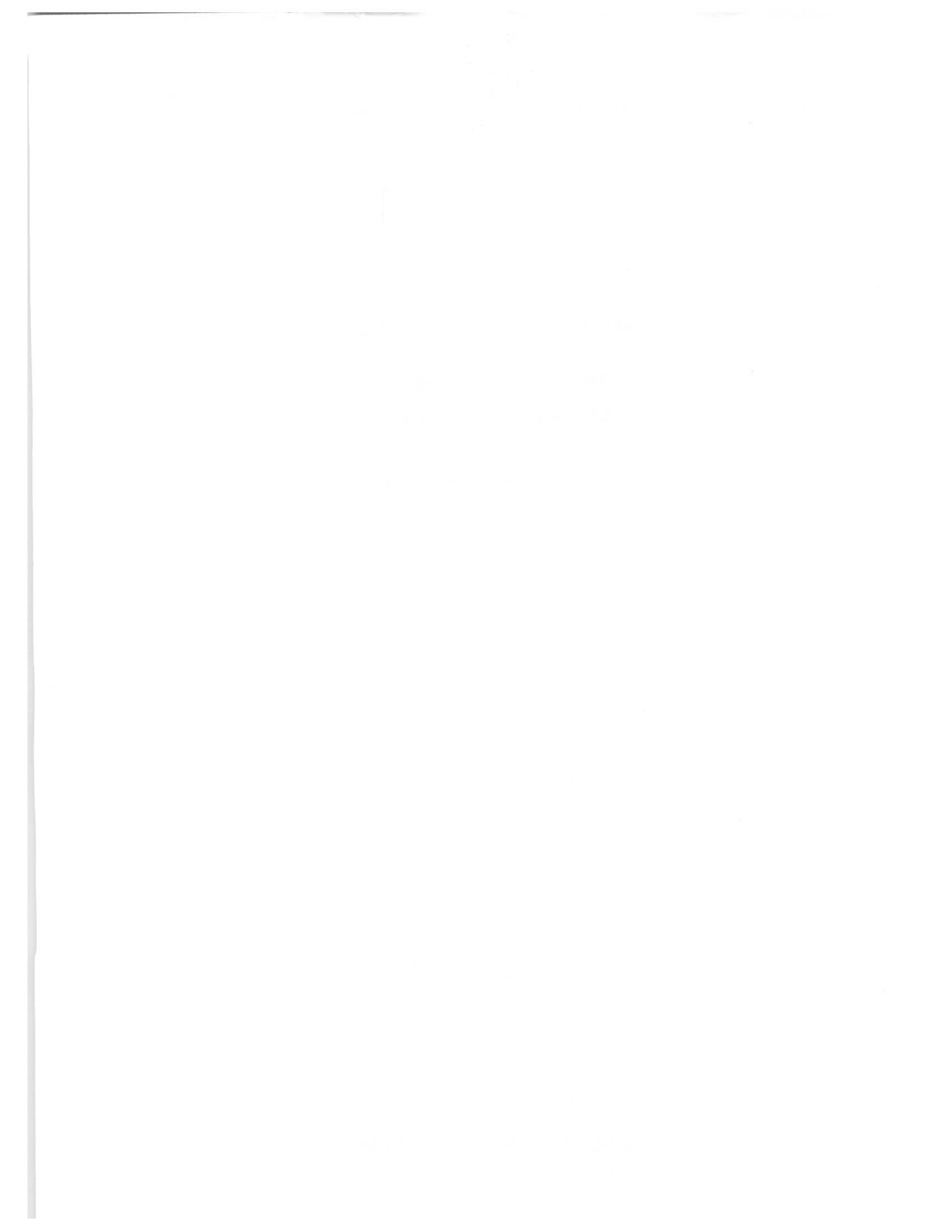
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WARRANTY

We warrant that this product is free from defects in material and workmanship and, when properly used, will perform in accordance with applicable IET specifications. If within one year after original shipment, it is found not to meet this standard, it will be repaired or, at the option of IET, replaced at no charge when returned to IET. Changes in this product not approved by IET or application of voltages or currents greater than those allowed by the specifications shall void this warranty. IET shall not be liable for any indirect, special, or consequential damages, even if notice has been given to the possibility of such damages.

THIS WARRANTY IS IN LIEU OF ALL OTHER WARRANTIES, EXPRESSED OR IMPLIED, INCLUDING BUT NOT LIMITED TO, ANY IMPLIED WARRANTY OF MERCHANTABILITY OR FITNESS FOR ANY PARTICULAR PURPOSE.



WARNING



OBSERVE ALL SAFETY RULES
WHEN WORKING WITH HIGH VOLTAGES OR LINE VOLTAGES.

**Dangerous voltages may be present inside this instrument. Do not open the case
Refer servicing to qualified personnel**

HIGH VOLTAGES MAY BE PRESENT AT THE TERMINALS OF THIS INSTRUMENT

WHENEVER HAZARDOUS VOLTAGES (> 45 V) ARE USED, TAKE ALL MEASURES TO
AVOID ACCIDENTAL CONTACT WITH ANY LIVE COMPONENTS.

USE MAXIMUM INSULATION AND MINIMIZE THE USE OF BARE
CONDUCTORS WHEN USING THIS INSTRUMENT.

Use extreme caution when working with bare conductors or bus bars.

WHEN WORKING WITH HIGH VOLTAGES, POST WARNING SIGNS AND
KEEP UNREQUIRED PERSONNEL SAFELY AWAY.



CAUTION



DO NOT APPLY ANY VOLTAGES OR CURRENTS TO THE TERMINALS OF THIS
INSTRUMENT IN EXCESS OF THE MAXIMUM LIMITS INDICATED ON
THE FRONT PANEL OR THE OPERATING GUIDE LABEL.

SPECIFICATIONS

WARRANTY — see page 65.

FOR 1620-A /-AP CAPACITANCE MEASURING ASSEMBLY

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): 19.75x19x11 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

FOR 1615-A CAPACITANCE BRIDGE

RANGES

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.

Dissipation Factor, D, At 1 kHz, 0.000001 to 1, 4-figure resolution; least count, 0.000001 (10⁻⁶); range varies directly with frequency.

Conductance, G, 10⁻⁶ μΩ to 100 μΩ, 2 ranges +, 2 ranges -, 4-figure resolution, least count 10⁻⁶ μΩ, independent of frequency; range varies with C range.

ACCURACY

At 1 kHz, ±(0.01% + 0.00003 pF). At higher frequencies and with high capacitance, additional error is

$$[\pm 3 \times 10^{-6}\% + 2 (C_{\mu F}) \times 10^{-3}\% \pm 3 \times 10^{-7} \text{ pF}] \times (f_{\text{kHz}})^2.$$

At lower frequencies and with low capacitance, accuracy may be limited by bridge sensitivity.

Comparison accuracy, unknown to external standard, 1 ppm.

$$\pm[0.1\% \text{ of measured value} + 10^{-6} (1 + f_{\text{kHz}} + 5 f_{\text{kHz}} C_{\mu F})]$$

$$\pm[1\% \text{ of measured value} + 10^{-6} \mu\Omega + 6 \times 10^{-2} f_{\text{kHz}} C_{\mu F} \times (1 + f_{\text{kHz}} + 5 f_{\text{kHz}} C_{\mu F}) \mu\Omega]$$

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 (30x f_{kHz}) volts, 300 V max. If generator and detector connections are interchanged, 150 to 500 V can be applied, depending on switch settings.

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, 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 ln): 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-P2 Coaxial Adaptor, GR900 to binding posts	1615-9601
	1615-9602

NOTE

The unit for conductance in SI terms is siemens, abbreviated S.*

*Ref: "The International System of Units (SI)", U.S. Dept. of Commerce, National Bureau of Standards, NBS Special Publication 330, SD Cat. No. C 13.10:330/2, U.S. GPO, Wash., D.C., 20402.

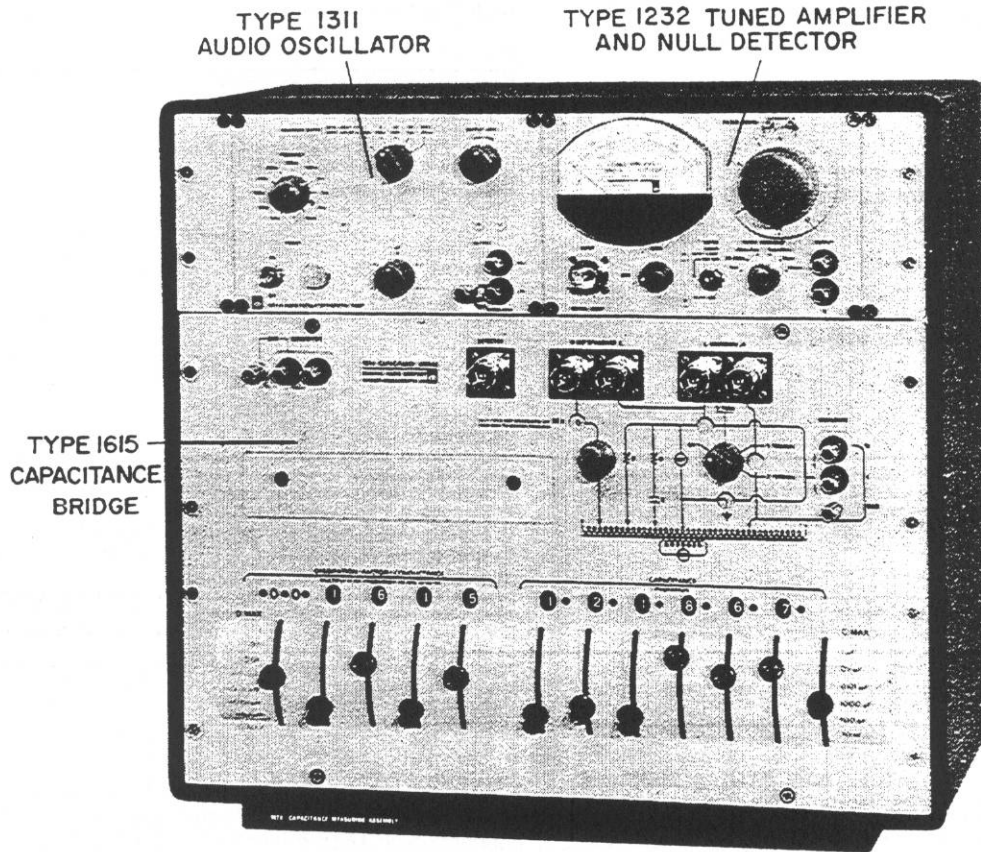


Figure 1-1. Type 1620-A Capacitance Measuring Assembly.

SECTION I

INTRODUCTION

NOTE: The abbreviation for cycles per second in this manual or on the instrument may be cps, c/s, or Hz.

1.1 PURPOSE.

The Type 1620-A Capacitance-Measuring Assembly (Figure 1-1) is designed for the precise measurement of capacitors and capacitance standards. In the standards laboratory, its high resolution for capacitance and dissipation factor make it well-suited for capacitance standards measurements. Its in-line readout system minimizes reading errors and permits rapid operation.

It can measure both 3-terminal and 2-terminal capacitors. Because transformer ratio arms are used in the bridge, 3-terminal measurements can be made accurately, even in the presence of large capacitances to ground. For instance, a ground capacitance of 1 μf produces an error of only 0.01% in the measurement of 1000-pf capacitor. This feature makes the assembly very useful for *in situ* measurements of circuit capacitances.

A wide range of capacitances can be measured, extending from a lower limit of 10 μpf (10^{-5} pf) to a maximum of 1 μf , with internal standards. With external standards, 1000 μf is the upper limit.

Since an important use of this bridge is the comparison of capacitance standards, an extra set of coaxial terminals is provided on the bridge to which a reference standard can be connected. The standard under test is then connected to the UNKNOWN terminal, and the internal standards used to complete the balance. If the difference between the unknown and reference standard is small, the accuracy of the measurement is equal to the

accuracy of calibration of the reference standard. In this measurement, the internal bridge standards can be compared with equal ease to either the unknown or reference standard; hence, both positive and negative differences can be measured.

1.2 DESCRIPTION.

1.2.1 GENERAL. The Type 1620-A Capacitance-Measuring Assembly consists of the Type 1615-A Capacitance Bridge with the Type 1311-A Audio Oscillator and the Type 1232-A Tuned Amplifier and Null Detector, a complete system for the precise measurement of capacitance.

Oscillator and detector are mounted side by side as shown in Figure 1-1 atop the bridge. The end frames are bolted together to make a rigid assembly obviating any requirement for the use of a relay rack. Connecting cables are supplied. An elementary system diagram is given in Figure 1-2.

1.2.2 BRIDGE CIRCUIT. The ratio arms of the bridge are transformer windings, tapped on the standard side in decimal steps from 0.1 to 1, and on the unknown side in decade steps from 1 to 0.001. Eight separate, fixed-capacitance standards are used, whose values range in decade steps from 0.0001 pf to 1000 pf. This combination of internal standards and transformer ratios makes possible the wide measurement range of $10^9:1$.

TYPE 1615-A CAPACITANCE BRIDGE

The loss component is read as either dissipation factor or conductance, the former being mandatory when D is greater than about 0.01. G must be used when external standards are used or internal standards are compared.

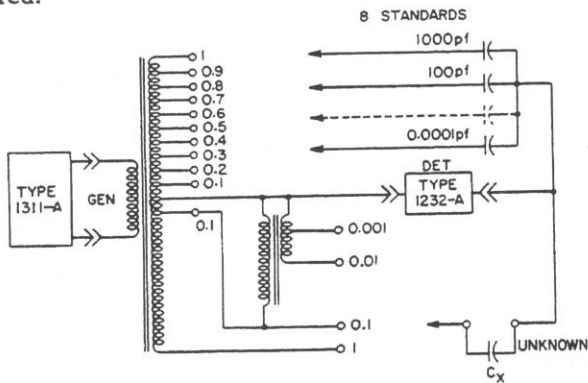


Figure 1-2. Type 1620-A Capacitance Measuring Assembly.

1.2.3 STANDARDS. Capacitance standards utilize plates fabricated from Invar steel for high dimensional stability and are hermetically sealed to eliminate changes in value resulting from changes in atmospheric pressure and humidity.

Provision is made for front panel adjustment of the internal capacitance standards in terms of the accurate transformer ratio or of external standards.

1.2.4 GENERATOR. The Type 1311-A Audio Oscillator is an ac powered, all-transistor instrument for use in bridge-measurement work requiring a compact source of distortion-free, audio-frequency, sine-wave signals. It

provides at least 1.0 watt output power into a wide range of load impedances at eleven frequencies between 50 and 10,000 cps with an accuracy of $\pm 1\%$. Other features include the ability to drive any impedance without clipping. For bridge measurements the shielded secondary winding on the output transformer permits the oscillator to be used as a floating source, thus minimizing or eliminating circulating ground currents.

1.2.5 NULL DETECTOR. The Type 1232-A Tuned Amplifier and Null Detector is a versatile instrument designed primarily as a bridge detector. It consists of a sensitive, low-noise preamplifier, a frequency-selective stage (feedback amplifier and null network), an amplifier-compressor stage, and a meter-rectifier circuit. The total gain capability of the amplifier is about 120 db. Full-scale meter sensitivity is 1 microvolt, or better, over most of a frequency range which is continuously tunable from 20 cps to 20 kc, with additional fixed-tuned frequencies of 50 kc and 100 kc. This null detector permits balances to a resolution of 1 part in 10^6 .

1.3 CONTROLS AND CONNECTORS.

1.3.1 BRIDGE CONTROLS (See Figure 1-3). Lever-type switches are used for both capacitance and conductance-dissipation-factor balances. In addition to the usual decades steps (0.1.....0.9, X), each capacitance switch has a -1 position, which greatly facilitates the balancing procedure. The capacitance readout is in picofarads, with the decimal point automatically indicated in red.

Table 1-1 lists and describes all front-panel controls and indicators found on the Type 1615-A bridge.

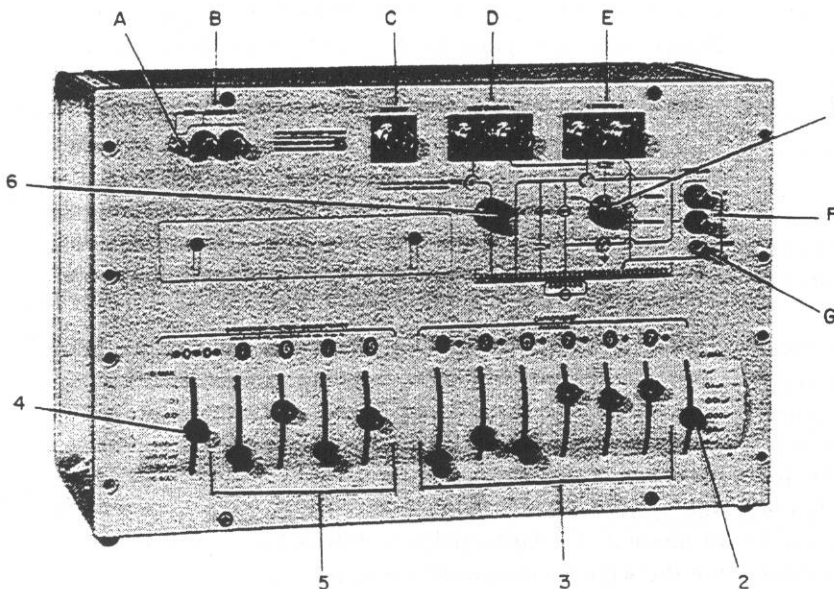


TABLE 1-1
CONTROLS AND INDICATORS - TYPE 1615

NAME	REF	TYPE	FUNCTION	RELATED INDICATOR
Terminal Selector (Gray Pointer Knob)	S113 Fig. 1-3 (1)	4-position rotary switch	Used to place bridge in desired operating mode, i.e. calibration, 3-terminal shielded, 3-terminal unshielded and 2-terminal.	Fixed simplified schematic engraved on front panel plus variable back-of-panel engraving.
C Range C MAX (Black Knob) M (Black Knob)	S112 Fig. 1-3 (2)	6-position lever-switch	a. Used to select range of capacitance to be measured and automatically place decimal point on readout. b. Determines M factor by which CONDUCTANCE reading (if used) must be multiplied to compute value in micromhos, and by which EXT STANDARD must be multiplied, if used.	a. White vertical scale on front panel- C MAX 10 pf through 1 μ f. b. Red vertical scale on front panel- M : 1 - 1000.
CAPACITANCE Set of 6 (Gray Knobs)	S106 through S111 Fig. 1-3 (3)	12-position lever switches	Used to balance bridge and give direct reading on associated digital scale.	Horizontal, digital, window-type readout in PICO FARADS with automatically adjustable decimal point: 0 through 1, plus X and -1.
D MAX (Black Knob)	S101 (Partial) Fig. 1-3 (4)	3-position lever-switch	Used to select range of DISSIPATION FACTOR measurements and automatically place decimal point on readout.	Vertical scale (white): 1, 0.1 and 0.01.
G MAX (Black Knob)	S101 (Partial) Fig. 1-3 (4)	4-position lever-switch	Used to set range for CONDUCTANCE measurements and automatically place decimal point on readout.	Vertical scale (red): +0.1 μ Ω , +0.01 μ Ω -0.01 μ Ω , -0.1 μ Ω .
DISSIPATION FACTOR- CONDUCTANCE Set of 4 (Gray Knobs)	S102 through S105 Fig. 1-3 (5)	11-position lever switches	Used to balance bridge and give direct reading on associated digital scale.	Horizontal, digital, window-type readout with automatic decimal-point. (Affected by M setting, S112)
MULTIPLY EXT STANDARD BY M x.... AND ADD TO DECADE READING (Gray Bar Knob)	S114 Fig. 1-3 (6)	11-position rotary	Used to connect EXTERNAL STANDARD connectors to ground or to any of 10 taps on ratio-transformer of bridge.	Decimal window-type readout: 0 through 1. (Affected by M setting, S112)

1.3.2 BRIDGE CONNECTORS. Table 1-2 lists and describes all front-panel connectors found on the Type 1615-A Bridge.

1.3.3 GENERATOR CONTROLS AND CONNECTORS. Controls and connectors listed and described in Table

1-3 are on the front panel of the Type 1311-A Audio Oscillator.

1.3.4 DETECTOR CONTROLS AND CONNECTORS. Table 1-4 lists and describes controls and connectors on the Type 1232-A Tuned Amplifier and Null Detector.

**TABLE 1-2
CONNECTORS - TYPE 1615**

NAME	REF	TYPE	FUNCTION
GND	J101 Fig. 1-3 (A)	Binding Post, General Radio Type 938	Case ground.
GENERATOR	J102/J103 Fig. 1-3 (B)	Binding Post, General Radio Type 938, insulated	Receives input from external generator.
DETECTOR	J104 Fig. 1-3 (C)	Coaxial, General Radio Type 874	Shielded connection from bridge to external null detector.
EXT STANDARD* H & L	J105/J106 Fig. 1-3 (D)	Coaxial, General Radio Type 874	Shielded connection for external 3-terminal standards.
UNKNOWN H & L	J107/J108 Fig. 1-3 (E)	Coaxial, General Radio Type 874	Shielded connection for 3-terminal unknown capacitors.
UNKNOWN H, L	J110/J111 Fig. 1-3 (F)	Binding Posts, General Radio Type 938 (insulated)	Unshielded connection for 3- or 2-terminal unknown capacitors.
GND	J109 Fig. 1-3 (G)	Binding Post, General Radio Type 938	Case ground.

*Type 874-WO coaxial termination must always be installed on L connector unless capacitor is attached. Needed to shield sensitive DETECTOR input.

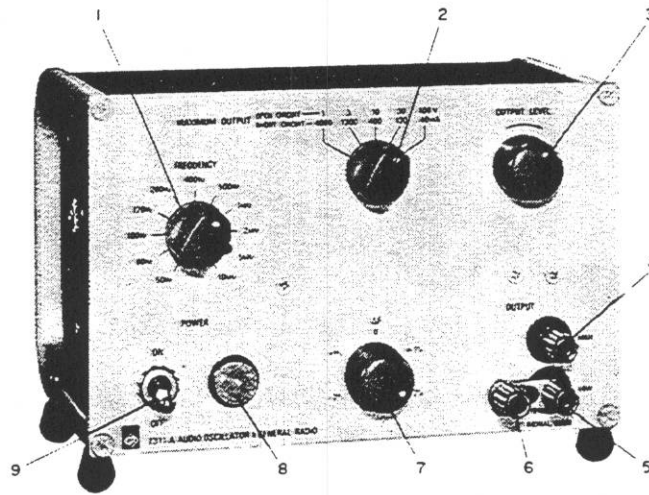


Figure 1-4. Type 1311 Audio Oscillator (see Table 1-3).

TABLE 1-3
CONTROLS AND CONNECTORS - TYPE 1311-A

REF FIG. 1-4	NAME	TYPE	FUNCTION
1	FREQUENCY	12-position rotary switch	Used to select output frequency.
2	MAXIMUM OUTPUT	5-position rotary switch	Used to select output transformer tap.
3	OUTPUT	Rotary Control	Used for fine output level variations.
7	ΔF	Rotary Control	Used to adjust output frequency ($\pm 2\%$ about nominal)
9	POWER	Toggle switch	Power ON/OFF control.
4-6	OUTPUT	Binding Posts (3) General Radio Type 938	Output terminals and ground.
	----	Power plug, General Radio Type 109-A	Power input terminal.
	----	Phone jack (on side panel)	Accept synchronizing signal from external frequency standard.

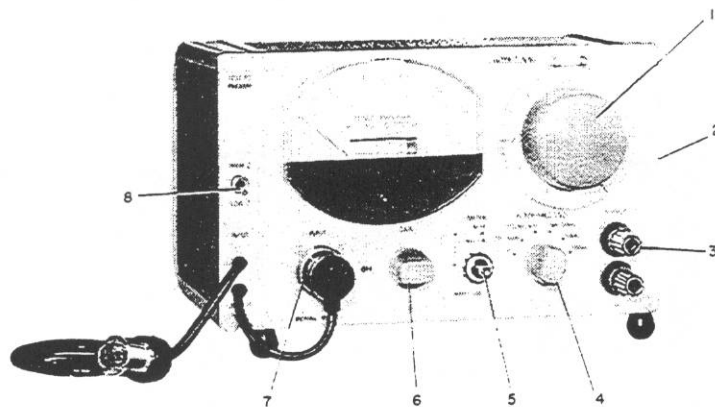


Figure 1-5. Type 1232-AP Tuned Amplifier and Null Detector (see Table 1-4). Consists of a Type 1232-A Tuned Amplifier and a Type 1232-P2 Preamplifier.

TABLE 1-4
CONTROLS AND CONNECTORS - TYPE 1232-A

REF FIG. 1-5	NAME	TYPE	FUNCTION
1	FILTER TUNING	Continuous rotary control	Tunes filter within selected tuning range.
4	FILTER FREQUENCY	6-position rotary switch	Selects desired frequency: tuning-frequency range of 20-200 cps, 200 cps-2 kc, or 2-20 kc; flat, 50-kc or 100-kc response.
6	GAIN	Rotary control	Turns instrument on or off and controls gain.
5	METER	Toggle switch	Selects linear or logarithmic response.
7	INPUT	Coaxial, General Radio Type 874	Input terminal.
3	OUTPUT	Binding Posts, General Radio Type 938	Amplifier output terminals (not used).
2	EXT FILTER	Phone jack	Connection for external filter.
8	HIGH Z - LOW Z (1232-AP only)	Toggle switch	Use HIGH Z position only when measuring small capacitances or small dissipation factors below 1 kHz.

SECTION 2

INSTALLATION

2.1 GENERAL.

The precision capacitance measuring system described in this manual may be obtained in four forms. Purchased as the Type 1620-A Capacitance Measuring Assembly it is complete, assembled and ready for bench use as shown in Figure 1-1. For those already in possession of either (or both) Type 1232-A Tuned Amplifier and Null Detector and Type 1311-A Audio Oscillator, these instruments may be readily combined with the Type 1615-A Capacitance Bridge to assemble a Type 1620-A, or (with the preamplifier, Figure 1-5) a 1620-AP.

An adaptor set can be used to join the generator and detector (Figure 2-1, with or without the preamplifier) into a rack-width module. This module and the bridge can then be mounted conveniently in a cabinet (Figure 1-1). Alternatively, the module can be provided with end frames so that it sits (or is bolted) onto the end frames of the bridge (Figure 1-3; Section 7, Mech. P.L.).

For electrical connections among the instruments, use the patch cords supplied with the bridge. (Refer to SPECIFICATIONS, page iii.)

Those planning to use detectors and generators other than General Radio Types 1232-A and 1311-A with either Type 1615 Capacitance Bridge may make similar combinations to suit particular needs and conditions.

2.2 TYPE 1620-A INSTALLATION.

2.2.1 SITING. The Type 1620-A Capacitance Measuring Assembly is a highly precise system for laboratory use. It is intended for bench mounting and is completely self-contained, requiring no further enclosure, such as racks or cabinets. Some open bench area around the assembly should be provided to support capacitors under test, or external standard capacitors, when used.

2.2.2 POWER INPUT. The Type CAP-22 Three-Wire Power Cord supplied should be attached to PL501 on the rear panel of the Type 1311-A Audio Oscillator and plugged into a standard grounding-type receptacle supplying ac power at 50 to 400 cps. The supply voltage,

105 to 125 or 210 to 250, should agree with that indicated on the engraving or nameplate near PL501. The Type 1232-A is battery operated and is shipped complete with batteries; the Type 1615-A requires no power connection.

NOTE

If the Assembly has been stored for any prolonged period prior to installation, the batteries of the Type 1232-A should be checked. Refer to the operating instructions supplied separately for that instrument for the recommended procedures.

2.2.3 ENVIRONMENTAL CONSIDERATIONS. The Type 1620-A will operate within specifications under environmental conditions normally encountered in standards laboratories. While all internal capacitance standards used are virtually immune to environmental variations, it should be borne in mind that marked changes in temperature or humidity can have a considerable effect on the capacitors under test and thus degrade the precision measurements possible with this instrument assembly. Other special environmental considerations are as follows:

1. Type 1615-A --- high concentrations of dust obscure the read-out and stiffen the balancing controls.
2. Type 1311-A --- ambient temperatures should not exceed 50°C.
3. Type 1232-A --- strong magnetic or electrostatic fields should not be maintained close to this instrument.

2.2.4 OPEN-CIRCUIT TERMINATION. The Type 874-WO Open Circuit Termination is supplied as an accessory to shield the EXT STANDARD L coaxial connector. It may be stored on any unused coaxial connector on the Type 1615-A bridge without affecting the electrical performance of the circuit associated with the connector. Such a practice is recommended to prevent loss of the termination.

2.3 ASSEMBLY OF TYPE 1620-A.

2.3.1 GENERAL. The Type 1620-A consists of the following instruments: Type 1232-A Tuned Amplifier and Null Detector, Type 1311-A Audio Oscillator, Type 1615-A Capacitance Bridge. The Type 1232-A and Type 1311-A are available as the Type 1240-A Bridge Oscillator-Detector Assembly, or (with Preamplifier) Type 1240-AP.

TABLE 2-1
ADDITIONAL ACCESSORIES REQUIRED

QUAN-TITY	DESCRIPTION	PART NO.
2	Adaptor plates: for 1620-A, right (insulating) for 1620-A, left (metal) for 1620-AP, right (insulating) for 1620-AP, left (metal)	0480-7010 0480-8724 0480-7011 0480-8725
1	Insulating screw, No. 10-32	1620-7000
1	Nut, No. 10-32	5810-3300
1	Hardware Set (includes 6 clips, 4 No. 10-32 X 0.5" screws with nuts and washers, 4 No. 10-32 rack-panel screws).	0480-3050
1*	Cabinet: for 1620-A for 1620-AP	4177-1620 4177-1621
1**	End frame, right	5310-3080
1**	End frame, left	5310-3081
4**	Bushing, .47" long, .22" dia. hole	7660-2015

*Not used for stack or rack mounting.
**Not used for cabinet or rack mounting.

2.3.2 STACKMOUNTING. If the instruments are purchased separately, they can be combined to form the Type 1620-A Capacitance Measuring Assembly as follows:

Subassembly (see Figure 2-1):

- Remove the rubber feet from the Type 1232-A and 1311-A.
- Remove the screws that secure the front panel to the aluminum end frames and remove the spacers between the front panel and the end frames.
- On one instrument, install the clips with the front-panel screws removed above. Δ
- Secure the two instruments together with front-panel screws through the remaining hole in each clip. Remove the covers, insert a nylon screw through the end panels, install a 10-32 nut, tighten, and replace the covers. Δ

Note that the instruments can be bench-mounted in this manner: simply do not remove the feet from the outside end frames.

e. Install two clips on each adaptor plate with the wing screws, lockwashers, and nuts supplied. Δ

f. Install the adaptor plates to the instruments with the front-panel screws removed earlier.

g. Install the 5310-3080 and 5310-3081 end frames to the adaptor plates with the 10-32 screws and cup washers supplied.

h. Place the subassembly atop the Type 1615-A. Place two bushings between each end frame of the sub-assembly and the Type 1615-A, insert 7/8-inch screws through the end frames and bushings, install lockwashers and nuts, and tighten. (Screws are not supplied.)

Electrical connections (see Figure 3-1):

i. Connect the Type 874-R22A Patch Cord between the DETECTOR terminal of the Type 1615-A and the INPUT terminal of the Type 1232-A. This must be the only ground connection to the detector.

j. At the OUTPUT terminals of the Type 1311-A, slide the shorting link away from the LOW binding post.

k. Connect the Type 274-NL Patch Cord between the GENERATOR terminal of the Type 1615-A and the OUTPUT terminal of the Type 1311-A. The polarity indicators (screw heads) at the plug-ends of the cable must be at the left for the Type 1615-A connection and at the bottom for the Type 1311-A connection.

2.3.3. CABINET MOUNTING. Proceed as above except for steps g, h. Remove end frames from the bridge. Install the instruments in the cabinet and fasten with rack-panel screws as shown in Figure 1-1.

2.3.4. RACK MOUNTING. Proceed as in para. 2.3-3, except install the instruments in your rack.

2.4 EQUIPMENT SUBSTITUTIONS.

Assemblies using the Type 1615 Capacitance Bridge in combination with generators and detectors other than the Types 1311-A and 1232-A can be utilized. For instance, General Radio Type 1310 Oscillator, while not specifically designed for use with the Type 1615, will give excellent service.

In general, laboratory-type instruments which meet the following performance specifications should give adequate service when used with the Type 1615 Capacitance Bridge:

- Generator - Stable sine-wave source with output power adjustable to a level not greater than 30 v/kc.
- Detector - Tunable with 1 μ v sensitivity, minimum.

INSTALLATION

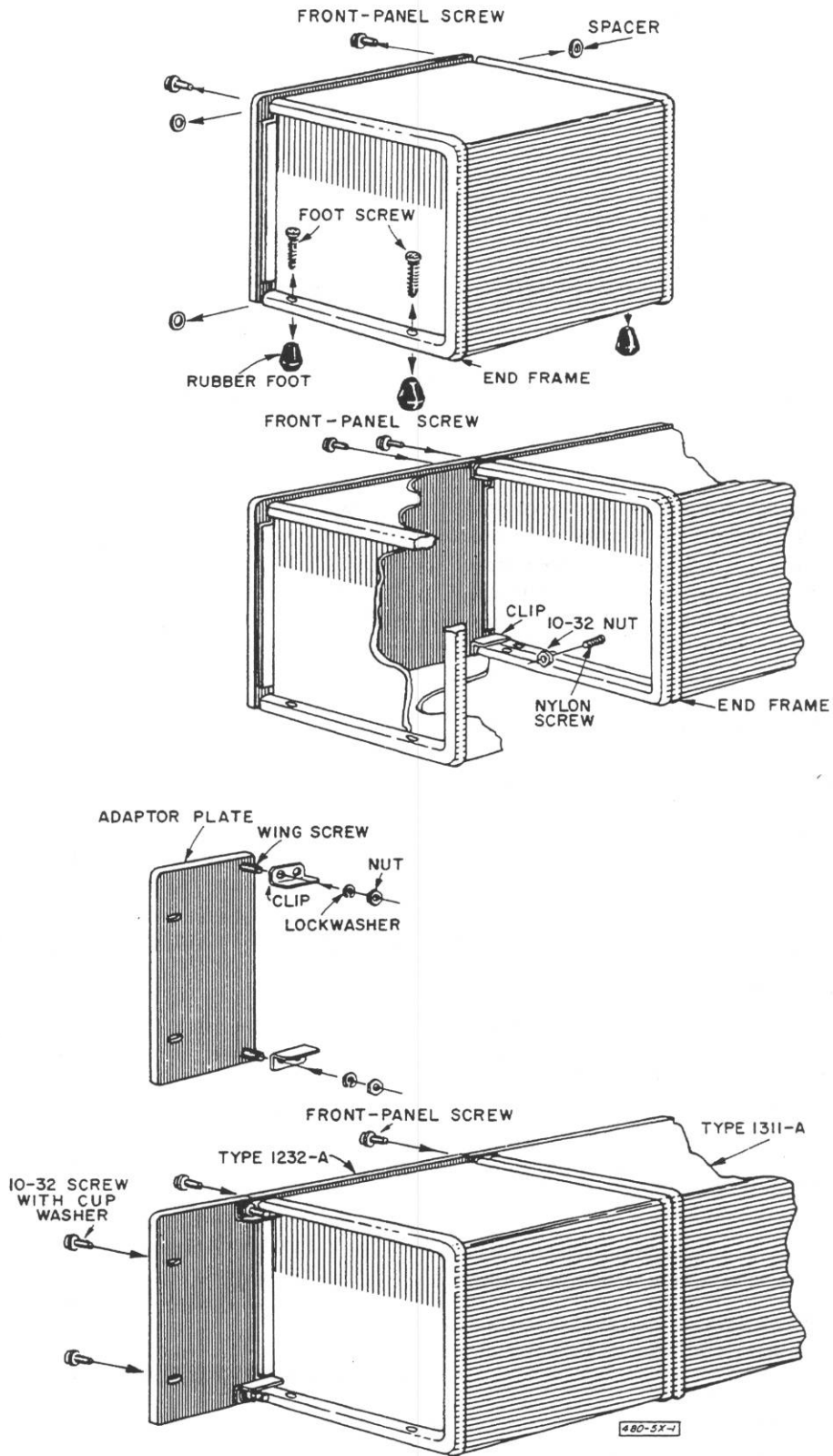


Figure 2-1.

SECTION 3

OPERATING PROCEDURES

3.1 GENERAL

Complete operating instructions are given in this section for the Type 1620-A Capacitance Measuring Assembly or a closely equivalent system assembled around a Type 1615-A Capacitance Bridge. It is recommended that Section 4, Theory of Operation, be read and understood when the equipment is first received, before performing the detailed procedures appearing in this section. Subsequently, for routine measurements, reference to the condensed operating-instruction sheet supplied should suffice. The sheet is laminated in clear plastic to permit frequent handling without deterioration. It is punched along the margin to permit insertion in standard three-ring binders. Alternatively, it is punched at the top so that it may be hung on the wall near the equipment, for maximum accessibility.

NOTE

Procedures which follow assume the use of the Type 1311-A as the generator and the Type 1232-A as the detector, both operating at 1 kc. For operational details, refer to the respective operating instructions for those instruments.

3.2 PREPARATION FOR USE

Prior to energizing the equipment, check that the following connections have been made (see Figure 3-1):

a. Type 1311-A OUTPUT to Type 1615-A GENERATOR (insulated) terminals via Type 274-NL Patch Cord.

NOTE

Polarity indicators (screw heads) at plugs must be at bottom for Type 1311-A connection and at left for Type 1615-A connection.

c. Type 1311-A power cord to appropriate 3-wire ac outlet.

d. Type 874-WO Open Circuit Termination supplied is installed on EXT STANDARD L coaxial connector if no capacitor is to be connected there.

3.3 EQUIPMENT TURN-ON

3.3.1 BRIDGE. The Type 1615-A Capacitance Bridge is a purely passive instrument and has no primary power or turn-on requirements. Apply power to the generator and detector, and allow for warm-up time, as required.

3.3.2 GENERATOR. To adjust the Type 1311-A:

a. Set FREQUENCY selector to desired frequency.

b. Set MAXIMUM OUTPUT selector and OUTPUT CONTROL for a voltage level not greater than 30 volts per kilocycle (300V max):

1.8 V max at 60 Hz

3 V max at 100 Hz

30 V max at 1000 Hz

300 V max at 10 kHz

300 V max at 100 kHz

3.3.3 DETECTOR. To adjust the Type 1232-A:

a. Adjust FILTER FREQUENCY switch to approximate frequency of generator.

b. Rotate FILTER TUNING control to peak meter.

c. Set METER to LOG position.

d. Adjust GAIN control for midscale indication.

3.4 EQUIPMENT SELF-CHECK

As a check of the proper operation of bridge, generator, and detector, a bridge balance can be made at any time with no external capacitors connected. Proceed as follows:

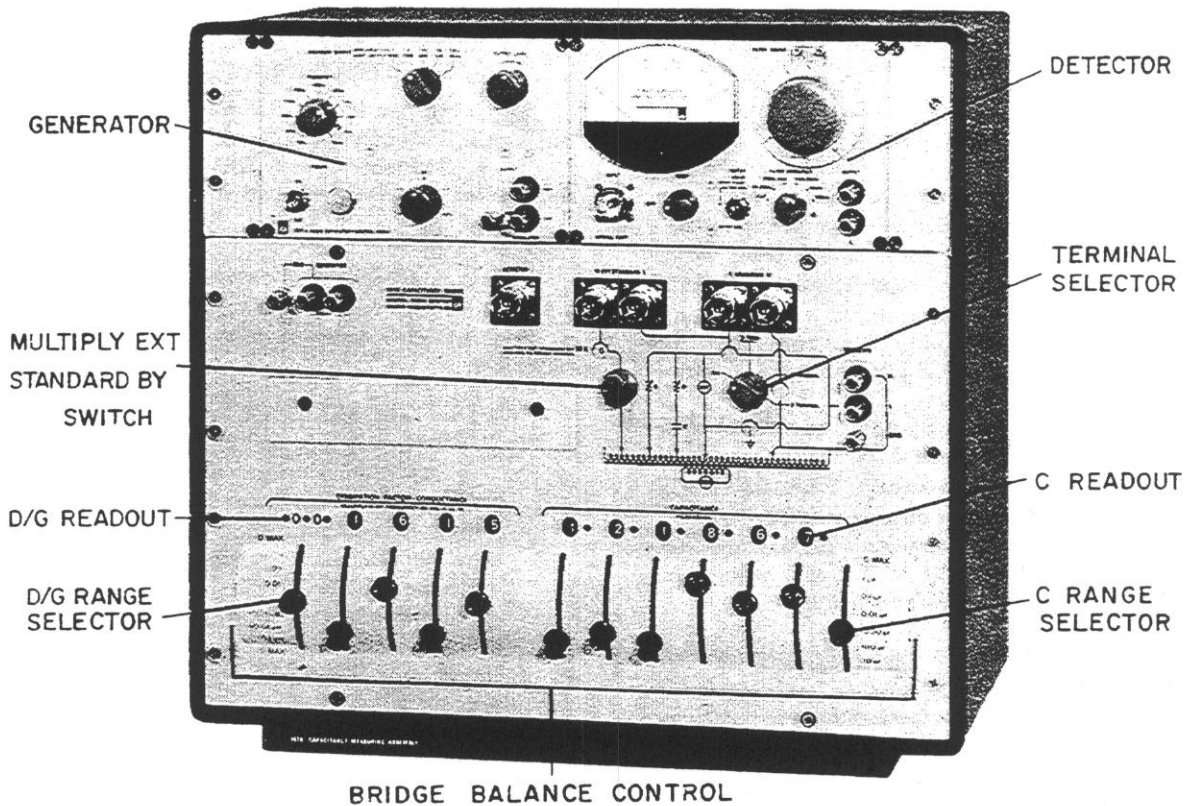


Figure 3-1. Operator controls and indicators.

- b. Set MULTIPLY EXTERNAL STANDARD BY to 0.
- c. Set C MAX to any position.
- d. Set D MAX to 0.01.
- e. Null should occur with DISSIPATION FACTOR balance controls at 0000 and CAPACITANCE balance controls at 000000 (position of decimal point varies with C MAX settings). Detector deflection should increase if any CAPACITANCE balance control is moved from the 0 position. If balance is not accomplished, refer to Section 6. The foregoing is a qualitative, "proof-of-function", check only.

3.5 DIGITAL READOUT ON TYPE 1615-A

Digital readouts appear in windows directly above all balance controls, as do red decimal-point indicators, automatically positioned by range settings.

Direct six-digit CAPACITANCE readouts in picofarads (with appropriate decimal point) are provided in ranges determined by the position of the C MAX switch.

DISSIPATION FACTOR readouts of four digits in three ranges, dependent on D MAX switch settings,

are available with automatically positioned decimal. Readouts should be multiplied by frequency in kilocycles.

Direct four-digit readouts of CONDUCTANCE measurements, in μ mhos, are provided in four ranges determined by setting of the G MAX switch, which also places the decimal point. However, in the three highest capacitance ranges, this readout must be multiplied by the (red) M factor corresponding to the C MAX setting.

All readouts offer 0 through 9 indications plus X, which indicates 10. Thus a reading of 348X12 is equivalent to 349012.

In addition, the CAPACITANCE readout has a -1 position, which indicates that the corresponding unit of internal standard capacitance has been placed across the UNKNOWN arm of the bridge and is to be subtracted from the bridge reading. A reading of 348(-1)12 is equivalent to $348012 - 000100 = 347912$.

CONDUCTANCE values add loss to the standard side of the bridge in +0.1 and +0.01 positions and to the unknown side in -0.1 and -0.01 positions. A negative G means the conductance of the unknown is the conductance of the internal and external standards minus the bridge G reading.

Decimal readouts in the MULTIPLY EXT STANDARD BY...window indicate the 11 steps by which the capacitor (if any) connected to the EXT STANDARD connectors can be varied.

3.6 BRIDGE BALANCE PROCEDURES

3.6.1 GENERAL. The following procedures apply for all modes of operation. Procedures for terminal selection and attachment of capacitor under test, which appear in paragraph 3.7, are here assumed to have been completed.

a. Move C MAX control to a setting slightly in excess of approximate value of capacitor being measured.

b. Set D MAX switch to 0.01 and set all DISSIPATION FACTOR controls to 0.

c. Position first (left-most) CAPACITANCE control for minimum deflection on detector meter.

d. To refine balance, position remaining CAPACITANCE controls, beginning at left and proceeding to right, until no further improvement occurs.

NOTE

To improve sharpness of balance indication, increase GAIN on detector, but restrict meter to lower half of scale.

e. Manipulate DISSIPATION FACTOR controls, starting with right-most, to refine balance further.

f. Alternately manipulate first CAPACITANCE and then DISSIPATION FACTOR controls until final null is accomplished. An increase in D MAX may be required.

NOTE.

If no null can be achieved in D MAX positions, try G MAX settings (same lever switch).

g. Observe direct CAPACITANCE readout in picofarads in the six digital windows above controls, noting placement of red decimal point.

h. Observe direct DISSIPATION FACTOR reading, if appropriate, from digital windows above controls, noting placement of decimal point. At 1 kc, dissipation factor is as indicated; otherwise, multiply by frequency in kilocycles.

i. If appropriate, observe CONDUCTANCE in μ mhos, reading from digital windows above controls. Multiply reading by M factor (red engraving on C MAX dial) to calculate final value.

3.6.2 BALANCE PROCEDURE WHEN NOMINAL CAPACITANCE IS NOT KNOWN. To obtain a bridge balance when even an approximate magnitude of the unknown capacitance cannot be estimated, or when difficulty has been encountered in obtaining balance:

a. Set terminal selector in CAL position.

b. Set C MAX at 1 μ f.

c. Set CAPACITANCE decade controls at 001 000. pf.

d. Set G MAX to +0.1 μ U.

e. Set CONDUCTANCE decades to 0000 .

f. Adjust detector GAIN control for about 1/3 full-scale deflection with meter set for LOG response.

g. Connect unknown to the appropriate terminals and switch terminal selector to corresponding position.

NOTE

The voltage at the UNKNOWN terminals is only 0.001 times the generator voltage applied to the bridge, so there is little danger of damage to the bridge or capacitor.

h. Set CAPACITANCE decades to 000 000. pf.

i. Observe deflection of detector meter:

(1) If deflection is near the 1/3-full-scale reading to which it was set in step f, the unknown is a capacitance of the order of 1000 pf, or a conductance of the order of 5μ U (a resistance of 200 kilohms).

(2) If the deflection is much greater than 1/3 full scale, the unknown is a capacitance much larger than 1000 pf, or a conductance much larger than 5μ U (a resistance much smaller than 200 kilohms).

(3) If the deflection is much less than 1/3 full scale, the unknown is a capacitance much less than 1000 pf or a conductance much less than 5μ U (a resistance much greater than 200 kilohms).

j. Adjust CAPACITANCE decades, appropriate to the indicated magnitude, for minimum meter deflection by the usual bridge balance procedure (refer to paragraph 3.6.1).

k. If CAPACITANCE decade controls produce no indication of balance, adjust CONDUCTANCE decade controls.

l. When partial balance has been attained with these C MAX and G MAX settings, change to other C MAX and G MAX (or D MAX) positions as required for a balance to the desired precision.

3.7 CAPACITANCE BALANCE CONTROLS

The bridge has three principal modes of operation for capacitance measurement. They are determined by the setting of the terminal selector switch and the choice of UNKNOWN terminals made. In turn, these selections are determined by the nature of the unknown capacitor. Specific criteria for the proper selection of operating mode are supplied in the following paragraphs:

1. Three-terminal coaxial (para. 3.7.3).

2. Three-terminal binding post (para. 3.7.4).

3. Two-terminal binding-post (para. 3.7.5).

Procedures concerning the fourth (CAL) position of the terminal selector switch are covered in Section 6.

3.7.1 "C MAX" SWITCH.

1. When the nominal value of capacitance to be measured is not known, set the C MAX switch to 1 μ F and follow procedure of paragraph 3.6.2.

2. When the nominal value of capacitance is known, set C MAX to a position which makes the first significant figure of the bridge CAPACITANCE readout appear in the window of the first or second CAPACITANCE decade for maximum accuracy and precision.

See Figure 3-2 for an illustration of the bridge range of unknown capacitance vs the six positions of the C MAX switch and the readouts from 1 to X of the six CAPACITANCE decades. The "X" readout indicates that the value is in terms of the upper bound of the "unknown capacitance" range and the "1" indicates the lower bound.

Use any of the possible C MAX switch positions which has adequate resolution for direct-reading accuracy of 0.01%, when the capacitance can be measured on more than one position.

For the measurement of very small capacitance differences, use the C MAX position which gives the maximum number of significant figures in the CAPACITANCE readout. For minimum error in difference measurements, use the same internal standard capacitor for the first significant figure in all bridge readings. The internal capacitors used for each position of each CAPACITANCE decade are shown in the horizontal bars in the readout symbols in Figure 3-2.

For minimum error from external noise sources, use the C MAX position of maximum resolution. This gives maximum voltage at the UNKNOWN terminals

and maximum detector deflection for a given percent unbalance. The voltage between the UNKNOWN H and GND terminals, V_{HG} , for a voltage E_{GEN} at the bridge

GENERATOR terminals is

$$V_{HG} = E_{GEN} / M \tag{3-1}$$

where M is the multiplier from 1 to 1000 engraved on the C MAX switch and, shown at the far right in Figure 3-2. With C MAX at 1 μ F and M=1000, the voltage on the capacitor is 0.01 times that applied when C MAX is 0.01 μ F (M=10) and the voltage into the detector is proportionally reduced, so errors are more likely to appear on the 1 μ F C MAX position when noise sources are present.

Example (voltage across UNKNOWN terminals):
If the maximum voltage of 30 V at 1 kHz is applied to the bridge GENERATOR terminals, the voltage across the unknown for the six C MAX ranges is:

C MAX	M	UNKNOWN volts for $E_{GEN} = 30V$
1 μ F	1000	0.03 V
0.1 μ F	100	0.3 V
0.01 μ F	10	3. V
1000 pF	1	30. V
100 pF	1	30. V
10 pF	1	30. V

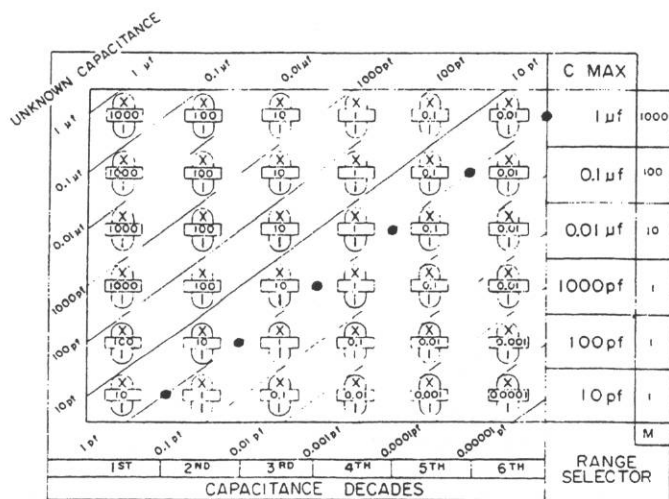


Figure 3-2. Selections of C MAX ranges for varying accuracy requirements in readout.

3.7.2 THREE-TERMINAL MEASUREMENTS. The two three-terminal measurement procedures applicable to this bridge are distinguished by the bridge connectors used. Measurements using coaxial terminations are covered in para. 3.7.3 and those using binding-post terminations in para. 3.7.4. Some considerations common to both are:

1. The measured direct capacitance is not changed in most three-terminal measurements when the connections to the capacitor are reversed, i.e., bridge H to capacitor L instead of bridge H to capacitor H.

2. The H terminal, at the high voltage but low-impedance output of the transformer, is not sensitive to pickup from external sources and seldom needs to be shielded. There is voltage from the H terminal to GND. High capacitance or conductance connected from the H terminal to GND reduces the transformer output voltage and introduces errors into the measured direct capacitance and conductance.

3. The L terminal, the low voltage but high-impedance input to the detector, is very sensitive to noise and signal pickup from external sources and must be completely shielded for low-capacitance mea-

TYPE 1615-A CAPACITANCE BRIDGE

measurements. There is no voltage from L to GND when the bridge is balanced. High capacitance or conductance from the L terminal to GND shunts the detector and reduces the sensitivity of the bridge.

3.7.3 THREE-TERMINAL COAXIAL CONNECTIONS (see Figure 3-3).

Used to Measure:

1. Three-terminal capacitors with shielded, coaxial connectors, such as General Radio Types 1403, 1404, 1422, and 1423.

2. Direct capacitance at the end of long, shielded cables, such as in a test chamber or in a remote equipment.

Terminal Selector: Set to 3 TERM position.

Terminals: Connect capacitor to UNKNOWN H and L coaxial terminals. Coaxial cable should always be used to connect L terminal (high-impedance side of detector). Unshielded lead may be used to connect to H terminal (low-impedance output of transformer), and, if coaxial connection is not used, the H binding

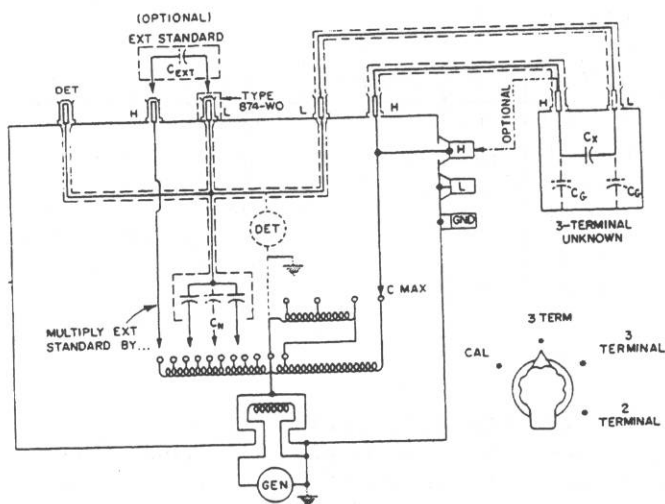


Figure 3-3. Type 1615-A bridge circuit for 3-terminal coaxial measurement.

post should be used. Use Type 874-R20A or -R22A Patch Cord, with appropriate Type 874 coaxial adaptor, if required.

Capacitance Measured: Direct capacitance, C_X , between H and L terminals.

Capacitance Excluded: All capacitances, C_G , to ground, including cable capacitances. Any GND or coaxial outer-conductor terminal on the bridge is a guard point.

External Standard: Not required for most measurements. May be used to extend range and resolution of bridge; refer to Section 5. When EXT STANDARD terminals are not used, install Type 874-WO termination on EXT STANDARD L coaxial terminal to complete shielding of the detector.

Connect any three-terminal capacitor used as an external standard to EXT STANDARD H and L coaxial terminals. Coaxial cable should always be used to connect the L terminal (high-impedance side of the detector). Type 1403 series of capacitors or Type 1615-P1 Range-Extension Capacitor may be plugged directly into the H and L terminals, but care should be taken to align the connectors properly so that the conductors are not bent.

Bridge Balancing Procedures: As in paragraph 3.6

3.7.4 THREE-TERMINAL BINDING-POST CONNECTIONS (see Figure 3-4).

Used to Measure:

1. Three-terminal capacitors with unshielded, banana-plug connectors, such as Type 1409 series.

2. Capacitors with two terminals, when ground or cable capacitance must be excluded from the measurements; for example, capacitors measured with the Type 1650-P1 Test Jig.

Terminal Selector: Set to 3 TERMINAL position.

Terminals: Connect the capacitor to the UNKNOWN H and L binding posts. Connect the shields, or case, to the GND binding post. When long leads are used, shield the lead to the L binding post (high-impedance side of detector). For capacitors with two terminals and with one terminal connected to the capacitor case or shield (which can be insulated from external ground) connect the case to the bridge H terminal (low-impedance output of transformer).

Capacitance Measured: Direct capacitance between the H and L binding posts, including about 0.2 pF capacitance between the open posts, C_{HL} .

Capacitance Excluded: All capacitances, C_G , to ground from either H or L posts. Any GND terminal on the bridge is a guard point. To determine the capacitance added by the unknown capacitor:

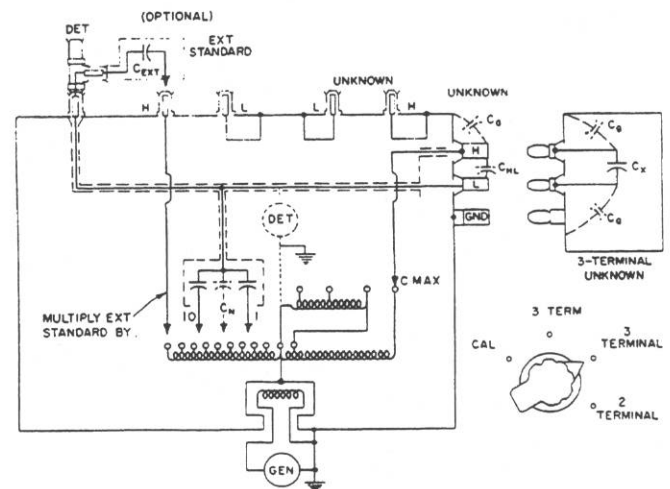


Figure 3-4. Type 1615-A bridge circuit for 3-terminal binding-post measurement.

- a. Remove the capacitor from the bridge terminals or leads.
- b. Measure the capacitance of the open terminals (about 0.2 pf) or open leads.
- c. Subtract this capacitance from the total capacitance measured with the capacitor connected.

External Standard: Not required for most measurements. May be used to extend range and resolution of bridge; to use external standards, refer to Section 5. Connect any three-terminal capacitor used as an external standard to the EXT STANDARD H coaxial terminal and to the detector through a coaxial-Tee connector (Type 874-T), at the bridge DETECTOR terminal. Use coaxial cable for the connection to the detector.

NOTE

The bridge L coaxial terminals cannot be used because they are connected to ground instead of to the detector when the terminal selector is in this position.

When EXT STANDARD terminals are not used, the Type 874-WO termination is not required on EXT STANDARD or UNKNOWN L coaxial connectors; these connectors are internally grounded.

Bridge Balancing Procedures: Refer to paragraph 3.6.

3.7.5 TWO-TERMINAL BINDING-POST CONNECTIONS
(see Figure 3-5).

Use to Measure:

1. Two-terminal capacitors with banana-plug connectors, such as the Type 1401 and 1409 series.
2. Capacitors with capacitance greater than 1 μ f, whose leads must be short to reduce loss, such as the Type 1424.
3. Capacitors with one lead permanently connected to an external ground.

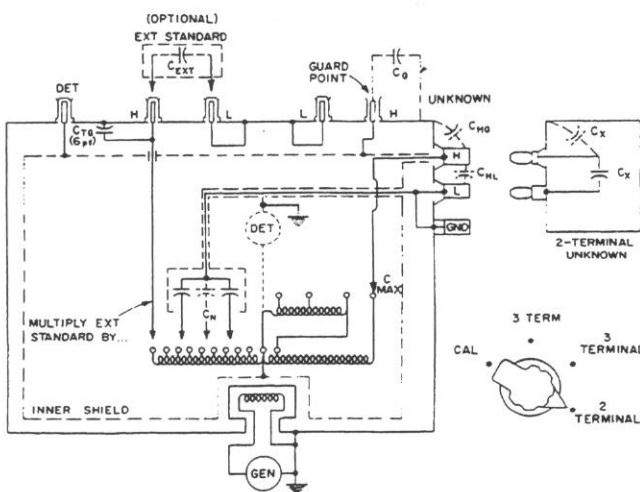


Figure 3-5. Type 1615-A bridge circuit for 2-terminal capacitance measurement.

Terminal Selector: Set to 2 TERMINAL position.

Terminals: Connect capacitor to the UNKNOWN H and L binding posts, with the case, low, or ground side of the capacitor connected to the L post. The L post is internally connected to the GND post.

Connect any bridge GND terminal to an external ground to eliminate changes in the bridge balance which may be produced by motion of the operator's hands near the balance controls (not in the vicinity of unshielded UNKNOWN terminals). Adequate grounding is provided through the three-wire power connection of the Type 1311-A oscillator. If the oscillator ground is not otherwise connected to the bridge ground, do so with a clip lead. The bridge GENERATOR gray binding post is internally connected to GND.

Capacitance Measured: All capacitances from the H post and leads to the L and GND posts, to the bridge case, and to external grounds, including about 1.4 pf capacitance between the open H posts and the grounds around it, C_{HG} , C_{HL}

Capacitance Excluded: Only capacitances inside the bridge to the shields, which are connected to the transformer center tap and to the high side of the detector. A guard point, connected to the inner shields, is accessible at the UNKNOWN H coaxial terminal center conductor and at the DETECTOR coaxial terminal center conductor. Since the guard point is also the high side of the detector, any guard connections used outside the bridge must usually be enclosed in a grounded shield to prevent noise from entering the detector.

To determine the capacitance added by the unknown capacitor:

- a. Remove the capacitor from the bridge terminals or leads.
- b. Measure the capacitance of the open terminals (about 1.4 pf) or open leads.
- c. Subtract this capacitance from the total capacitance measured with the capacitor connected.

External Standard: Must be a 2-terminal capacitor. Not required for most measurements. May be used to extend range and resolution of bridge; refer to Section 6.

When EXT STANDARD terminals are not used:

- a. Set MULTIPLY EXT STANDARD BY...switch to 0.
- b. Remove Type 874-WO termination from EXT STANDARD or UNKNOWN L coaxial connectors; these connectors are internally grounded.
- c. Install Type 874-WO on UNKNOWN H coaxial connector (which is connected to high side of detector) when complete shielding is required, as in the measurement of very small capacitance differences.

When EXT STANDARD terminals are used:

- a. Connect any two-terminal capacitor used as an external standard to the EXT STANDARD H coaxial-terminal center conductor and to any ground, such as the outer conductor, or the L terminal (inner or outer) or either GND post.

b. Convert the coaxial H terminal to two binding-post H and L terminals for convenient connection of two-terminal capacitors with Type 874-Q2 adaptor.

c. Convert the coaxial H terminal to a single binding-post H terminal with Type 874-MB Coupling Probe.

NOTE

When the MULTIPLY EXT STANDARD BY ... switch is not set to 0, external capacitance is added to the bridge even though no external capacitor is connected to the bridge. Capacitance to ground in the EXT STANDARD H coaxial connector and internal bridge wiring, C_{TG} , (about 6 pf), acts as external standard capacitance, and any adaptors or wires connected to the EXT STANDARD H terminal add to this.

3.8 LOSS BALANCE CONTROLS.

3.8.1 GENERAL. The loss balance in the bridge can be made in terms of either the dissipation factor, D, or the parallel conductance, G, of the unknown capacitor (see Figure 3-6).

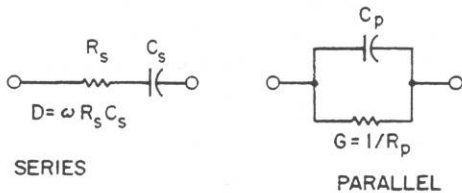


Figure 3-6. Equivalent circuits of unknown capacitors.

On the D MAX ranges, the bridge measures the equivalent series capacitance, C_s , and the dissipation factor, $D = \omega R_s C_s$.

On the G MAX ranges, the bridge measures the equivalent parallel capacitance, C_p , and the parallel conductance, G. Many measurements can be made with either D or G and C_s or C_p . When only one can be measured, the other can be calculated from the relations:

$$D = \omega R_s C_s = G / \omega C_p = 1 / \omega R_p C_p \quad (3-2)$$

$$C_s = C_p (1 + D^2) \quad (3-3)$$

$$G = 1/R_p = \omega C_s D / (1 + D^2) \approx \omega C_s D \quad (3-4)$$

$$R_s = G / [(\omega C_p)^2 (1 + D^2)] \approx G / (\omega C_p)^2 \quad (3-5)$$

where C = capacitance in farads

G = conductance in mhos

R = resistance in ohms

$\omega = 2\pi f$

f = frequency in cps

NOTE

Any error in generator frequency affects the accuracy of a conversion from G to D or from D to G. Dial calibration of most oscillators is no better than $\pm 1\%$. For D or G calculation accuracy of $\pm 1\%$ or better, measure frequency to higher accuracy or use source of standard frequency.

Some of the differences which determine the choice of D or G appear below.

3.8.2 DISSIPATION FACTOR, D. For many measurements, the dissipation-factor or D MAX ranges provide the greater range, accuracy, and convenience in loss balance.

Range: At 1 kc, .000 001 to 1. Multiply by frequency in kilocycles. Independent of capacitance. Four-figure resolution. Smallest increment, 1 ppm at 1 kc. Accuracy: Basic D accuracy is $\pm(0.1\%$ of measured value +10 ppm) at 1 kc and over most of the range from 50 cycles to 10 kc.

Principal Uses:

1. For general capacitance measurements in which the primary interest is the capacitance value.
2. When the capacitor loss and D are relatively high, e.g., D greater than 0.01.
3. For accurate measurement of capacitor loss.
4. When an external standard is used to measure large capacitance with high loss. Accurate C and G can then be obtained from the bridge readings only by computation. Refer to Section 4.

5. When the loss in the unknown capacitor is primarily equivalent series resistance, e.g., the lead resistance of capacitors with low reactance. The bridge reading of D is then related in a simple manner to the resistance of the unknown as frequency changes.

Corrections:

1. Multiply reading of bridge decades by frequency in kc when operation frequency is not 1 kc.
2. For maximum accuracy in the measurement of small D or small differences, add 1 to reading of fourth decade. Minimum resistance of decade switches and wiring when the four decades are set at 0000 is about 0.1 ohm, which is one step in fourth resistance decade.

3.8.3 CONDUCTANCE, G. Conductance ranges (G MAX) are provided primarily to permit loss balances if dissipation-factor measurements cannot be used. The range and accuracy of G are generally lower than those of D.

Range: .000 001 to 0.1 μ mho, multiplied by factor M=1, 10, 100, or 1000, determined by C MAX range selected. Two positive ranges add G to internal standards; two negative ranges add G to unknown. All are independent of frequency.

TABLE 3-1
D EQUIVALENTS FOR MAX AND MIN G WHEN C_X EQUALS C_{MAX}

RANGE SETTING		D AT 1 KC FOR C _X = C _{MAX} WITH .	
C _{MAX}	M	MAX G (0.1 x M) μΩ	MIN G (.000 001 x M) μΩ
1 μf	1000	.016	.000 000 16
0.1 μf	100	.016	.000 000 16
0.01 μf	10	.016	.000 000 16
1000 pf	1	.016	.000 000 16
100 pf	1	.16	.000 001 6
10 pf	1	1.6	.000 016

Notes:

1. For any other unknown capacitance or C_{MAX} range, multiply D values by C_{MAX}/C_X.
2. For any other frequency, f, multiply D values by 1/f(kc).

Example: 100 pf measured at 100 cps with C_{MAX} set at 1000 pf.
 Max D = .016 x (1000/100) x (1/0.1) = 1.6.
 Min D = 0.16 ppm x (1000/100) x (1/0.1) = 16 ppm = .000016.

Dissipation factor, D, corresponding to a given G, depends upon frequency and capacitance; the relation is:

$$D = \frac{G (\mu\text{mhos})}{6.28} \times \frac{1}{f(\text{kc})} \times \frac{1000}{C(\text{pf})} \quad (3-6)$$

where G is the bridge readout in μmhos multiplied by M.

D values from this equation are given in Table 3-1 for the maximum and minimum G of the bridge at 1 kc and for six values of unknown capacitance, C_X, equal to the nominal maximum capacitance of the six C_{MAX} ranges.

Accuracy: Basic G accuracy is ±(1%+0.00 001 μmho). This is independent of frequency from 50 cycles to 10 kc.

Principal Uses:

1. When the loss of the unknown is less than that of the internal and external standard capacitors. This may occur in the measurement of reference standard capacitors, whose loss is extremely low, and in measurements with an external standard capacitor connected to the bridge. Balance the loss by using the -0.1 or -0.01 μmho G_{MAX} ranges to connect the bridge conductance decades across the unknown.

2. When the internal standard capacitors are compared for a ratio check. The dissipation factor re-

sistance decades are connected in series with the common side of all bridge capacitors and provide no adjustment of the loss of any one relative to another.

3. When the minimum D equivalent to the smallest G step provides better resolution for precision balance (see Table 3-1). For example, in the measurement of 1000 pf at 1 kc, the smallest step of adjustment with the D_{MAX} ranges is 1 ppm; with the minimum G step of 1 x 10⁻⁶ μmho, the resolution of the equivalent D is 0.16 ppm.

4. When the loss of the unknown is primarily equivalent parallel resistance, e.g., the leakage resistance of insulators in air capacitors of high reactance. The loss balance is then relatively independent of frequency.

Corrections:

1. Multiply reading of bridge decades by factor M, which is indicated on C_{MAX} switch. Error in decimal point often results from the omission of M for the C_{MAX} ranges above 1000 pf, where M is not 1.

2. For maximum accuracy in the measurement of small G or small differences, add 1 to the reading of the fourth decade. Minimum resistance of the decade switches and wiring, when the four decades are set at 0000, is about 0.1 ohm, which is one step in the fourth resistance decade.

NOTE

As a result of this zero error, the bridge balance will change when the decades are set at 0000 and the G MAX is moved from +0.01 $\mu\Omega$ to -0.01 $\mu\Omega$. When the correction is applied, the two conductances are +.000 001 and -.000 001 μmho , respectively. To obtain conductance less than this minimum for some capacitances and frequencies, use D MAX ranges and calculate equivalent G (see Table 3-1).

Example: For 10 pf at 1 kc, minimum G of .000 001 μmho corresponds to D of 16 ppm. On 0.01 D MAX range, minimum D is 1 ppm, and equivalent G is .000 000 06 μmho .

3. For accuracy of $\pm 1\%$ when the first G decade reading is 3 or more, apply the corrections indicated in Figure 3-7. These corrections are necessary because the relation of G to the resistance, RN, of the decades is not linear. (Refer to Section 4.)

To use Figure 3-7.

a. Take the four-digit reading of G dials (for example, 7413). Ignore the position of decimal point and units of G.

b. Enter the vertical "G Decades Read" scale at this value and, at the intersection with the curve, find on the horizontal "Subtract from Reading" scale, the corresponding correction value (110).

c. Subtract the correction from the reading to obtain the corrected G, with an accuracy of $\pm 1\%$ ($7413 - 110 = 7303$).

d. The units of G and the position at the decimal point are those indicated by the bridge readout.

For greater precision in the correction than that obtainable from Figure 3-7, to be used, for example, in measurements of G differences, calculate the correction as follows:

a. Divide the four-digit G reading by 1000. ($7413/1000 = 7.413$.)

b. Square this number (55.0 with slide-rule accuracy).

c. Multiply by 2 (110.0).

d. Subtract this from the reading to obtain the corrected G ($7413 - 110 = 7303$).

3.9 ERRORS FROM TRANSFORMER IMPEDANCES AND OTHER SOURCES

3.9.1 INTRODUCTION. The transformers in the Type 1615-A Bridge are not quite the ideal transformers shown, for example, in Figures 4-11 and 4-12. The resistance, leakage inductance, and capacitances of the ratio-transformer windings, which are assumed to be zero in the simplified bridge theory, have been kept sufficiently small in the actual bridge components so that the errors from these residual impedances are usually negligible (compared to, say, 100 ppm) for capacitances

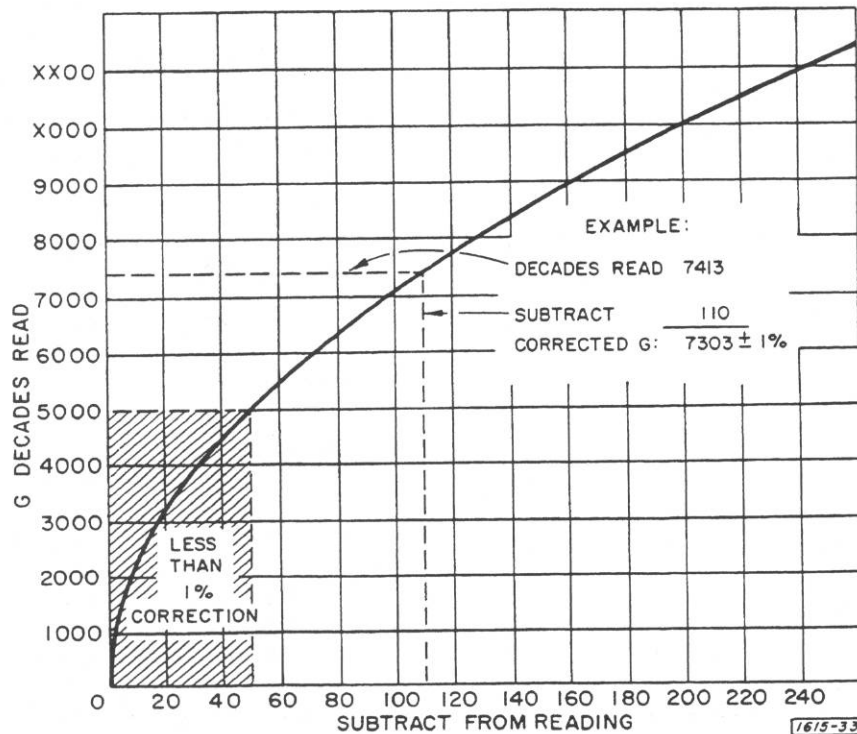


Figure 3-7. Corrections for high G readings.

up to 1 μF at frequencies up to 1000 cps. However, the residual impedances make the voltages at the transformer terminals differ from the voltages induced in the windings and produce bridge errors that increase with frequency and with the magnitude of the measured capacitance. The sources and magnitudes of such error for frequencies from 1 kc to 100 kc and for capacitances above 1 μF will be described in the following paragraphs.

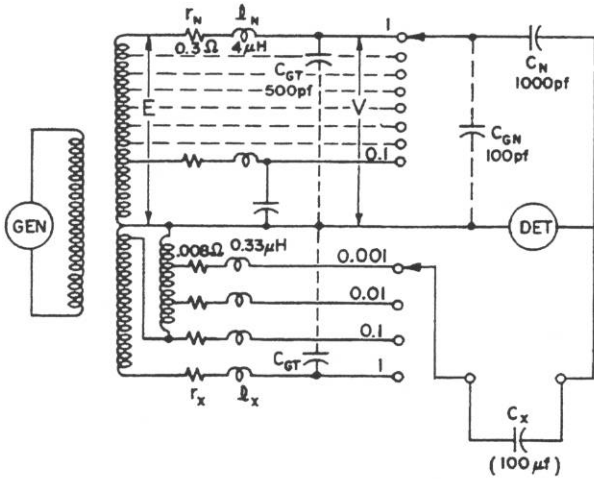


Figure 3-8. Bridge circuit with residual transformer impedances.

3.9.2 RESIDUAL IMPEDANCES. The bridge schematic diagram of Figure 3-8 is similar to that of Figure 4-11 but shows in the equivalent circuit of the transformer winding resistances (r), leakage inductances (l), and winding capacitances (C_{GT}) in both the standard and unknown ratio arms. The magnitudes of the residuals vary on the standard side as the lever decade switches are moved to change voltages and on the unknown side as the C MAX lever is moved to change range. The resistance r and inductance l are closely proportional to turns ratio from 1 to 10, but the minimum values set by wiring and switches prevent a proportional decrease for higher ratios. Typical values of r and l are given in the following table:

C MAX	M	Turns	r	l
10, 100, 1000 pF	1	100	0.33 Ω	3.5 μH
.01 μF	10	10	.019	0.41
0.1	100	10	.023	0.48
1	1000	1	.008	0.33

The winding capacitances (C_{GT}) are not simply proportional to turns. An estimate of the order of magnitude of capacitance across each 100-turn secondary winding is 500 pF, but the capacitance across the first 10-turn section is about 0.01 μF instead of ten times the capacitance of the 100-turn winding.

These residual impedances (as shown in the circuit of Figure 3-8) make the voltage, V , applied to the capacitors differ from the voltage, E , induced in the transformer winding.

The relation of V to E is:

$$V/E = 1 + \omega^2 l C_T - j \omega r C_T \quad (1)$$

$$\text{where } C_T = C_N + C_{GT} + C_{GN}$$

This change in the voltage applied to the capacitor C_N , for example, can be expressed for convenience as a change in the effective capacitance, C'_N , of C_N , when the bridge is at balance, through the relation $EC'_N = VC_N$. The effects of the residual impedances on the bridge readings can then be written:

- a. The capacitance C'_N is greater than C_N :

$$C'_N = C_N (1 + \omega^2 l C_T)$$

The fractional increase is $\omega^2 l C_T$.

This error is proportional to frequency squared.

- b. The dissipation factor of C'_N is greater than that of C_N (which is assumed to be zero in Figure 3-8.)

$$D'_N = + \omega r C_T$$

This error is proportional to frequency.

- c. The equivalent conductance ($G = D\omega C$) is increased.

$$G'_N = \omega^2 r C_T C_N$$

This error is proportional to frequency squared.

3.9.3 MAGNITUDE OF ERRORS. Errors from the transformer impedances are always present; they are not always significant. To determine when the errors may not be negligible, consider two typical, although oversimplified, numerical examples.

An order of magnitude for the effects of the residuals upon the standard capacitors in the bridge can be found, first of all, from the numerical values given for components on the upper or standard side of the bridge in Figure 3-8. The largest internal capacitor, C_N , of 1000 pF is shown connected to the full 100-turn secondary winding, with $r = 0.3 \Omega$, $l = 4 \mu\text{H}$ and $C_{GT} = 500 \text{ pF}$. With the ground capacitance of the capacitor C_N and the associated wiring equal to 100 pF, the total load capacitance connected to the transformer is $C_T = 1600 \text{ pF}$. From the error formulas above, the calculated possible errors at frequencies of 1 kc and 100 kc are:

Frequency	C error $\omega^2 l C_T$	D error $\omega r C_T$
1 kc	0.26 ppm	3.0 ppm
100 kc	2600 ppm or 0.26%	300 ppm or 0.03%

TYPE 1615-A CAPACITANCE BRIDGE

These figures are intended only to indicate that these errors can often be neglected at 1 kc but that, as the frequency is increased toward 100 kc, the bridge errors may exceed considerably the normal 0.01% limit.

As an example of the effects of residuals upon the measurement of large capacitance, consider the numerical values shown on the lower or unknown side of the bridge in Figure 3-8. An unknown capacitor of 100 μF is shown connected to the transformer tap for a ratio $M = 1000$ (C_{MAX} at 1 μF), where $r = .008 \Omega$, $l = 0.33$, and the winding capacitance is negligible compared to 10 μF . (The bridge will not balance with only the 1000-pF standard capacitor shown in Figure 3-8; an external standard of 0.1 μF must be used in the measurement of 100 μF , but need not be considered in this example.) The calculated errors for the 100- μF capacitor and also for a 1- μF unknown at a frequency of 1 kc are:

Capacitor	C error	D error
1 μF	13 ppm	50 ppm
100 μF	1300 ppm or 0.13%	5000 ppm or 0.5%

The figures indicate that these errors can often be neglected for the normal capacitance range up to 1 μF at 1 kc. With higher capacitance or with a higher frequency, the errors may be appreciable.

Both examples above illustrate only the order of magnitude of possible errors. Since all error sources in the circuit have not been included, the calculated errors should not be taken as typical of a Type 1615-A Bridge. A more detailed examination of actual bridge errors will follow.

3.9.4 SMALL ERRORS FOR 1:1 RATIO. The errors in the bridge readings can be determined by the measurement of a calibrated capacitor. A convenient standard of capacitance and loss is a three-terminal air capacitor, such as the Type 1403, that can be connected directly to the bridge terminals to add a minimum of series inductance and resistance. For such a capacitor, it can be assumed with good accuracy that the capacitance and loss have negligible changes with frequency up to about 100 kc and that any changes in bridge readings with frequency indicate bridge errors. In the 1000-pF Type 1403, for example, the internal series inductance is about 0.05 μH , so the capacitance increase at 100 kc should be only $\omega^2 l C = 20$ ppm. Although the dissipation factor is not generally a simple function of frequency, in a clean air capacitor the magnitude should be sufficiently low, i.e., in the tens of ppm, that it can also be neglected.

The following results were obtained when such a 1000-pF Type 1403-A Capacitor was measured on a Type 1615-A Bridge. The capacitor was slightly modified by the addition of a series 16-ohm resistor to insure that the bridge D reading remained positive.

Frequency	D	C	C Change from 1 kc
1 kc	.00 0110	X00.747 pF	0
10	.00 0107 (x10)	.745	-2 ppm
50	.00 0107 (x50)	.710	-37
100	.00 0108 (x100)	.480	-267

Note that the capacitance change at 100 kc is only 267 ppm, as compared to the estimated possible error of 2600 ppm above. The smaller error results from a partial cancellation of transformer-impedance errors in the two ratio arms of the bridge. When, as in this example, the ratio is 1:1, the residual r and l are equal on both the standard and unknown sides of the transformer in Figure 3-8. If the total load, C_T , is the same on both sides, the errors in V are equal and make $V_N/V_X = E_N/E_X$ and at balance $C_X = C_N$ at any frequency.

In this example, and in general, the errors in the two bridge arms do not quite cancel because the total C_T on one side does not equal that on the other. The internal and external stray capacitances to ground, C_{GN} and C_{GX} , are seldom equal since the bridge shields and wiring make C_{GN} relatively high. The voltage on the standard side is, therefore, usually higher, and the bridge capacitance decade readings are low. For example, an excess C_{GN} of 100 pF makes the bridge reading low by 160 ppm at 100 kc.

This error changes with any changes in the internal ground capacitances, such as those produced by any changes of decade switches to select alternative internal standards. In the following example, the same 1000-pF capacitor is measured with two of the several possible decade settings:

1 kc	100 kc
X00.747	X00.480
9X0.747	9X0.310

The 100-kc reading is lower for the decade setting of 9X0 than for X00 because the capacitance to ground has changed. With the X00 setting, only the internal 1000-pF standard and its ground and wiring capacitance load the transformer; with the 9X0 setting, both the 1000-pF and 100-pF standards are connected and the ground capacitance is increased about 100 pF.

The D readings in the example above seem at first glance to change very little with frequency. When, however, the bridge reading is multiplied by frequency in kc, as indicated, the change at 100 kc is -200 ppm. The uncertainty in this error is of the order of ± 100 ppm, both because the bridge resolution is only 100 ppm and because the loss in the standard may vary by a similar amount. The bridge D error is probably less than the 200 ppm at 100 kc.

For a bridge ratio of 1:1, therefore, the bridge errors in C and D are typically less than, say, 500 ppm at 100 kc. The C error is proportional to frequency squared and the D error to frequency. It is not usually practical to apply corrections for these errors to the bridge readings, chiefly because the magnitudes of the stray capacitances to ground and their variations with decade settings are not easily determined.

3.9.5 LARGER ERRORS FOR 10:1 RATIO. Bridge errors from transformer residuals can, in theory, be reduced or eliminated by symmetry in the bridge circuit for any transformer ratio, just as in the example of the 1:1 ratio. All that is required is that $\omega^2 l_X C_{TX} = \omega^2 l_N C_{TN}$ or $l_X/l_N = C_{TN}/C_{TX}$ to make $C_X = C_N$; hence, the residuals should be proportional to the ratio.

In practice, there are several reasons why the errors, $\omega^2 l C_T$ or $\omega r C_T$, cannot be kept the same on both sides of the bridge as the ratio is increased. The residual impedances r and l , tabulated above in paragraph 3.9.2, differ slightly from proportionality to ratio up to a 10:1 ratio. For higher ratios, the r and l on the unknown side cannot decrease in proportion below the minimum values set by the wiring, switch, and terminal impedances. Any wires used to connect the unknown to the bridge will increase these residual impedances. The capacitance residuals are also seldom proportional to ratio. Although the bridge ratio is determined by the ratio of the unknown and standard capacitances, C_X/C_N , the error depends upon total capacitance in the bridge arm, e.g., $C_{TN} = C_N + C_{GT} + C_{GN}$; and neither the transformer-winding capacitances, C_{GT} , nor the ground capacitances of the capacitors, C_{GN} , are proportional to ratio.

With a 10:1 ratio, the following bridge errors appear when a 100-pF Type 1403-D Capacitor is measured. The C MAX switch is set at 1000 pF so that the bridge balances with the decades set near 100.00, i.e., the external 100 pF is connected to the 100-turn arm and balanced by the internal 1000-pF standard connected to 10 turns of the other arm.

Frequency kc	G $\mu\Omega$	D = G/ ωC ppm	C pF	C Change from 1 kc
1	+ .00 0010	16	100.011	0 ppm
10	+ .00 0030	5	100.008	-30
50	- .0046	-150	10(-1).956	-550
100	- .030	-500	10(-1).843	-1670

The error of nearly 0.2% at 100 kc is produced by the relatively large winding capacitance of the 10-turn winding and ground capacitances on the standard side of the bridge, which are not compensated by proportional capacitances of the 100-turn winding and the 100-pF unknown.

For a ratio of 10:1, the bridge errors in C may be as high as 0.2% at 100 kc. The errors are again dependent upon decade settings and stray capacitances in the unknown, so that corrections are not easily made.

3.9.6 ERRORS FOR RATIOS ABOVE 10, CAPACITANCE ABOVE 0.01 μF . When the capacitance being measured is of the order of 1000 pF or less, the bridge errors depend more upon winding and stray capacitances than upon the magnitude of the unknown, as shown above. When the unknown is considerably greater than 1000 pF, the bridge ratios of 100 or 1000 must be used for balance. The transformer residuals on the unknown side of the bridge then are much larger than 0.1 or 0.01 times those on the standard side. At the same time, the winding and stray capacitances become a small fraction of the total C_{TX} on the unknown side. As a result, the bridge errors not only increase with the larger C_X but become more simply dependent upon $\omega^2 l_X C_X$ and $\omega r_X C_X$.

As an illustration, the following measurements were made of a 0.1- μF Type 1409-T Capacitor on the 0.1- μF C MAX range, where M = 100.

Frequency kc	D	C pF	C Change from 1 kc
1	.00 0060	999 74.1	0
10	.00 0016(x10)	999 93.7	0.02%
50	.00 0025(x50)	X05 54.5	0.58%
100	.00 0037(x100)	X21 30.0	2.16%

When C MAX is at 0.1 μF , the transformer leakage inductance l_X is, typically, about 0.48 μH ; so for 0.1 μF at 100 kc, $\omega^2 l C = .019$ and the bridge should read high by 1.9%. The measured increase of 2.1% is larger because the Type 1409 Capacitor has an internal inductance of about .055 μH , which causes a capacitance increase of about 0.2% at 100 kc. In dissipation factor, the measured D change is .0037 at 100 kc; the calculated $\omega r C$ for $r = .023$ ohms is .0014. Part of the difference is the increase in D of the mica Type 1409 Capacitor at 100 kc, perhaps as much as .001. Some error in D is also contributed by phase shifts that result when the main ratio transformer is loaded by the second transformer connected for ratios of 100 and 1000.

Corrections of the bridge readings of C and D can be made for the major errors produced by the l and r of the transformers on the upper two C MAX ranges. These corrections are tabulated below for typical residual impedances at the bridge terminals to an accuracy of $\pm 10\%$:

C MAX	Subtract from Bridge			
	l μH	r ohm	C Reading $(\omega^2 l C_x)$	D Reading $(\omega r C_x)$
0.1 μF	0.48	.023	19 f ² _{kc} C _{μF} PPM	140 f _{kc} C _{μF} PPM
1 μF	0.33	.008	13	50

When leads must be used to connect the capacitor to the bridge terminals, these values of l and r will be increased by the inductance and resistance of the leads.

As an example of error correction, a 1- μ F Type 1409-Y Capacitor is measured at 10 kc on the 1- μ F C MAX range of the bridge. The C reading is X01596 pF, the D reading is .00 0088 (x10). The C correction is $13 \times (10)^{-2} \times (1.0) = 1300$ ppm or $1300 \times 10^{-6} \times 1.0 \mu\text{F} = 1300$ pF; so the corrected capacitance is $X01596 - 1300 = 1.0003 \pm .0001 \mu\text{F}$, if the accuracy of the correction is $\pm 10\%$. The D correction is $50 \times (10) \times (1.0) = 500$ ppm; so the corrected D is $880 - 500 = 380$ ppm = .00038. The accuracy of the correction is $\pm 10\%$ or ± 50 ppm, but the specified accuracy of the bridge reading is only $\pm 0.00001 (1 + f_{kc}) = \pm 110$ ppm even after this correction because of the other errors from winding and stray capacitances.

3.9.7 ERRORS FOR CAPACITANCE LESS THAN 10 PF.

The residual impedances previously described are the chief, but not the only, sources of error with increasing frequency. Another source of error is the voltage induced in the internal bridge wiring connected to the detector circuit by currents flowing in the bridge circuits connected to the transformer. The bridge does not have the short, coaxial current paths required for high-frequency accuracy, and mutual inductances of the order of 0.1 μ H between bridge arms may result. Since the currents drawn from the transformer by the bridge capacitors increase with frequency ($i = \omega C E$) and the voltages induced in the detector circuit are proportional to $\omega M i$, these error voltages, $e = \omega^2 M C E$, increase with the square of frequency. The errors depend also upon the internal capacitors used and upon the transformer voltages applied to them; hence they are a complicated function of the settings of the bridge decades. Experiments confirm, however, that these errors appear not as a percentage of the measured capacitance but as more-or-less constant picofarad error. The order of magnitude of the error is 0.003 pF or less.

This error can often be seen when the internal capacitance standards are intercompared by use of the 10:1 ratio and the procedure described in paragraph 6.2.5. The measured results on one Type 1615 Bridge are:

Capacitors	1 kc		100 kc	
	C	G	C	G
1000 vs 100 pF	(-1)X0.000	(-1)X0.168	+0.0317	
100 vs 10	(-1)X.0 000	(-1)X.0 170	+0.0031	
10 vs 1	(-1).X0 000	(-1).X0 430	+0.0007	

The 100-kc error of about 0.17% is that produced by a ground-capacitance asymmetry on the 10:1 ratio. The additional error of about .0026 pF in the measurement of 10 vs 1 pF may be attributed to voltages induced in the detector circuit.

3.9.8 ERRORS FROM COMMON IMPEDANCE TO GROUND. Similar errors that are small fractions of a picofarad or of a few picomhos are produced by common ground impedances in the three-terminal bridge capacitors and in similar external capacitors. The three-terminal capacitor shown in Figure 3-9 has an impedance Z_G between the ground point G of the bridge and the junction

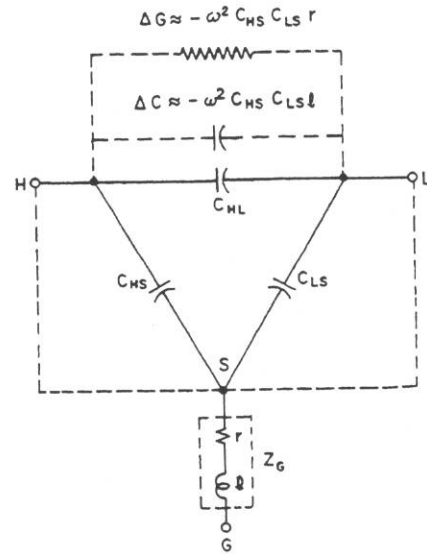


Figure 3-9. Negative G and C errors from common ground impedance, Z_G , in a three-terminal capacitor.

So of the two capacitances, C_{HS} and C_{LS} . This impedance Z_G represents, for example, the resistance r and inductance l of a wire used to connect the shield of a three-terminal capacitor to the junction of the bridge ratio arms. The effect of any such impedance common to both C_{HS} and C_{LS} is to subtract from the direct capacitance C_{HL} a capacitance equal to $\omega^{-2} C_{HS} C_{LS} l$ and conductance $\omega^2 C_{HS} C_{LS} r$. The error most commonly seen is that of the negative loss, both because it is often larger of the two components and because negative loss in a capacitor is an obvious indication of the presence of error. As a simple example of orders of magnitude, assume $C_{HS} = C_{LS} = 100$ pF and let $r = 0.01$ ohms, $l = 0.1 \mu\text{H}$; then at 100 kc the capacitance change is $\Delta C = .0004$ pF and the negative conductance is $\Delta G = .000 04 \mu\text{mho}$. Such errors are usually small, unless the magnitudes of Z_G , C_{HS} , and C_{LS} are considerably increased, as for example, by the use of long cables between capacitor and bridge.

3.9.9 BRIDGE ACCURACY.

The curves in Figures 3-10 and 3-11 indicate the possible errors when no corrections are applied to the bridge readings. Corrections can be used in the regions to the right of the sloped lines on the right-hand end of each curve to reduce the errors from transformer series impedances to approximately the level of the horizontal part of the curve.

The plotted dots show typical variations of error with transformer ratio at 100 kc/s and indicate the reduction in error when the ratio is close to unity; i.e., when the unknown is nearly equal to the internal standard (see paragraph 3.9.4).

The low-frequency limits set by the bridge sensitivity are typical of the Type 1620-A Assembly.

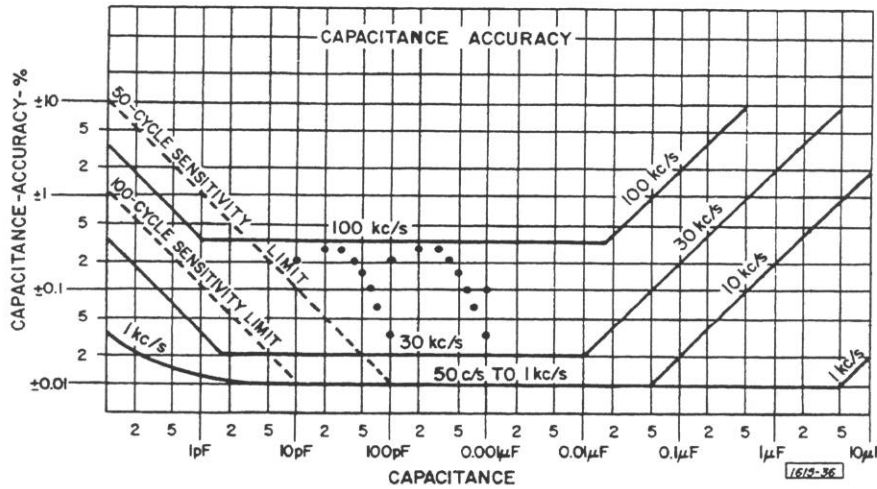


Figure 3-10.

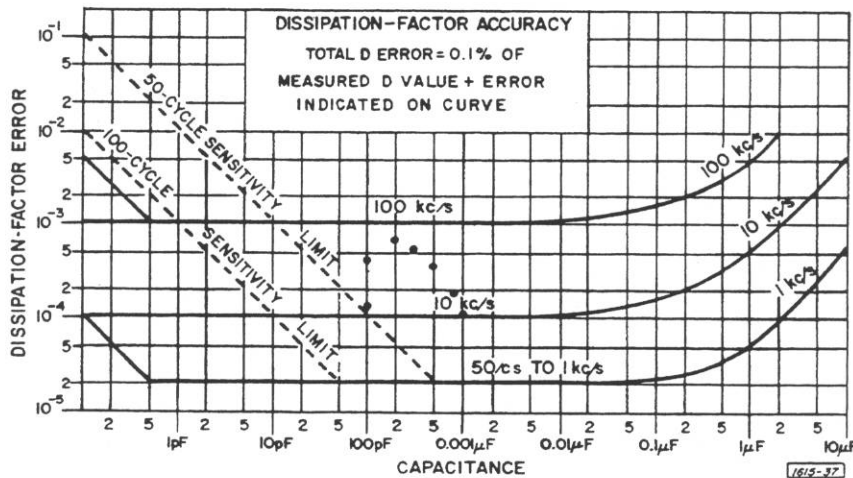


Figure 3-11.

SECTION 4

THEORY OF OPERATION

NOTE

This section is limited to a discussion of the Type 1615-A Capacitance Bridge, as the theories of operation of Types 1311-A and 1232-A are covered in their respective manuals.

4.1 INTRODUCTION.

4.1.1 GENERAL. The Type 1615-A Capacitance Bridge is a standards laboratory instrument designed for accurate precision measurements of capacitance and dielectric properties, and for the intercomparison of capacitance standards over a wide range of values.

4.2 PROPERTIES OF CAPACITORS.

4.2.1 GENERAL. Most physical capacitors can be accurately represented by the three capacitances shown in Figure 4-1: the direct capacitance, C_{HL} , between the terminals H and L (capacitance between the plates of the capacitor), and the two terminal capacitances, C_{HG} and C_{LG} , capacitances from the corresponding terminals and plates to the capacitor case, surrounding objects, and to ground (to which the case is connected either conductively or by its relatively high capacitance to ground).

4.2.2 TWO-TERMINAL AND THREE-TERMINAL CONNECTIONS. In the two-terminal connection, the capacitor has the L and G terminals connected together, i.e.,

the L terminal is connected to the case. The terminal capacitance, C_{LG} , is thus shorted, and the total capacitance is the sum of C_{HL} and C_{HG} . Since one component of the terminal capacitance C_{HG} is the capacitance between the terminal and surrounding objects, the total capacitance can be changed by changes in the environment of the capacitor and particularly by the introduction of the wires required to make connection to the capacitor.

The uncertainties in the calibrated value of a two-terminal capacitor can be of the order of tenths of a picofarad if the geometry, not only of the capacitor plates, but of the environment and of the connections is not defined and specified with sufficient precision. For capacitors of 100 pf and more, the capacitance is usually adequately defined for an accuracy of a few hundredths per cent if the terminals and method of connection used for calibration are specified. For smaller capacitances or for higher accuracy, the two-terminal capacitor is seldom practical and the three-terminal arrangement is preferred.*

A three-terminal capacitor (Figure 4-2) has connected to the G terminal a shield which completely surrounds at least one of the terminals (H), its connecting wires, and its plates except for the area that produces the desired direct capacitance to the other terminal (L). Changes in the environment and the connections can

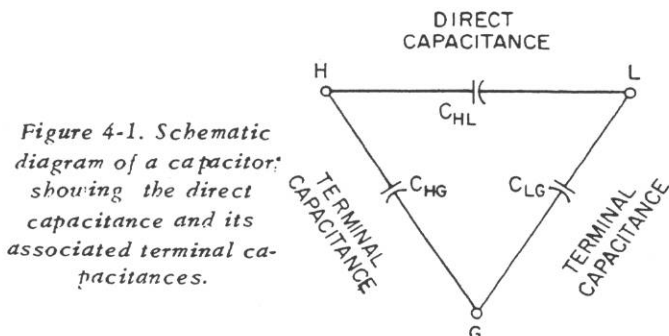


Figure 4-1. Schematic diagram of a capacitor, showing the direct capacitance and its associated terminal capacitances.

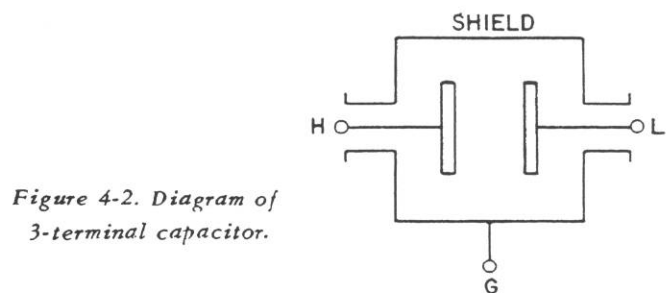


Figure 4-2. Diagram of 3-terminal capacitor.

*John F. Hersh, "A Close Look at Connection Errors in Capacitance Measurements," *General Radio Experimenter*, 33, 7, July, 1959.

vary the terminal capacitances, C_{HG} and C_{LG} , but the direct capacitance C_{HL} - usually referred to simply as the capacitance of the three-terminal capacitor - is determined only by the internal geometry.

This direct capacitance can be calibrated by three-terminal measurement methods, such as guard circuits or transformer-ratio-arm bridges, which exclude the terminal capacitances.

The direct capacitance can be made as small as desired, since the shield between terminals can be complete except for a suitably small aperture. The losses in the direct capacitance can also be made very low because the dielectric losses in the insulating materials can be made a part of the terminal impedances. When the three-terminal capacitor is connected as two-terminal, the two-terminal capacitance will exceed the calibrated three-terminal value (C_{HL}) by at least the terminal capacitance C_{HG} .

4.2.3 FREQUENCY CHARACTERISTICS. Although the characteristics of capacitors sometimes approach the ideal, small deviations from ideal performance must be examined and evaluated for the capacitors to be known with high accuracy. The residual parameters which cause such deviations are shown in the lumped-constant, two-terminal equivalent circuit of Figure 4-3. R represents the metallic resistance in the leads, supports and plates; L , the series inductance of the leads and plates; C , the capacitance between the plates; C_k the capacitance of the supporting structure. The conductance, G , represents the dielectric losses in the supporting insulators, the losses in the air or solid dielectric between capacitor plates and the d-c leakage conductance.

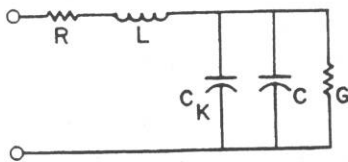


Figure 4-3. The equivalent circuit of a capacitor.

The effective terminal capacitance, C_E , of the capacitor becomes greater than the electrostatic or zero-frequency capacitance, C_0 , as the frequency increases because of the inductance L . When the frequency, f , is well below the resonance frequency f_0 (defined by $\omega_0^2 LC_0 = 1$), the fractional increase in capacitance is approximately

$$\frac{\Delta C}{C_0} \approx \omega^2 LC_0 = \left(\frac{f}{f_0}\right)^2 \quad (4-1)$$

With this information, the increase in capacitance at, for example, a frequency of 1 Mc can be computed with high accuracy from the calibrated value at 1 kc. For small increases, the accuracy may be greater than

that of a measurement at 1 Mc because of the difficulties in determining the measurement errors produced by residuals in the connecting leads outside the capacitor.

The three-terminal capacitor has a similar increase in capacitance produced by inductance. The lowest resonance is determined not solely by the calibrated direct capacitance but also by the terminal capacitances, which may be much larger than the direct capacitances.

When the capacitor has a solid dielectric, such as mica, there is another source of capacitance change with frequency. The capacitance increases at low frequencies as the result of dielectric absorption caused by interfacial polarization in the dielectric. The change in capacitance with frequency of a 1000-pf capacitor with mica dielectric is shown in Figure 4-4. The dotted

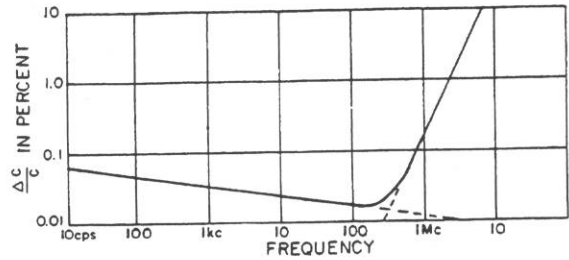


Figure 4-4. Variation of capacitance with frequency.

line slanting downward to the right represents the change in the dielectric constant of mica resulting from interfacial polarization; that slanting upward to the right shows the change in effective capacitance resulting from series inductance. The magnitude of the change at low frequencies depends upon the dielectric material and is, for example, much smaller for polystyrene than for mica.

4.2.4 DISSIPATION FACTOR AND STORAGE FACTOR. An important characteristic of a capacitor is the ratio of resistance to reactance or of conductance to susceptance. This ratio is termed dissipation factor, D , and its reciprocal is storage factor, Q .

$$D = \cot \theta = \frac{R}{X} = \frac{G}{B} = \frac{1}{Q} = \tan \delta \quad (4-2)$$

$$Q = \tan \theta = \frac{X}{R} = \frac{B}{G} = \frac{1}{D} = \cot \delta \quad (4-3)$$

This ratio is defined in Figure 4-5 in terms of phase angle θ and loss angle δ . Dissipation factor is directly proportional to the energy dissipated, and storage factor to the energy stored, per cycle. Power factor is defined as

$$P.F. = \cos \theta = \sin \delta \quad (4-4)$$

and differs from dissipation factor by less than 1% when their values are less than 0.1.

In Figure 4-5, R and X are the series resistance and reactance, and G and B are the parallel conductance and susceptance.

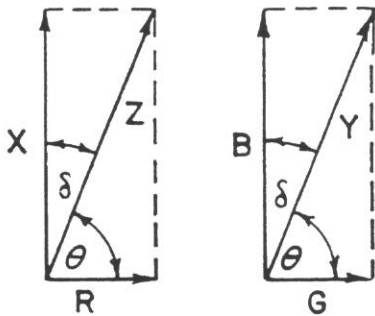


Figure 4-5. Vector diagram showing the relations between factors D and Q, and angles θ and δ .

The dissipation factor of a capacitor is determined by the losses represented in Figure 4-3 by R and G. The resistance R is not usually significant until the frequency is high enough for the skin effect to be essentially complete. At such frequencies the resistance varies as the square root of frequency and may be expressed as $R_1 \sqrt{f}$, where R_1 is the resistance at one megacycle and f is the frequency in megacycles. The total dissipation factor at high frequencies is then

$$D = \frac{G}{\omega C} + R_1 \sqrt{f} \omega C \quad (4-5)$$

At low frequencies only the losses represented by G are important. The leakage conductance component is negligible at frequencies above a few cycles and is important only when the capacitor is used at dc for charge storage. The dominant components at audio frequencies are the dielectric losses in the insulating structure and in the dielectric material between the plates.

In the air capacitor the losses in the air dielectric and on the plate surfaces are negligible under conditions of moderate humidity and temperature. The loss, is, therefore, largely in the insulating supports. When good-quality, low-loss materials, such as quartz, ceramics, and polystyrene are used for insulation, the conductance varies approximately linearly with frequency. The total dissipation factor of an air capacitor, whose equivalent circuit is that of Figure 4-3, may be expressed at low frequencies as

$$D = \frac{G}{\omega(C + C_k)} \quad (4-6)$$

When the capacitance C is variable, this D is then inversely proportional to the total terminal capacitance.

In a capacitor with a solid dielectric the dominant component of the conductance G is the loss in the dielectric, which varies with frequency. The resulting variation of D with frequency, shown for a mica capacitor in Figure 4-6, is the sum of three principal components: a constant dissipation factor caused by residual polarizations and shown by the horizontal dotted line; a loss produced by interfacial polarizations, which contributes the D shown by the dotted line slanting downward to the right; and an ohmic loss in the leads and plates, which results in a D proportional to the $3/2$ power of frequency and is shown as the dotted line slanting upward to the right. The total dissipation factor has a minimum value at a frequency which varies inversely with capacitance and which ranges from 1 kc to 1 Mc for capacitance values from 1 μ f to 100 pf.

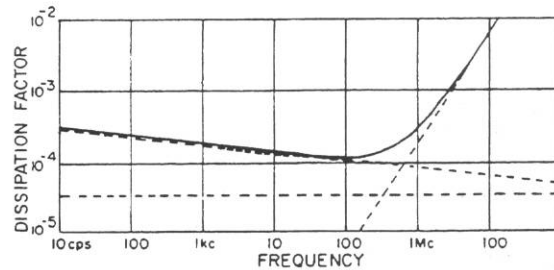


Figure 4-6. Variations of dissipation factor with frequency.

4.2.5 SERIES VS PARALLEL CAPACITANCE. Every capacitance can be expressed in terms of either series or parallel components. The choice is a matter of convenience for the problem at hand. One cannot tell from a single measurement whether a combination of a resistive and a reactive element is actually parallel or series. Regardless of the physical arrangement, the resistive and reactive components can be measured. The series notation is as shown in Figure 4-7a, where C_s is the pure capacitive component and R_s is the series resistance or loss component. The vector diagram for the series equivalent is given in Figure 4-7b, where θ is the phase angle and δ is the dielectric-loss angle.

In the series equivalent case, the dissipation factor, D, defined as the cotangent of the dielectric phase angle, is:

$$D = \cot \theta = \tan \delta = \frac{R_s}{\frac{1}{\omega C_s}} = \omega C_s R_s \quad (4-7)$$

In parallel notation, the equivalent circuit is that of Figure 4-7c, where the resistance, R_p , represents the loss component, G is the conductance, and the capacitance, C_p , is the pure capacitive component. The vector diagram for the equivalent parallel circuit may be represented as in Figure 4-7d, where again θ is the phase angle and δ is the dielectric-loss angle.

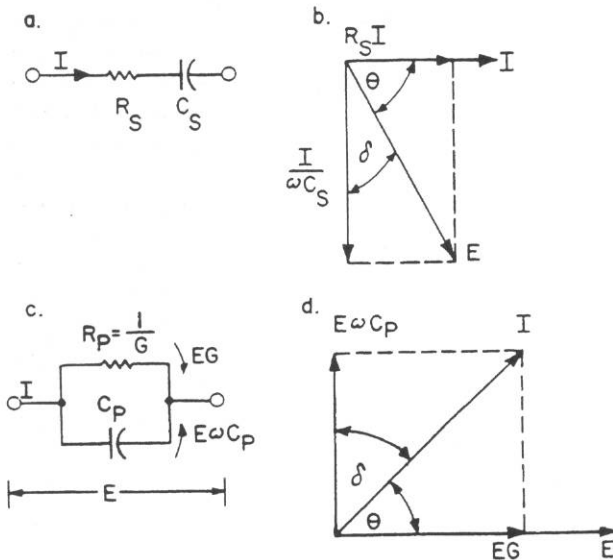


Figure 4-7. Series and parallel equivalent circuits of capacitors.

Then, the dissipation factor, D , is:

$$D = \cot \theta = \tan \delta = \frac{G}{\omega C_p} = \frac{1}{\omega C_p R_p} \quad (4-8)$$

The relation of series and parallel equivalent values is:

$$C_p = \frac{C_s}{1 + D^2} = \frac{C_s}{1 + \tan^2 \delta} = C_s \cos^2 \delta \quad (4-9)$$

$$R_p = \frac{R_s(1 + D^2)}{D^2} = \frac{1 + D^2}{D \omega C_s} \quad (4-10)$$

Note that the C values are essentially equal when D is small.

4.3 CAPACITANCE MEASUREMENTS.

4.3.1 GENERAL. Measurements of capacitance, particularly those of high accuracy, are made by a null method which uses some form of the basic ratio bridge, shown in Figure 4-8. The capacitance of the unknown, C_x , is balanced by a calibrated, variable, standard

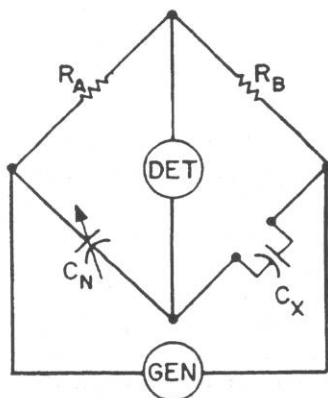


Figure 4-8. Basic ratio bridge.

capacitor, C_N , or by a fixed standard capacitor and a variable ratio arm, such as R_A . Such bridges with resistive ratio arms and with calibrated variable capacitors or resistors can be used over a wide range of both capacitance and frequency and with a direct-reading accuracy which seldom exceeds 0.1%.

For higher accuracy, resolution, and stability in capacitance measurements at audio frequencies, a bridge with inductively-coupled or transformer ratio arms has many advantages, and increasing use of transformer-ratio-arm bridges is being made in the measurement of many types and sizes of capacitors.

4.3.2 TRANSFORMER RATIO ARMS. The advantages of transformer ratio arms in a bridge are that accuracies within a few parts per million are not difficult to obtain over a wide range of integral values, even for ratios as high as 1000 to 1, and that these ratios are almost unaffected by age, temperature, or voltage. The low impedance of the transformer ratio arm also makes it easy to measure direct impedances and to exclude the ground impedances in a three-terminal measurement without the use of guard circuits and auxiliary balances.

To illustrate these characteristics, a simple capacitance bridge with transformer ratio arms is shown in Figure 4-9. On the toroidal core, a primary winding, connected to the generator, serves only to excite the core; the number of primary turns, N_p , determines the load on the generator but does not influence the bridge network. If all the magnetic flux is confined to the core — as it is to a high degree in a symmetrically wound toroid with a high-permeability core — the ratio of the open-circuit voltages induced in the two secondary windings must be exactly equal to the ratio of the number of turns. The ratio can be changed by the use of taps along the two secondaries, but, when the number of turns between taps is fixed, the voltage is highly

invariant. Changes in the core permeability with time and temperature have only very small effects on the ratio, because they modify only the very small amount of leakage flux that is not confined to the core in a practical transformer. The ratio is, therefore, both highly accurate and highly stable.

In Figure 4-9, the two transformer secondary windings are used as the ratio arms of the capacitance bridge with the standard capacitor, C_N , and the unknown, C_X , as the other two arms in a conventional four-arm bridge network. The condition for balance, or zero detector current, is easily shown to be that

$$V_N C_N = V_X C_X \quad \text{or} \quad \frac{C_X}{C_N} = \frac{V_N}{V_X} = \frac{N_N}{N_X} \quad (4-11)$$

This balance condition is not affected by the capacitances shown from the H and L terminals of C_N and C_X to the terminal G connected to the junction of the ratio arms. The capacitances between L and G shunt the detector, so that they affect only the bridge sensitivity. The capacitances between H and G are across the transformer windings. To the extent that the transformer can be assumed ideal, i.e., with no resistance in the secondary windings and with no flux that does not link equally both secondaries, the current drawn by the H-G capacitances does not change the voltages V_N and V_X or the balance conditions. In practice, the transformer resistances and leakage inductances can be kept so small that quite low impedances or large capacitances can be connected from H to G before there is appreciable error in the bridge.

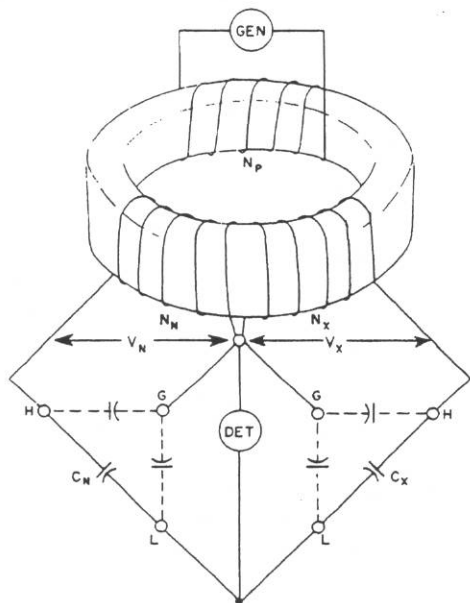


Figure 4-9. A capacitance bridge with transformer ratio arms.

The junction of the ratio arms, G, is therefore a guard point, or guard potential, in the bridge. All capacitances to G from the H or L corners of the bridge are excluded from the measurement. In the three-terminal capacitors represented by the H, L, G terminals in Figure 4-9, the bridge measures only the direct capacitance, C_X , of the unknown in terms of the direct capacitance, C_N , of a standard, without additional guard circuits or balances.

One can take advantage of the accurate and stable ratios of the transformer by the use in the bridge of a standard arm which is fixed and a ratio which can be varied to balance the bridge.

Figure 4-10 shows three of the possible ways of balancing a simple transformer-ratio capacitance bridge. For simplicity, the generator and primary are not shown, but it is assumed that the two secondaries have 100 turns each and are excited so that there is 1 volt per turn. The capacitor in the unknown arm is assumed to be 72 picofarads.

In Figure 4-10a, the two ratio arms are equal and the bridge is balanced in the conventional way with a variable standard capacitor which is adjusted to 72 pf.

The detector current can equally well be adjusted by a variation in the voltage applied to a fixed standard capacitor. In Figure 4-10b, the standard capacitor is fixed at 100 pf, and this is balanced against the 72-pf unknown connected to the 100-volt end of the transformer by connection of the standard to 72 volts of the opposite phase, obtained from suitable taps on the transformer windings. The inductive divider shown has a winding of 100 turns with taps every 10 turns and, on the same core, another winding of 10 turns tapped every turn. If, as shown, the second winding is connected to the 70-volt tap on the first winding and the capacitor to the 2-volt tap on the second winding, the required 72-volts is applied to the capacitor. Six or more decades for high precision can be obtained in a similar fashion with more turns on one core and the use of additional cores driven from the first. Such inductive dividers have very accurate and stable ratios, but the errors increase with the number of decades because of loading effects.

Another method of balance by voltage variation is shown in Figure 4-10c, where a single decade divider is used in combination with multiple fixed capacitors. The 100-turn secondary is tapped every 10 turns to provide 10-volt increments. If, then, a 100-pf capacitor is connected to the 70-volt tap and a 10-pf capacitor to the 20-volt tap, the resulting detector current balances that of the 72-pf unknown connected to 100 volts. This bridge can be given six-figure resolution, for example, through the use of six fixed capacitors in decade steps from 100 pf to 0.001 pf, each of which can be connected to any one of the taps on the transformer.

In any of these bridges, the bridge ratio can also be varied by use of taps on the unknown side of the

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transformer to vary the voltage applied to the unknown capacitor. For example, if the unknown capacitor were connected to a 10-turn or 10-volt tap on the upper half of the transformer, then a capacitance of 720 pf instead of 72 would be balanced by the standard capacitors shown. The range of the bridge can thus be extended to measure capacitors which are much larger than the standards in the bridge.

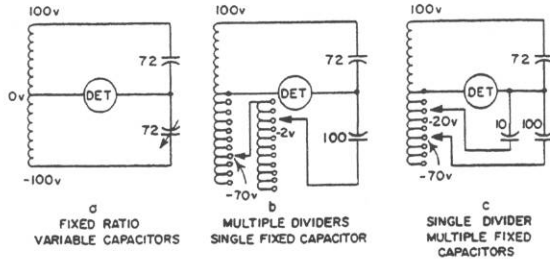


Figure 4-10. Methods of balancing capacitance in a transformer-ratio bridge.

These advantages of transformer ratio arms and dividers make possible a bridge of wide range and high accuracy, since not only are the ratios stable and accurate but, when only a few fixed capacitors are required as standards, the standards can be constructed to have high stability and accuracy. This bridge can also have a wide range of frequencies. At low frequencies, a limit is imposed on sensitivity by the maximum voltage obtainable from the transformer, since, for a given core, the voltage at saturation is proportional to frequency. At high frequencies there is a decrease in accuracy resulting from the decrease in core permeability with frequency, from the increased loading of the transformer by its self-capacitance as well as the bridge capacitances and, of course, from the usual residual capacitances and inductances in the bridge wiring and components.

4.4 THE TYPE 1615-A CAPACITANCE BRIDGE.

4.4.1 GENERAL. The Type 1615-A Capacitance Bridge is a transformer-ratio bridge of the type that uses a single decade of transformer voltage division and multiple, fixed, standard capacitors to provide six decades of resolution in capacitance.

4.4.2 CAPACITANCE MEASUREMENT. As shown in the elementary diagram of Figure 4-11, one side of the secondary of the ratio transformer is tapped at intervals of one-tenth, and to these taps can be connected six standard capacitors in any combination required to balance the bridge. If, for example, the standards connected to the six decade switches are 1000, 100, 10, 1, 0.1, and 0.01 pf, the range of the unknown that can be balanced is from 1000 pf to 0.001 pf when the

unknown is connected to the full voltage of the other secondary of the transformer. This unknown side of the transformer has, however, a tap at one-tenth of the full voltage, so that when the unknown is driven from this lower voltage, the range is multiplied by ten, and an unknown up to 10,000 pf, or 0.01 μf , can be balanced by the same internal standards. The range is extended still further by further division of voltage on the unknown side through a second transformer or inductive divider driven from the 0.1 tap on the ratio transformer. This second divider provides additional ratios of 0.1 and 0.01, so that, with the voltage applied to the unknown reduced to 0.01 and 0.001, the bridge is given two more ranges of 0.1- μf and 1- μf maximum capacitance.

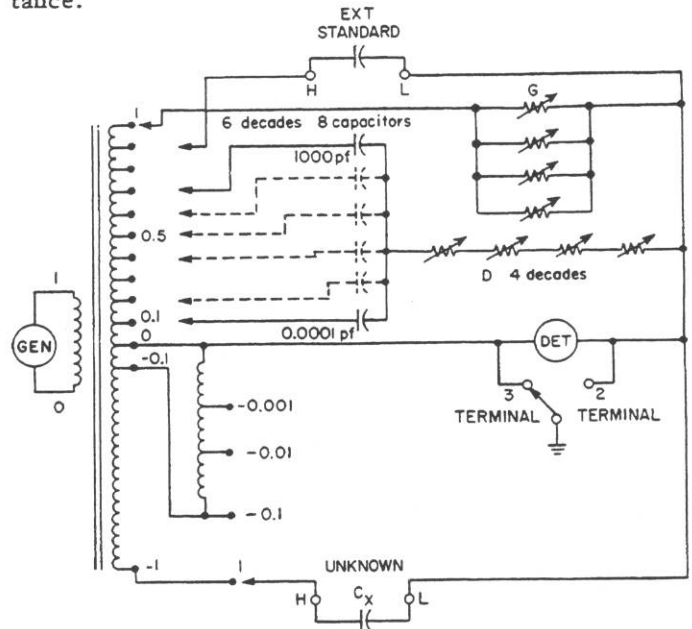


Figure 4-11. Elementary schematic diagram of the Type 1615-A Capacitance Bridge.

To extend the range to smaller capacitances, two additional standards are used, of 0.001 and 0.0001 pf. This yields two more ranges, 0.0001 pf to 100 pf and 0.00001 pf to 10 pf. There are, therefore, eight standard capacitors, only six of which are used for any one range. The necessary standard connections are made by the same range switch that selects the transformer taps.

With this combination of eight internal-standard capacitors and four voltage ratios to which the unknown can be connected, the capacitance range of the bridge extends from a maximum of 1.111,110 μf to a minimum step of 0.00001 pf or 10^{-11} μf . The capacitors and ratios used for each range are indicated in Figure 4-12.

4.4.3 LOSS MEASUREMENTS. To obtain a precision of six figures in the capacitance balance, the loss balance must be made equally precise. As shown in

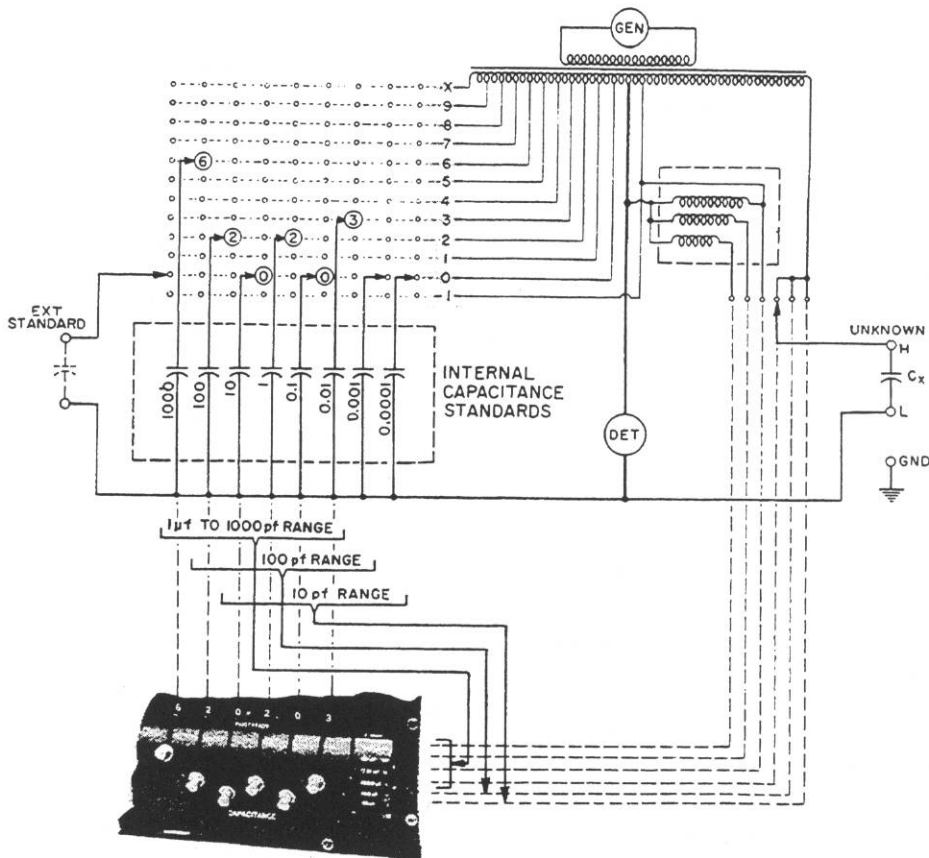


Figure 4-12. Capacitance balance control.

Figure 4-11, the loss balance in this bridge can be made in terms of either the dissipation factor, D , or the shunt conductance, G , of the unknown. For most purposes, dissipation factor offers the greater range and convenience. Conductance is useful in some measurements of dielectric materials and is necessary when external standards are added to the bridge and when the loss in the bridge standards exceeds that of the capacitor being measured.

4.4.3.1 Dissipation Factor. (Figure 4-13). The balance of loss in terms of dissipation factor is made by means of four resistance decades connected in series with the common side of all the internal capacitance standards, as shown in Figure 4-11. Since there is some capacitance from the junction point of capacitors and resistors to the bridge shields, the basic network which provides the effective bridge-dissipation-factor adjustment is the T-network shown in Figure 4-13b. The effective direct impedance of this network between the terminals a and b is

$$Z_{ab} = \frac{1}{j\omega C_N} [1 + j\omega R_N (C_N + C_D)], \quad (4-12)$$

which is equivalent to a capacitance C_N with a dissipation factor

$$D_N = \omega R_N (C_N + C_D). \quad (4-13)$$

Although the effective capacitance, C_N , of the bridge is varied by varying the voltages applied to any of the several bridge capacitors, the total capacitance, $C_N + C_D$, which includes all the direct and stray capacitance connected to the junction of C_N and R_N , remains constant. The resistance of the R_N decades can, therefore, be calibrated to read D directly at a particular frequency, in this bridge at 1000 cps. With four decades of 100, 10, 1, and 0.1 ohms per step and with the total capacitance adjusted to $0.001592 \mu\text{f}$, the range of D at 1000 cps is from 0 to 0.01 in 1 ppm steps. The capacitance value of $0.001592 \mu\text{f}$ is selected to make $2\pi fC = 10^{-5}$, so that R_N can be converted to D_N by a simple shift of decimal point in the read-out.

At other frequencies, the indicated D must be multiplied by the frequency in kilocycles. To extend the range to higher D , additional capacitors are added by a range switch to make $C_T = 0.01592 \mu\text{f}$ for a maxi-

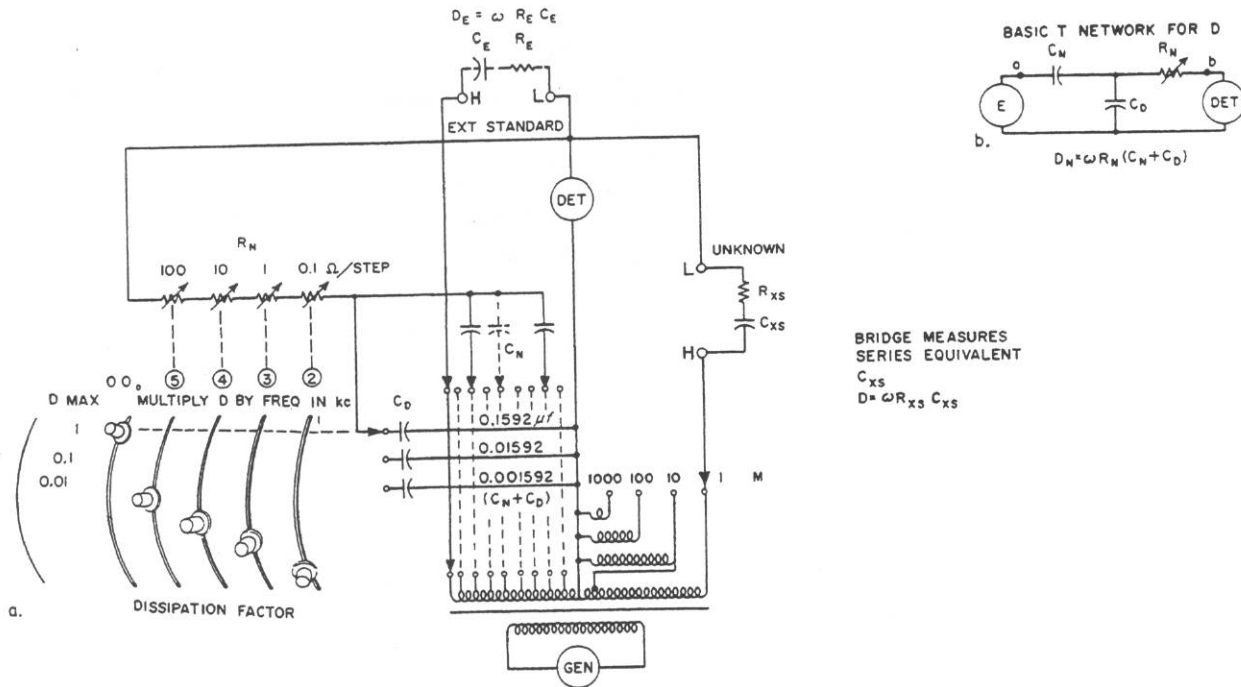


Figure 4-13. Dissipation-factor balance controls.

imum D of 0.1 and to make $C_T = 0.1592 \mu f$ for a maximum D of 1.

The effective direct capacitance C_N is not changed when capacitance is added to C_D to increase the total, $C_N + C_D$, since C_D appears only in the D term in Equation 4-12. Note that the series connection of bridge standard capacitors and resistors means that the capacitance (C_B) and loss (D_B) readings of the bridge on the D ranges measure equivalent series components of the unknown,

$$C_{XS} = C_B \tag{4-14}$$

and

$$R_{XS} = \frac{D_B}{\omega C_B} \tag{4-15}$$

4.4.3.2 External Standards. When an external standard is added to the bridge, a connection of its capacitance parallel to C_N and in series with R_N would change the calibrated total capacitance. The bridge as shown in Figure 4-13, has, therefore, the EXT STANDARD H terminal connected through a decade switch to the transformer taps, the L terminal to the detector. The ten steps of voltage which can be applied to the H terminal divide the external capacitance C_E by the decade steps indicated in the window of the MULTIPLY EXT STANDARD switch, but they do not change the D_E of the external standard. The bridge D decades vary only the dissipation factor of the effective bridge capacitance, indicated by the C_N decades,

and this capacitance with variable loss is in parallel with any external standard used.

The D of the unknown can be determined when an external standard is used on the bridge by calculating the total D of the bridge and external capacitors in parallel, as in the circuit shown in Figure 4-14a. The known components of the impedances are the bridge readings of the internal effective series capacitance C_B and dissipation factor D_B and the series capacitance C_E and dissipation factor D_E of the external capacitor. The total D of this circuit is

$$D_T = \frac{C_B D_B (1 + D_E^2) + C_E D_E (1 + D_B^2)}{C_B (1 + D_E^2) + C_E (1 + D_B^2)} \tag{4-16}$$

and any D is defined as $D = \omega RC$ for series equivalents. The total series capacitance of the circuit is

$$C_{TS} = C_E + C_B - \frac{C_E C_B (D_B - D_E)^2}{C_B (1 + D_E^2) + C_E (1 + D_B^2)} \tag{4-17}$$

The equations can be simplified for small D, where D^2 can be neglected and $1 + D^2 \approx 1$. Then

$$D_T \approx \frac{C_B}{C_B + C_E} D_B + \frac{C_E}{C_B + C_E} D_E \tag{4-18}$$

and

$$C_{TS} \approx C_B + C_E \tag{4-19}$$

From these equations it is easier to see why a very large bridge D_B may be required to balance a small unknown $D_X (=D_T)$ when an external standard is used and why balance with D_B may not be possible on the bridge. As one extreme example, if the external C_E equals the unknown $C_X (=C_T)$, then $C_B = 0$ and D_B can have no effect on D_T . The loss is balanced only if the external standard D_E happens to equal D_X , or adjustment of D_E is provided outside the bridge. If the external standard is only slightly smaller than the unknown, say, $C_E = 0.99 C_X$, then C_B balances the difference capacitance and $C_B = 0.01 C_X$. In this case, $\frac{C_B}{C_B + C_E} = 0.01$, and, if the external standard D_E can be neglected, the bridge D_B must be 100 times the D_X of the unknown.

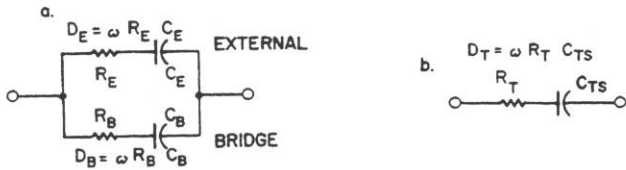


Figure 4-14. Equivalent circuit with external standard for D.

In general, when the bridge capacitance is a small fraction of the total capacitance of bridge and external standard, the bridge D may have to be very large, perhaps beyond the bridge D range. Furthermore, if the external standard D_E exceeds the D_X of the unknown, but the capacitance C_E is smaller than the un-

known, the bridge cannot add loss to the unknown to reach balance. Because the balance and calculation of D are not simple in many cases when external standards are used, loss balance with conductance G is recommended.

4.4.3.3 Conductance: G. (Figure 4-15). It is simple, however, to use the low-resistance decades in the basic T-network for G, shown in Figure 4-15b, to obtain a variable conductance. The relation between the decade resistance R_N and the direct conductance G_{ab} between the terminals a and b is

$$G_{ab} = \frac{R_N}{AB + R_N A + R_N B} = \frac{R_N \times 10^{-10}}{1 + 2 \times 10^{-5} R_N} \quad (4-20)$$

when 100-kilohm fixed resistors are used as the series arms A and B. The four decades of resistance, R_N , then provide a range of G from 0.1 μmho to 10 pmho. The conductance is reduced by a factor of ten when the network is switched to the 0.1 tap on the transformer (Figure 4-15a) instead of to the full winding, and the range is then from 0.01 to 0.000001 μmho . When the loss in the standard capacitors, external or internal, exceeds that of the unknown, the bridge must be able to add loss to the unknown. With the conductance balance of loss, the T-network can be readily switched to the taps at full or tenth voltage on the unknown side of the bridge to provide the same two ranges of conductance across the unknown -G as there

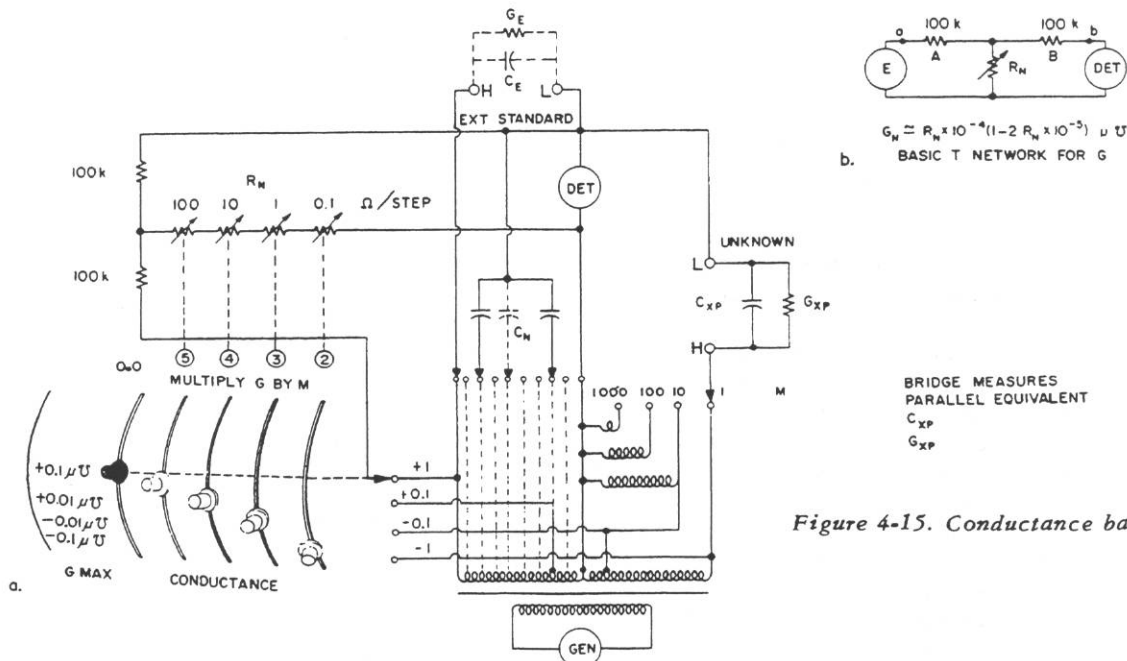


Figure 4-15. Conductance balance controls.

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are for conductance across the internal and external standards +G.

The conductance range is also changed when the transformer ratios on the unknown side of the bridge are changed by the C MAX range lever. The reading of the G dials must then be multiplied by the factor M (1, 10, 100, or 1000) engraved on the C MAX scale adjacent to the lever. Since the conductance relations do not involve frequency, no frequency multiplier is required.

Note that the conductance network is connected in parallel with the bridge capacitance standards, (C_N). The capacitance (C_B) and loss (G_B) readings of the bridge on the G ranges therefore measure equivalent parallel components of the unknown, $C_{XP} = C_B$ and $G_{XP} = G_B$.

The bridge will measure not only capacitors with small, or no, conductance but also resistors with small, or no, capacitance. Since the bridge conductances are relatively small, the resistors which can be measured are relatively large. Table 4-1 shows maximum and minimum resistances which can be measured at the unknown terminals.

4.4.3.4 Correction of G Dial Readings. Since the relation between G and R_N in Equation 4-20 is not linear, the G reading of the bridge, which is proportional to R_N , requires some correction when R_N is near maximum. The error is more evident when Equation 4-20 is written in the form

$$G \approx R_N \times 10^{-10} (1 - 2 \times 10^{-5} R_N + \text{higher order terms}). \quad (4-21)$$

The conductance is, therefore, lower than indicated by the bridge reading of the R_N decades by an amount which is $2 \times 10^{-3} R_N$ percent or $2 \times 10^{-15} R_N^2$ mhos. For a conductance accuracy of 1%, the error is significant only when the first G decade is set above 3, i.e., when R_N is greater than 300 ohms. For example, when the first decade is set at its maximum indication of X, $R_N = 1 \text{ K}\Omega$ and $2 \times 10^{-3} R_N = 2\%$; the effective conductance is 2% less than the bridge reading. Since the error varies with the square of R_N , the corrections are negligible for most G readings, as shown in Figure 3-7.

4.4.3.5 External Standard. The EXT. STANDARD H terminal, connected to the transformer taps through a decade switch, and L terminal, connected to the detector, permit the connection of external capacitance and conductance in parallel with the bridge C and G internal standards, as shown in Figure 4-15a. With the parallel connection of equivalent parallel components, shown in Figure 4-16, the total capacitance and conductance can be found by simple addition of bridge and external C and G. The known components are the bridge readings of effective parallel capacitance C_B and conductance G_B and the parallel capacitance C_E and conductance G_E of the external capacitor. The total conductance is

$$G_T = G_B + G_E, \quad (4-22)$$

and the total capacitance is

$$C_T = C_B + C_E \quad (4-23)$$

TABLE 4-1
RESISTANCE RANGE OF TYPE 1615-A

G Dials $\mu\Omega$	C MAX	M	R_X
0.0X 000 .000 001	10 100 pf 1000	1	10 M Ω 10 ⁶ M Ω
0.0X 000 .000 001	0.01 μf	10	1 M Ω 10 ⁵ M Ω
0.0X 000 .000 001	0.1 μf	100	100 K Ω 10 ⁴ M Ω
0.0X 000 .000 001	1 μf	1000	10 K Ω 10 ³ M Ω

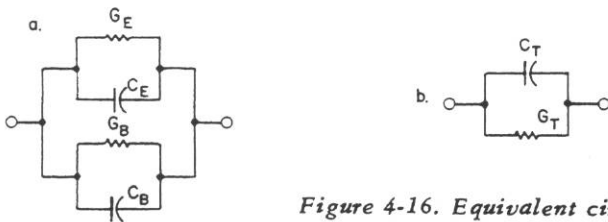


Figure 4-16. Equivalent circuit with external standard for G .

Since the bridge has negative ranges of G and -1 positions on the C levers, the bridge can be balanced with external standards either larger or smaller in C and G than the unknown. The G balance does not depend upon either the sign or relative magnitude of the bridge and external capacitances.

4.5 TYPE 1615-A ACCURACY.

4.5.1 GENERAL. The accuracy of the bridge is determined primarily by the accuracy of the transformer ratios and by the accuracy of the internal standard capacitors. The accuracy of the ratios depends upon the magnitude of the ratio, upon frequency, and upon the load connected to the transformer. The accuracy of the capacitors, which depends initially upon the accuracy of the reference standard with which they are calibrated, is usually limited subsequently by the changes produced by aging and by fluctuations in temperature, pressure, and humidity. To achieve an accuracy of 0.01% in the bridge reading over a wide range of frequency and capacitance and without frequent recalibration, particular care has been taken in the construction of the transformers and capacitors.

4.5.2 RATIO TRANSFORMERS. Relatively low numbers of turns are used in the transformers to keep the leakage inductance, stray capacitance, and resistances of the windings so small that the ratio accuracy remains high, even with loads greater than $1 \mu f$ and frequencies above 10 kc. These small residual impedances make it possible, for example, when a 1000-pf capacitor is being measured at 1000 cps with unity ratio, to load the transformer with as much as $1 \mu f$ of ground or cable capacitance before the error in the measured direct capacitance exceeds 0.01%. The small bridge inductances are not insignificant, however, when high capacitance is measured at high frequency, and the bridge error is then of the order of $+0.002\% C \mu f \left(\frac{f}{1000}\right)^2$ if no correction for the inductance is used.

The accuracy of the ratios when the transformer is lightly loaded is better than 0.1 part per million for the unity ratio and is better than 2 ppm for the 0.1 ratio at 1000 cps or lower frequencies. The winding self-capacitances act as a load as frequency increases, so that the error in the 0.1 ratio increases to about 20 ppm

at 10 kc and to 0.2% at 100 kc. When the auxiliary transformer is connected for ratios of 0.01 and 0.001, the ratio errors are increased by the loading effects of the input impedance of the auxiliary transformer. These errors are eliminated by compensating resistors, R247 and R248, and the 0.01 and 0.001 ratios in the bridge are adjusted to within ± 20 ppm in the frequency range below 10 kc. The phase errors are, in general, somewhat larger than the magnitude errors of the ratios. At 1000 cps, the phase error is probably within $\pm 10 \mu$ radians, but the error increases in approximate proportion to ratio and to the square of frequency.

4.5.3 CAPACITANCE STANDARDS. The bridge can be calibrated quickly and accurately by the measurement of a single calibrated external standard capacitor of almost any size within the range of the bridge. Since the six-figure resolution of the bridge permits comparison with a precision better than 0.01% down to 1 pf, the accuracy of calibration is usually determined by the accuracy of the standard. Only one external standard, most conveniently a three-terminal 1000-pf standard such as the General Radio Type 1404-A, is required because the accurate, internal 0.1 transformer ratio can be used to insure an accurate ratio of the internal capacitance standards. A -1 position on each capacitance balance switch connects the corresponding internal capacitor to the 0.1 tap on the unknown side of the transformer. This capacitor can be compared with the next lower decade capacitor, which is connected to the maximum voltage on the standard side when the adjacent lever is set on the X position, and any adjustments required can be made with trimmers accessible beneath a sliding cover on the bridge front panel.

Such checks or recalibrations of the bridge need not be made often. The capacitors are constructed to have such small changes with time, temperature, and environment that the initial calibration to $\pm 0.01\%$ may be expected to change less than 0.01% per year in normal use. The temperature coefficients of the 1000-, 100-, and 10-pf units, which are multiple-plate capacitors, are less than 5 ppm/ $^{\circ}C$; the coefficients of the Zickner-type 1-, 0.1-, and 0.01-pf units and of the cylindrical 0.001- and 0.0001-pf units are less than 20 ppm/ $^{\circ}C$.

For almost zero changes of capacitance with atmospheric pressure and humidity, all but the two smallest capacitors are hermetically sealed in an atmosphere of dry nitrogen. This sealing is necessary where stability of better than 0.01% is expected, because in an unsealed capacitor the capacitance changes about 2 ppm for each 1% change in relative humidity; hence a 50% change in humidity produces a 0.01% change in capacitance. And the pressure change, for example, resulting from moving the capacitor from the near-sea-level altitude of Washington, D.C. to the more

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than 5000-ft altitude of Boulder, Colorado, produces a capacitance decrease of about 0.01%.

To minimize long-term drift, the capacitor plates are constructed of a single metal (Invar) to avoid differential stresses, and they are annealed and temperature-cycled to relieve strains and to accelerate the initial aging.

4.5.4 RESISTANCE DECADES. Although the accuracy of the measurement of loss is not important in the measurement of many capacitors, the Type 1615-A Capacitance Bridge makes possible measurements of dissipation factor to an accuracy of $\pm(0.1\% + 10 \text{ ppm})$ of the measured value. This accuracy is applicable over the D range from 1 to 0.000001 and over almost the whole capacitance range from 1 μf to 1 pf and the frequency range from 50 cycles to 10 kc. At low frequencies and small capacitance the accuracy will be limited by the reduced sensitivity of the bridge. At high frequencies and at ratios other than unity, the phase errors of the transformers will reduce the accuracy. Within these extremes, the accuracy of the D reading is determined by the resistance decades, which are adjusted within $\pm 0.05\%$, and by the total capacitance connected to the decades, which is trimmed to adjust the D reading to within $\pm 0.1\%$ when a standard of known D is measured.

The loss measurement in terms of shunt conductance G, is limited to an accuracy of $\pm(1\% + 0.00001 \mu\text{mho})$ by the accuracy of the 100-kilohm resistors used in the T-network. Higher accuracy is seldom needed. It would not only add to the cost but would also require corrections to the bridge G reading. These corrections, amounting to a maximum of 2%, are due to the non-linear relation between the decade resistance and the equivalent conductance of the network.

The loss measured by the bridge as either D or G is the loss of the unknown capacitor relative to the loss of the internal standards. Since the bridge capacitors are carefully cleaned and sealed in dry nitrogen, it is estimated that their dissipation factor does not exceed a few parts per million. The accuracy of absolute loss measured by the bridge is, therefore, the same as that of the loss relative to the bridge capacitors.

The four resistance decades (R201-R240) used in conductance and dissipation-factor measurements are wire-wound resistance elements designed to minimize inductance in low-resistance values and to minimize capacitance for high values of resistance. All units up through 100 ohms utilize a so-called Ayrton-Perry winding, in which each resistor consists of two parallel windings of opposed direction, so that the current flow in the two windings is in opposite directions. The external magnetic field, as a result, is effectively canceled so that, typically, the residual inductance of such a winding is of the order of 1% of the inductance of a corresponding single winding.

Elements having 200 ohms resistance or higher are unifilar-wound on their flat rectangular "cards." The inherent phase angle of these resistors is substantially lower than that obtained with so-called "non-inductive" spool-wound resistors.

4.6 CONTROLS AND INDICATORS. (Refer to Table 1-1).

The moderate size and weight of Type 1615-A Capacitance Bridge permit it to be moved about the laboratory with ease, and the bridge is sufficiently rugged to be transported into the field should its accuracy be required there. It is easy to balance, easy to read, and the reading is accurate without corrections.

A feature which contributes much to the ease of balance and of reading is the use of lever, or linear, rather than rotary controls on the switches for the decades. The small panel space occupied by these controls makes it possible to position the six decades and range switch for capacitance and the four decades and range switch for loss within the span of the operator's right and left hands, respectively. The throw of the switches is about three inches, so the 12-position range of any decade can be covered with only a slight motion of hand or finger.

The position of each decade is indicated by a number appearing in the window above each balance control. The bridge capacitance readout thus appears in the form of six closely-spaced digits in a horizontal line and the D or G readout as a similar line of four digits. As S112 is moved to change capacitance range, the decimal point is automatically positioned in the six-figure readout to indicate without multipliers the capacitance in picofarads from a maximum of 1, 111, 110 pf to a minimum of 0.00001 pf. S101 similarly moves the decimal point when the D range is changed to indicate directly the dissipation factor. The decimal point is also positioned automatically to read conductance in micromhos, but since G must be multiplied by the factor M, this factor is indicated in red engraving adjacent to each position of the C MAX range switch lever. This multiplier is required only for G and for external standards, and the color is used on the panel to indicate all quantities to which M must be applied.

When even the approximate magnitude of a capacitor is not known, the initial balance can be found quickly on this bridge by the use of the maximum capacitance range, so that the six decades cover the range from 1 μf to 1 pf and the six controls can be tried in quick succession to determine the balance point without a change in range. The -1 position on each of the capacitance decades, which was mentioned above as useful in the self-calibration of the bridge, also facilitates balance in the region near any zero by permitting a trial reduction of bridge capacitance by one step in a decade without the necessity of moving the adjacent lever.

4.7 CONNECTION OF UNKNOWN.

4.7.1 GENERAL. Two types of connector for the unknown capacitors are provided at the upper right corner of the bridge panel: a pair of Type 874 Coaxial Connectors and a set of three Type 938 Binding Posts with standard 3/4-inch spacing. For three-terminal measurements with complete shielding, as is required particularly for very small capacitance, three-terminal capacitors, such as the Type 1403 and 1404-A Standard Air Capacitors and Type 1422-CD Precision Capacitor, can be connected with coaxial cables to the coaxial bridge terminals. Capacitors having other common types of coaxial connectors can also be connected to the bridge terminals by the use of the appropriate Type 874-Q Adaptor. Capacitors, such as the Type 1401 and Type 1409 Standard Capacitors, which have Type 274 Plugs as terminals, can be plugged into the jack-top binding posts. The binding posts can also be used for the connection of patch cords and leads of many types.

The appropriate set of unknown terminals is connected to the bridge (and the unused terminals disconnected) by means of a four-position terminal selector switch (S113) located next to these terminals. As this switch is moved to change terminals, it also shows the corresponding changes of connections and grounds in the simple equivalent circuit which is engraved on the panel. The resulting circuit diagrams are shown in Figure 4-17.

4.7.2 CALIBRATION. When the terminal switch is set in the position marked CAL, the L sides of all the terminals are disconnected. This permits a self-check or -calibration of the bridge capacitors at any time without the need for disconnecting any unknown.

4.7.3 THREE-TERMINAL MEASUREMENT. In the next position, marked 3 TERM, the coaxial Type 874 UNKNOWN terminals are connected to the bridge, with the L terminal connected to the detector and the H terminal to the transformer. The shields of the connectors and all ground points on the bridge are connected to the guard point, so that all capacitances to the shields or

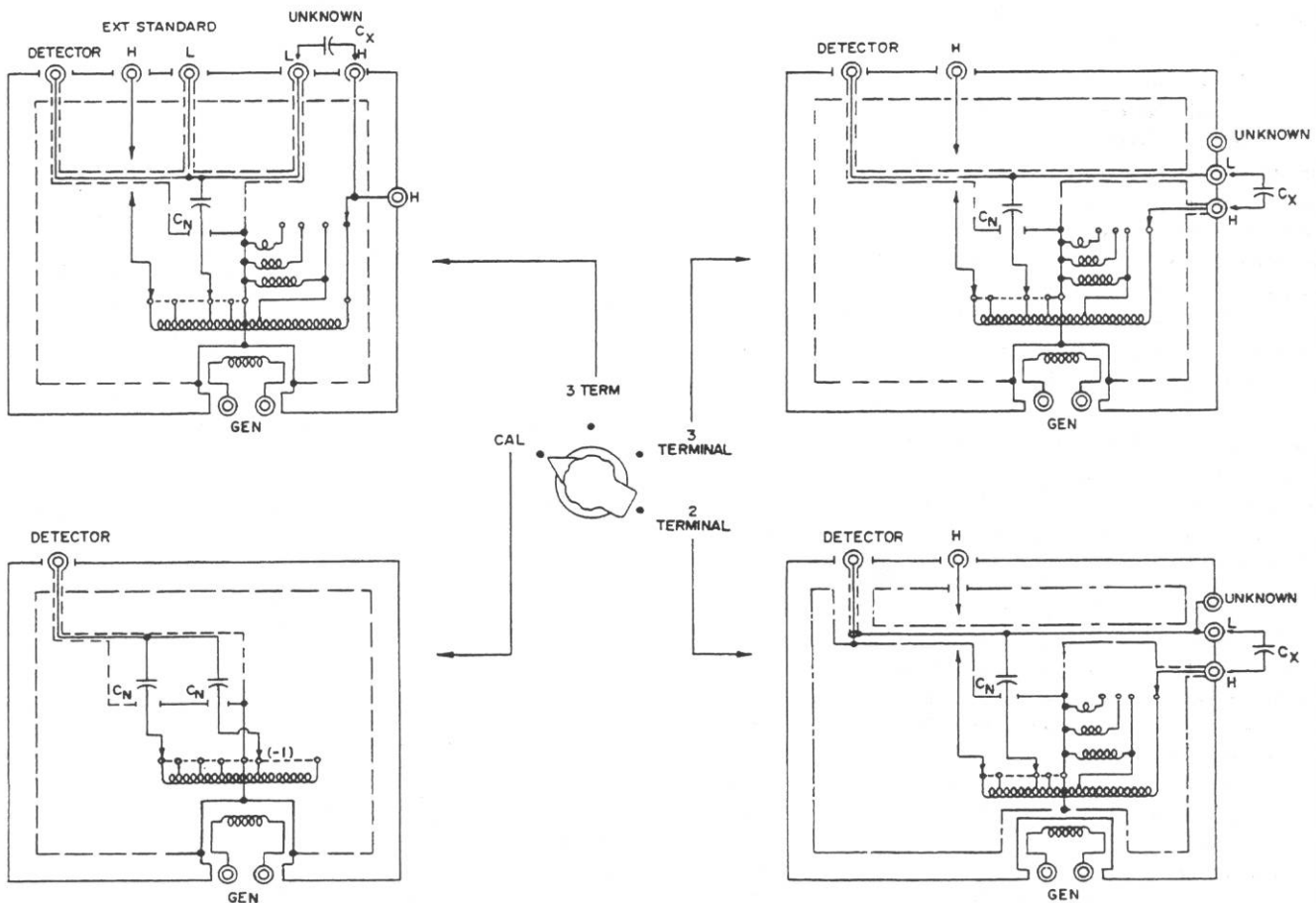


Figure 4-17. Terminal selections of Type 1615-A.

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to ground are excluded from the direct capacitance between H and L measured by the bridge.

The third position of the switch, marked 3 TERMINAL, connects to the bridge the H, L, and GND binding posts instead of the coaxial terminals. The H post is connected to the transformer, the L post to the detector, and the GND post to the transformer midpoint and bridge ground. As in the coaxial three-terminal measurement, the bridge measures only the direct capacitance between the H and L posts and excludes capacitances from H or L to any GND or guard point. The open binding posts have a direct capacitance of about 0.2 pf, which must usually be measured and subtracted from the value measured when a capacitor is connected. The bridge can, of course, measure this small terminal capacitance, as well as that of any leads connected between terminals and capacitor.

4.7.4 TWO-TERMINAL MEASUREMENT. The fourth position of the switch, marked 2 TERMINAL, deserves special attention because of the important changes it makes in bridge connections and bridge measurements. The bridge is again connected to the binding-post terminals with the H post connected to the transformer, but the L and GND posts are now connected together and to the bridge case and panel and to any external ground used. The bridge now measures all capacitances between the H terminal and L or GND, including stray capacitances from posts and leads to the panel and other environment.

In principle, this change of the inherently three-terminal transformer bridge to two-terminal operation is made as shown in Figure 4-11; the ground point is simply switched from the center of the transformer arms to the junction of the standard and unknown capacitors, thereby grounding one side of the unknown. In practice, this change is complicated by the fact that the center of the transformer, which is the guard point to which the bridge shields are connected, is then connected to the high-impedance side of the detector instead of to ground. To prevent error voltages from entering the detector, all the wires and bridge shields connected to the high side of the detector must be enclosed by a grounded shield. To provide this extra shielding for two terminal measurements, the bridge components are enclosed in an inner shield box which is enclosed by, but insulated from, the outer box and panel, and the primary of the main ratio transformer is also enclosed in two separate shields.

4.8 EXTERNAL STANDARDS.

4.8.1 RANGE EXTENSION. The usefulness of the bridge is further increased by the provision on the bridge panel of a pair of terminals to permit the connection of an external standard capacitor, or resistor, to supplement or replace the standards in the bridge.

This pair of coaxial Type 874 Connectors, located to the left of the coaxial pair for the unknown, has the L terminal connected to the L terminal of the unknown and the H terminal connected to the standard side of the transformer through a rotary switch, S114, by means of which any of the tens steps of voltage from the transformer can be applied to the external standard. This rotary switch, with its digital readout through a window, provides a seventh decade of capacitance, or a fifth of conductance, whose magnitude is determined by the external standard chosen. For example, the capacitance range can be extended to 11 μf by the connection of an external standard of 0.01 μf (Type 1615-P1). With the C MAX range switch (S112) set at the 1 μf maximum, the rotary decade then provides a balance control of 1 μf per step and the balance controls extend the range six more decades from 0.1 μf through 1 pf per step.

4.8.2 ACCURACY EXTENSION. Since both the unknown and external standard capacitors can be connected to a wide range of accurate transformer ratios, a comparison of external capacitors can be made with an accuracy even higher than that of the direct bridge reading; and the ratios can be chosen so that the magnitudes of the external capacitors do not have to be decade multiples. For example, the Type 1404-A standard capacitor (1000 pf) has a calibration accuracy higher than 0.01% which can be transferred to a capacitor of, say, 5000 pf by connecting that capacitor to the appropriate unknown terminals and the Type 1404-A to the external standard terminals. When the rotary decade switch for the external standard is set to 0.5 and the C MAX lever to the 0.01- μf position (where $M = 10$), the external standard is effectively multiplied by 5 to balance the unknown. Small differences between the external capacitors can, of course, be balanced with the internal standard capacitance and conductance decades, and any small errors in the bridge reading of the difference are insignificant in the comparison measurement as long as the difference is a small percentage of the total capacitance.

4.8.3 RESOLUTION EXTENSION. The resolution, as well as the accuracy, of the bridge can be extended by the use of an external standard capacitor. It has already been noted above that the external standard and its decade switch S114 add a seventh decade, which can have increments either larger or smaller than those of the six balance control decades. Even higher resolution is possible when, for example, two 1000-pf external capacitors are compared, because the bridge decades can be used to measure a difference as small as 0.00001 pf or 1 part in 10^8 in this example. Usable resolution of 0.1 ppm is not hard to obtain with the recommended Type 1232-A Null Detector, but higher resolution usually requires special detectors.

SECTION 5

SPECIAL MEASUREMENTS

WARNING

Dangerous voltages may be present at the terminals of this instrument.
Refer to specific warnings contained in this section.

5.1 GENERAL.

The Type 1615-A Capacitance Bridge is a precision instrument of considerable versatility. The contents of this section describe measurement procedures that are less usual and routine than those given in Section 3. Five applications of external standards to increase the range, resolution, accuracy, and flexibility of operation of the bridge are given. In addition, coverage is supplied on methods of extending three-terminal measurement advantages to two-terminal capacitors.

5.2 USE WITH EXTERNAL STANDARDS.

5.2.1 GENERAL. External standards of capacitance or conductance can be connected in parallel with the internal bridge standards at the EXT STANDARD coaxial H and L terminals. The H terminal is connected to the standard side of the ratio transformer through a rotary switch, by means of which any of the ten steps of voltage from the transformer can be applied to the external standard. This switch, MULTIPLY EXT STANDARD BY. . ., with its digital readout through a window, provides a seventh decade of capacitance or a fifth of conductance, whose magnitude is determined by the external standard chosen.

Operating procedures are given below for these principal uses of external standards:

1. Range extension to 11 μf .
2. Range extension above 11 μf .
3. Resolution extension to a seventh decade of capacitance or a fifth decade of conductance.
4. Comparison of external capacitors.
5. Balance of terminal and lead capacitances.

5.2.2 RANGE EXTENSION TO 11 μF . The Type 1615-P1 Range-Extension Capacitor is available as a convenient accessory to extend the range of the instrument to 11 μF . Procedures for using it appear in the Appendix. Other 0.01- μF capacitors, such as the Type 1409-L, may be also applied by use of the Type 1615-P1 procedures.

5.2.3 RANGE EXTENSION ABOVE 11 μf . External capacitance decades of 0.001, 0.01, and 0.1 μf per step, when multiplied by the 1000:1-transformer ratio of the bridge, can serve as bridge decades of 1, 10, and 100 μf per step to extend the capacitance range up to 1000 μf . The following General Radio capacitors are recommended (appendix contains complete specifications):

Type 1423-A Precision Decade Capacitor for $\pm 0.05\%$ decade accuracy.

Type 1419-K Decade Capacitor for $\pm 0.5\%$ decade accuracy.

Type 1419-A Decade Capacitor for $\pm 1\%$ decade accuracy.

The accuracy of measurement of large capacitance is usually limited by the bridge and lead inductance in series with the capacitance. The bridge reading of capacitance is greater than the unknown capacitance C by a capacitance error $\Delta C = \omega^2 C^2 L$. The bridge inductance of about 0.3 μh , in series with the UNKNOWN terminals, results in a minimum error of the order of $+0.002\% C_{\mu f} (f_{kc})^2$. Hence, at 1000 cps and 100 μf , the bridge reading is high by about 0.2%.

Additional loss range can be provided by using external resistance decades in parallel with the external capacitance decades. Maximum bridge decade conductance is 0.1 μmho , which is equivalent to an external standard resistance of 10 megohms. For continuous loss balance above the range of bridge decades, use external decades starting at 1 megohm per step and continuing as required to lower resistance (higher conductance).

5.2.3.1 Balance Procedures. The procedures are as follows:

a. Connect the two-terminal external decade capacitor and resistor H terminal to the bridge coaxial EXT STANDARD H terminal and L (and G) terminals to the bridge L (or GND) terminal. (Use Type 874-Q2 Adaptor to convert the coaxial bridge EXT STANDARD terminal to binding posts, or use Type 874-Q9 Adaptor

to convert the capacitor binding posts to a coaxial terminal.)

- b. Set terminal selector to 2 TERMINAL.
- c. Connect unknown (refer to para. 3.7.5).
- d. Set MULTIPLY EXT STANDARD BY. . . to 1.
- e. Set C MAX to 1 μ f.
- f. Balance capacitance with external decades and bridge CAPACITANCE decades.
- g. Balance loss with external R decades, bridge CONDUCTANCE decades, and appropriate G MAX setting.
- h. Calculate external standard conductance in μ mhos.
Example: $G_{EXT} (\mu\text{mhos}) = 10^6/R_{EXT}(\text{ohms})$
- i. Multiply G_{EXT} by reading of MULTIPLY EXT STANDARD BY. . . switch.
- j. Add product to reading of bridge CONDUCTANCE decades in μ mhos, with indicated decimal point.
- k. Multiply the sum by M (1000 with C MAX set at 1 μ f).

5.2.3.2 Refinement of Capacitance Reading. To determine capacitance of the unknown in pf:

- a. Determine total external standard capacitance of decades plus terminals, adaptors, and connecting cables (refer to para 5.2.3.3).
- b. Multiply total external capacitance in pf by reading of MULTIPLY EXT STANDARD BY. . . switch (set at 1) and by M (1000 with C MAX at 1 μ f).
- c. Add reading of bridge CAPACITANCE decades in pf, with indicated decimal point.
- d. Divide by 10^6 to obtain unknown capacitance in μ f.
- e. To read bridge directly in μ f, decimal point is placed before first figure of bridge CAPACITANCE readout and:

- External decade of 0.1 μ f per step reads 100 μ f per step
- External decade of 0.01 μ f per step reads 10 μ f per step
- External decade of 0.001 μ f per step reads 1 μ f per step
- First bridge decade reads 0.1 μ f per step
- Second bridge decade reads 0.01 μ f per step

NOTE

The corrections for lead and terminal capacitance in the external decades may be equivalent to one or more steps in the first bridge decade, i.e., to tenths μ f in the unknown.

5.2.3.3 Measurement of Terminal and Cable Capacitance. To measure capacitance of terminals, adaptors, and cables:

- a. Remove unknown from bridge terminals.
- b. Set terminal selector to 2 TERMINAL.
- c. Set MULTIPLY EXT STANDARD BY. . . to 0.
- d. Set C MAX switch to 1 μ f.

e. Balance bridge; CAPACITANCE decades should read 000 001. This can usually be assumed within a few pf without measurement.

f. Set external decades to 0 or to minimum capacitance.

g. Switch MULTIPLY EXT STANDARD BY. . . to 0.1.

h. Set first CAPACITANCE decade to -1.

i. Balance bridge with other CAPACITANCE decades and with CONDUCTANCE decades.

j. Calculate external capacitance from

$$C_{EXT} \times 0.1 \times (M = 1000) + C_B = C_X$$

Example: Type 1419-B decade attached to EXT STANDARD terminals (with Type 874-Q9 Adaptor and Type 874-R22A Patch Cord). With open UNKNOWN terminals and EXT STANDARD terminals disconnected (internally), bridge reads 000 001. pf. With Type 1419-B decades set at 0 and connected to bridge, bridge reads (-1)85 144. pf.

$$C_{EXT} \times 0.1 \times 1000 = 000\ 001 - (-100\ 000 + 085\ 144) \\ = 014\ 857$$

$$C_{EXT} = 148.57\ \text{pf}$$

k. Add this lead and terminal capacitance to any reading of the external decades to obtain the total external standard capacitance.

5.2.4 RESOLUTION EXTENSION. When higher bridge resolution of capacitance or loss is required for measurement of very small changes, an external standard can be added to the bridge to provide a seventh decade of capacitance or a fifth decade of conductance.

5.2.4.1 Capacitance. The value of capacitance to be connected to the bridge as an external standard to provide a seventh decade above or below the six bridge decades is shown in Table 5-1. The decade adjustment is provided by the MULTIPLY EXT STANDARD BY. . . switch, which has a digital readout of 0, 0.1, . . . , 0.9; 1. When these steps of the added decade are read as 0, 1, . . . , 9, 10, the corresponding picofarads-per-decade steps are those shown in the two EXT columns to the left and right of the six bridge decades, with the appropriate decimal point shown.

Example: With C MAX at 1000 pf and a 0.001-pf capacitor connected as an external standard, the MULTIPLY EXT STANDARD BY. . . switch provides a seventh decade below the sixth lever and extends the bridge resolution to 0.0001 pf per step for capacitance as high as 1000 pf.

Use a three-terminal capacitor for the external standard. When the external capacitor provides the first figure in a balance to seven-figure resolution, it must have correspondingly high stability. For such stability, use

TABLE 5-1
CAPACITANCE RESOLUTION EXTENSION

C MAX SETTING	EXT STANDARD CAPACITANCE for 7th Decade above Bridge	CAPACITANCE READING in pf with all decades set at 1**							EXT STANDARD CAPACITANCE for 7th Decade below Bridge	
		E* X T	6 Bridge Decades							E* X T
1 μ f	10,000 pf	1	1	1	1	1	1	1	1	.001 pf
0.1 μ f	10,000 pf	1	1	1	1	1	1	1	1	.001 pf
0.01 μ f	10,000 pf	1	1	1	1	1	1	1	1	.001 pf
1000 pf	10,000 pf	1	1	1	1	1	1	1	1	.001 pf
100 pf	1,000 pf	1	1	1	1	1	1	1	1	.000 1 pf
10 pf	100 pf	1	1	1	1	1	1	1	1	.000 01 pf

* Reading of 0.1 in window of MULTIPLY EXT STAND BY . . . switch.

** Each individually can be any number from 0-9.

a sealed capacitor with a low temperature coefficient, preferably equivalent to the bridge standards. When the external capacitor provides the seventh figure, the capacitance is very small. High stability and accuracy are not required in the capacitor of this last decade.

Capacitors recommended as external standards are:

- 10,000 pf - Type 1615-P1 Range-Extension Capacitor
- 1,000 pf - Type 1404-A Reference Standard Capacitor
- 100 pf - Type 1404-B Reference Standard Capacitor
- 0.001 pf - Type 1403-V Standard Air Capacitor

The procedures are as follows:

a. Select capacitor on the basis of the above.

b. Measure capacitance of external standard by procedure described in para. 3.7.2.

c. Move the external standard capacitor to the bridge H and L coaxial EXT STANDARD terminals.

d. Connect unknown and balance bridge.

5.2.4.2 Conductance. The value of conductance to be connected to the bridge as an external standard to provide a fifth decade above or below the four bridge decades is shown in Table 5-2. The decade adjustment is provided by the MULTIPLY EXT STANDARD BY . . . switch, which has a digital readout of 0, 0.1, . . . , 0.9, 1. When these steps of the added decade are read as 0, 1, . . . , 9, 10, the corresponding micromhos per step are shown in the EXT columns to the left and right of the four bridge decades, with the appropriate decimal point shown in the line of digits.

TABLE 5-2
CONDUCTANCE RESOLUTION EXTENSION

G MAX SETTING	EXT STANDARD for 5th Decade above bridge			CONDUCTANCE READING in μ S with all decades set at 1					EXT STANDARD for 5th Decade below bridge		
	G	R	T	E* X T	4 Bridge Decades				E* X T	G	R _T **
+0.1 μ S	1 μ S	1 M Ω	0.	1	1	1	1	1	1	10 pS	10 Ω
+0.01 μ S	0.1 μ S	10 M Ω	.0	1	1	1	1	1	1	1 pS	1 Ω

* Reading of 0.1 in window of MULTIPLY EXT STANDARD BY . . . switch.

** See Figure 5.1 for use of R_T in T network.

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Example: With G MAX at $+0.1 \mu\Omega$ and a resistor of 1 megohm (equivalent to a conductance of $1 \mu\Omega$) connected as an external standard, the MULTIPLY EXT STANDARD BY. . . switch provides a fifth decade above the first bridge decade with a conductance of $0.1 \mu\Omega$ per step. The maximum unknown conductance which can be balanced is then $1 \mu\Omega$ multiplied by the factor M corresponding to the C MAX position used.

For a standard of 1 or $0.1 \mu\Omega$, use a deposited-carbon or metal-film resistor of 1 or 10 megohms with an accuracy of $\pm 1\%$. Mount the resistor in a shield to reduce the capacitance across it and the noise pickup. The Type 874-X Insertion Unit is a convenient shielded housing for the resistor and has coaxial terminals for connection to the bridge directly, and/or through Type 874 patch cords.

For standards of very small conductance, a T-network of resistors, as shown in Figure 5-1, must be used. The direct conductance G between the H and L terminals is

$$G = R_T / (AB + R_T A + R_T B)$$

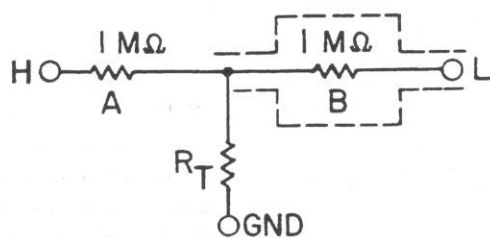


Figure 5-1. T-network for conductance standard.

When $A = B = 1$ megohm, the value of the resistance, R_T , and the corresponding conductance, G , is given in the right-hand columns of Table 5-2. Mount at least the resistor B, connected to the L or detector bridge terminal, in a shield to reduce capacitance and noise pickup. The Type 874-X Insertion Unit can be used to mount this resistor. Note that the error of the T-network conductance may be the sum of any errors in the resistances of R_T , A, and B.

a. Select conductance standard on the basis of the above.

b. Measure the resistance of all resistors used as the external conductance standard (with an ac or dc resistance bridge) and compute the conductance.

c. When the conductance is within the conductance range of the bridge, connect the conductance standard to the bridge UNKNOWN terminals and measure both conductance and capacitance. Follow procedures of para. 3.7.2. Refer to Table 4-1 for resistance and conductance ranges of bridge.

5.2.4.3 Negative External Conductance. When negative G MAX positions must be used to balance loss on the standard side of the bridge in excess of that on the unknown side, and the bridge conductance range or resolution is not adequate, add the external conductance standard in parallel with the unknown:

a. Connect external standard H terminal to UNKNOWN coaxial H terminal, or to H binding post, and connect the L terminal to bridge EXT STANDARD coaxial L terminal (same as connection to UNKNOWN coaxial L terminal).

b. Adjust external conductance for bridge balance by the use of a decade resistor as the external standard or by the use of a decade resistor as R_T in a T-network.

NOTE

The MULTIPLY EXT STANDARD BY switch cannot be used for decade adjustment of negative conductance.

5.2.5 COMPARISON OF EXTERNAL STANDARDS. The accurate calibration of one capacitor can be transferred to another with very small loss in accuracy by using the bridge to measure the capacitance difference between the two capacitors. This difference can be determined by measuring first the capacitance of one capacitor and then that of the other and subtracting, i.e., by a direct substitution of the uncalibrated capacitor for the calibrated one at the bridge UNKNOWN terminals. The difference can also be measured by connecting the calibrated capacitor to the bridge transformer as an external standard, and the uncalibrated as an unknown, and using the bridge decades to balance the capacitance difference, i.e., by a comparison using the transformer ratio arms. These methods can be used to increase calibration accuracy when the accuracy of the calibrated standard exceeds the 0.01% direct-reading accuracy of the bridge.

The possible error in the measurement of the unknown by the comparison technique is the sum of:

1. The error in the calibrated value of the external standard capacitor.
2. The error, $\pm(0.01\% + 0.00001 \text{ pf})$, in the reading of the bridge decades multiplied by the ratio of the decade reading to the unknown capacitance.
3. The error in the bridge transformer ratios, which is typically within ± 1 ppm for a ratio of 1, ± 10 ppm for ratios 2 through 10, ± 20 ppm for the ratios between 10 and 1000.

5.2.5.1 Direct or Equal Substitution. To calibrate a capacitor, A, by comparison with a similar calibrated capacitor, B, of nearly equal magnitude:

a. Connect capacitor A to the appropriate UNKNOWN terminals and measure its capacitance by the applicable procedure in para. 3.7.

b. Connect capacitor B to the same terminals and measure its capacitance. Do not change the setting used in step a for the first two or three bridge decades, if the balance can be made by the use of the (-1) or (X) positions of lower capacitance decades. Any errors in the bridge capacitors will cancel in the difference if the same decade has been used in both measurements.

Example: If the measurement of capacitor A was X00.003 pf and that of capacitor B was X00.(-1)85, the 1000-pf internal capacitor is used for the first decade but the 100-pf and 10-pf are not in use. The same balance could have been made with the bridge reading 999.985, and with all three internal capacitors a part of the balance. Since the measurement of capacitor A was made with the 1000-pf capacitor, any errors in this capacitor will cancel in the difference between A and B. When the 100- and 10-pf bridge capacitors are used for B, but not for A, their errors appear in the difference.

c. To obtain the capacitance of A, subtract the measured capacitance of B from that of A and add the difference to the calibrated value of B.

Example: The calibrated value of B is 1000.005 pf, the difference of the measurements above is X00.003 - X00.(-1)85 = .018 pf. The capacitance of A is 1000.023 pf.

NOTE

The capacitance of the bridge terminals does not have to be subtracted from the two readings of the bridge. When the same bridge terminals are used for both measurements, any terminal capacitance cancels in the difference. However, the calibrated value transferred from B to A is the capacitance added to the particular terminals used when the original calibration of B was made.

5.2.5.2 Comparison Using Transformer Ratio Arms. To calibrate a capacitor, A, by comparison with a calibrated capacitor, B, when the ratio of A/B is close to any integer from 1 to 10, multiplied by 1, 10, or 100:

a. Connect the capacitor, A, to the appropriate UNKNOWN terminals.

b. Connect capacitor, B, to the EXT STANDARD terminals. If B is much larger than A, connect B to the UNKNOWN terminals and A to the EXT STANDARD terminals.

c. Set C MAX and MULTIPLY EXT STANDARD BY. . . to the positions which make the product of M and the reading in the window as close as possible to the ratio A/B.

Example: The nominal capacitances are A = 5000 pf and B = 1000 pf, and A/B = 5. Set C MAX to 0.01 μ f, where M = 10, and set MULTIPLY EXT STANDARD BY. . . to read 0.5.

d. Balance the bridge with the CAPACITANCE and CONDUCTANCE controls.

e. Observe the capacitance of the unknown, A. It should equal the calibrated value of the standard, B, multiplied by M and the reading of the MULTIPLY EXT STANDARD BY. . . switch plus the reading of the bridge CAPACITANCE decades.

Example: Calibrated value of B is 1000.005 pf. C MAX set at 0.01 μ f (M = 10). MULTIPLY EXT STANDARD BY. . . reads 0.5. Bridge decades read 0003.14 pf. Capacitance of A is $1000.005 \times 0.5 \times 10 + 0003.14 = 5003.16$ pf.

5.2.6 BALANCE OF TERMINAL AND LEAD CAPACITANCE. The bridge can be made to read directly the capacitance added to terminals, or leads, by the use of external standard capacitors added to the bridge to balance the capacitance of the terminals and leads. This eliminates the need to subtract from the bridge reading the terminal, or lead, capacitance to obtain the added capacitance.

5.2.6.1 General Procedure.

a. Leave bridge terminals open; or with lead wires or cables connected to bridge terminals leave lead or jig terminals open; or with variable capacitor connected to bridge terminals set capacitor to chosen initial or zero point; or with decade capacitor connected to bridge terminals set capacitor to chosen initial or zero point.

b. Set all bridge CAPACITANCE decades to zero.

c. Balance bridge for capacitance with external variable capacitance connected to bridge EXT STANDARD terminals. Use MULTIPLY EXT STANDARD BY. . . switch to obtain multiplying ratios from 0.1 to 1, when needed.

d. Balance loss with external conductance or with bridge CONDUCTANCE decades.

e. Connect capacitor to be measured to terminals or leads, or change setting of variable capacitor to be measured.

f. Balance bridge with bridge CAPACITANCE and CONDUCTANCE controls. Do not change capacitance connected to EXT STANDARD terminals.

g. Read directly the capacitance added to terminals or leads from bridge CAPACITANCE indications.

5.2.6.2 External Standard Capacitors. Refer to para. 3.7 for connection procedures corresponding to the three measurement positions of the terminal selector. Use any combination of fixed and variable capacitors that will balance the bridge. Capacitors do not need to be calibrated. The external standard capacitance can

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be larger than the capacitance it balances on the unknown side, because it can be multiplied in steps from 0.1 to 1 by the MULTIPLY EXT STANDARD BY. . . switch.

1. Three-terminal measurements.

(Terminal selector set to 3 TERM or 3 TERMINAL)

Convenient capacitors are the calibrated, variable, three-terminal Type 1422 precision capacitors.

Capacitance in pf

Type	Max	Min
1422-CB	1100	50
1422-CC	110	5
1422-CD	11	0.5
	1.1	0.05

To use two-terminal external capacitors, such as Type 1422-D, for a three-terminal measurement:

a. Connect bridge EXT STANDARD L terminal with shielded cable to capacitor H or insulated terminal. (Type 874-Q9 Adaptor with Type 874-R20A Patch Cord is convenient.)

NOTE

Do not connect cable or adaptor shield (which is connected to the bridge ground) to either capacitor terminal.

b. Connect bridge EXT STANDARD H terminal to capacitor ground terminal (or case). Insulate case from bridge and other grounds, since bridge transformer voltage is connected to capacitor case.

c. Use MULTIPLY EXT STANDARD BY. . . switch, when required, to reduce the effective external capacitance to as little as one tenth that of the capacitor. Cable capacitance is excluded from the external standard capacitance.

2. Two-terminal measurements.

(Terminal selector set to 2 TERMINAL)

Convenient capacitors are the calibrated, variable, two-terminal Type 1422 Precision Capacitors:

Capacitance in pf

Type	Max	Min
1422-D	1150	100
	115	35

Cable or lead capacitance adds to the total external standard capacitance. Typical capacitance of Type 874 Patch Cords is 90 to 100 pf. Use similar cables to the unknown and to the external standard to balance most cable capacitances.

Avoid the use of flexible cable and unshielded leads when capacitance changes of less than 1 pf are important; the capacitance of cable and leads may change with position. Use rigid connections or three-

terminal measurements for accuracy in small capacitance.

To balance terminal capacitance less than 10 pf:

a. Use for partial balance the terminal and wiring capacitance of the bridge EXT STANDARD terminal (about 6 pf), multiplied by the ratios of the MULTIPLY EXT STANDARD BY. . . switch.

Example: The terminal capacitance at the open-binding-post UNKNOWN terminals of the bridge (about 1.3 pf) can be partially balanced by the 6-pf EXT STANDARD terminal capacitance multiplied by the 0.2 position of the switch.

b. Add capacitance to the terminals, or leads, on the unknown side of the bridge, when the minimum of external-standard capacitance cannot be reduced enough for balance. To add bridge standard capacitance to the unknown side, set first CAPACITANCE decade to (-1) position and other decades to 0. Balance augmented lead capacitance with external standard capacitors. Then, with first decade left in (-1) position, balance with remaining five CAPACITANCE decades the capacitance added to the leads.

NOTE

Do not use low-capacitance, three-terminal capacitors, such as Types 1422-CC or -CD, as two-terminal external standards. The two-terminal capacitance is the calibrated, small, direct capacitance plus the capacitance from the high terminal to case, which is much larger and has less range of variation.

5.3 CALIBRATION OF TWO-TERMINAL CAPACITORS. AT ENDS OF CABLES.

5.3.1 TWO-TERMINAL-BRIDGE METHOD. To measure two-terminal capacitors, such as the Type 1419 Decade Capacitors and the Type 1422 Precision Capacitors, which cannot be plugged directly into the bridge terminals:

a. Set the bridge terminal selector to 2 TERMINAL.

b. Connect the bridge binding posts to the capacitor posts with appropriate coaxial patch cords and adaptors. (Use Type 874-Q9 Adaptor to connect to Type 1422 Capacitors.)

c. Measure the total capacitance of capacitor plus cables and adaptors.

d. Remove the capacitor from the connector at the end of the cable.

e. Measure the capacitance of the cable and adaptors with the cable terminals open.

f. Subtract this cable or lead capacitance from the total to obtain the capacitance added by the capacitor.

g. Alternatively, balance the capacitance of the cable with an external-standard capacitor to make the bridge read zero when the cable terminals are open. The bridge then reads directly the capacitance added by any capacitor connected to the cable terminals. Refer to para. 5.2.6 for use of external standards to balance lead capacitance.

NOTE

Cable or lead capacitance must not change between or during measurements, for accurate measurement of added capacitance. The capacitance of typical coaxial cable may vary by the order of 0.01 to 0.1 pf when the cable is moved. When capacitance errors of this order are important, as in the calibration of Type 1422 Precision Capacitors, use rigid connections, or use the three-terminal-bridge method described below.

5.3.2 THREE-TERMINAL-BRIDGE METHOD. To measure two-terminal capacitors, such as Types 1419 and 1422, at the end of cables (with the cable capacitance and its variations excluded by a three-terminal connection):

- a. Set the bridge terminal selector to 3 TERM.
- b. Connect to the capacitor terminals the connector normally used, or specified, for two-terminal calibration (such as the Type 874-Q9 Adaptor for the Type 1422 Precision Capacitors). Connect the ground (or shield) terminal of the adaptor to the ground (or low terminal, or case) of the capacitor, and the insulated terminal of the adaptor to the insulated (or high) terminal of the capacitor.

c. Connect a coaxial cable to the bridge coaxial L UNKNOWN terminal in the usual manner, with cable shield connected to the outer conductor of the bridge connector.

d. Connect only the inner lead of this coaxial cable to the center (insulated) terminal of the adaptor which has been attached to the capacitor.

e. Leave a small, insulated gap between the shield of the coaxial cable and the connector shield. The gap should be made small (1/16-inch or less) to avoid a leak in the shielding around the inner conductor. The insulation resistance across the gap need be only high enough to avoid loading the bridge transformer (1 megohm or more). The shields and center conductor in the vicinity of the gap must be fixed in position so that the internal capacitances remain constant.

NOTE

To make this connection with an insulated gap in the shield, the components shown in Figure 5-2 can be used. Plug the binding post of a Type 874-MB Coupling Probe into the banana plug of a Type 874-Q9 Adaptor. Unscrew the head of the binding post to adjust its length until probe and adaptor fit tightly together with a gap of about 1/16-inch between their shields. For additional mechanical rigidity, wrap the gap with electrical tape. Connect one end of this assembly to the other Type 874-Q9 Adaptor, which is connected to the capacitor, and the other end to the coaxial cable.

f. Connect the bridge UNKNOWN H coaxial terminal or UNKNOWN H binding post to the shield of the

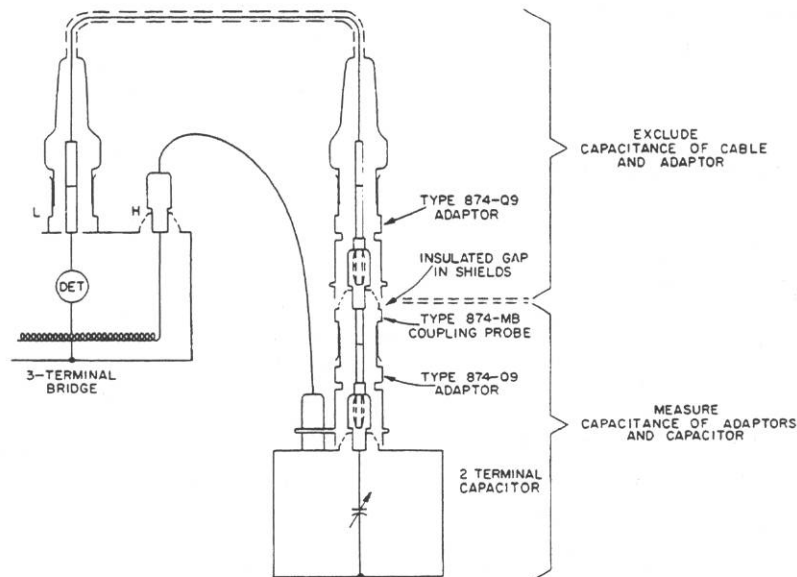


Figure 5-2. Connection for 3-terminal measurements on 2-terminal capacitors.

TYPE 1615-A CAPACITANCE BRIDGE

connector (Type 874-Q9) that is attached to the capacitor ground terminal. Insulate the capacitor case from any connection to the bridge ground or external grounds.

NOTE

The capacitances measured by the bridge are then, the capacitance within the capacitor from the high terminal to case and the capacitance within the connector from the center conductors to the outer shields as far up as the gap. The capacitances excluded are those from the cable center conductor to shields on the bridge side of the gap.

g. Measure the total capacitance of the capacitor plus the connectors.

h. Remove the capacitor from the connector and, with the lead from the H terminal of the bridge still connected to the connector shield, measure the capacitance of the open connector.

i. Subtract this connector capacitance from the total capacitance to obtain the capacitance added by the capacitor.

j. Alternatively, balance the connector capacitance with a three-terminal external-standard capacitor to make the bridge read zero when the connector is open. The bridge then reads directly any capacitance added to the connector. Refer to para. 5.2.6 for use of external standards in this application.

k. Use this three-terminal connection to exclude cable capacitance, and capacitance changes from any other measurement of two-terminal capacitance, where bridge ground can be isolated from capacitor ground.

5.4 APPLICATION OF DC BIAS TO UNKNOWN.

WARNING

- To minimize electrical shock hazard, limit bias to 60 V.
- Bias voltage is present at connectors, test fixtures and on capacitors under test.
- Capacitors remain charged after measurement.
- Do not leave instrument unattended with bias applied.

It should be noted that the instrument is rated to accept bias voltages up to 500 V rms or dc. However, to minimize the risk of electrical shock hazards, the use of biasing voltages of less than 60 V is highly recommended.

Dc biasing voltages may be applied in either of two ways to a capacitor that is being measured on the bridge.

CAUTION

Do not apply voltage at the bridge DETECTOR terminals in excess of the voltage, E_{MAX} , in Table 5-3.

5.4.1 NORMAL OPERATION. To apply bias in parallel with the detector, use the following procedures:

a. Connect the bridge for normal operation, but add the dc bias supply in parallel with the detector, as shown in the circuit of Figure 5-3.

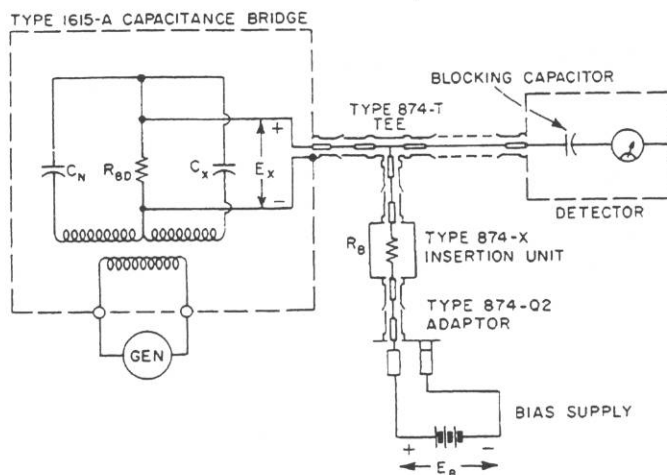


Figure 5-3. Circuit for applying bias to an unknown.

b. Shield all leads connected to the high side of the detector. Use a Type 874-T Tee connector for convenient parallel connection of bias.

c. Connect a series capacitor between detector input and bias supply to block bias voltage from the input stage. (This capacitor is usually built into the detector input stage.)

d. Connect a series resistor, R_B , between the high detector lead and the bias supply to prevent the low impedance of the bias supply from shorting the detector input. A resistance of about 100 kilohms will usually suffice. Lower resistance reduces the detector sensitivity; higher resistance reduces the dc voltage across the unknown since

$$E_X = \frac{E_B R_{BD}}{R_B + R_{BD}}$$

TABLE 5-3
MAXIMUM VOLTAGE AT BRIDGE DETECTOR TERMINALS

TERMINAL SELECTOR POSITION	G MAX-D MAX CONTROL SETTING	R_{BD} OHMS	E_{MAX}^* VOLTS
CAL, 3 TERM, 3 TERMINAL	D	>10 M	500
	G	100 k	150
2 TERMINAL	D	1 M	500
	G	90 k	150

* Dc or rms ac.

Refer to Table 5-3 for the bridge resistance, R_{BD} , at the DETECTOR terminals.

e. Install a shield such as a Type 874-X Insertion Unit around the resistor.

NOTE

Use a choke in place of R_B for high impedance, when low dc voltage drop is needed but shield the choke from both magnetic and electrostatic pickup.

f. Connect the bias power supply, or battery, between R_B and the outer conductor of the DETECTOR terminal of the bridge, which is also connected to the bridge case and ground. Either polarity of dc bias can be applied to the bridge. Connect the supply to apply the polarity required by the capacitor being tested.

5.4.2 REVERSE OPERATION. To apply bias in series with the generator, use the following procedure:

a. Connect the bridge for operation with reversed generator and detector. Refer to para. 5.5.

b. Connect the dc bias supply, or battery, in series with the ac generator. Use, for example, the Type 1265-A Adjustable DC Power Supply, which is designed for series connection to Type 1308-A Audio Oscillator and Power Amplifier.

5.4.3 DIRECT CURRENT IN TRANSFORMER.

When the capacitor (C_X , that is measured with bias by either of the preceding methods) has leakage resistance, a direct current will flow through one of the bridge ratio transformers. This current will magnetize the core and affect the accuracy of the ratios, and such use generally is not recommended. It is, however, possible to operate the bridge with some dc in the transformers, if the total current (dc plus peak ac) is kept below the values shown in Table 5-4 to avoid saturation of the cores. Operation within these limits will not damage the bridge, but the transformers should be demagnetized after such use to insure accuracy in normal operation.

To demagnetize, set 1311 generator frequency to 100 Hz, MAX OUTPUT to 10-V range, and make connections to bridge "normal". Set the C MAX switch to 1000 pF. Turn generator OUTPUT LEVEL control up fully cw and return it slowly to zero (ccw). If magnetization occurred while C MAX was set to 0.1 or 1 μ F, remove cabinet and reconnect generator between T102 pin 2 and pin 5 (ground); refer to para. 7.6; turn OUTPUT up and down, as before.

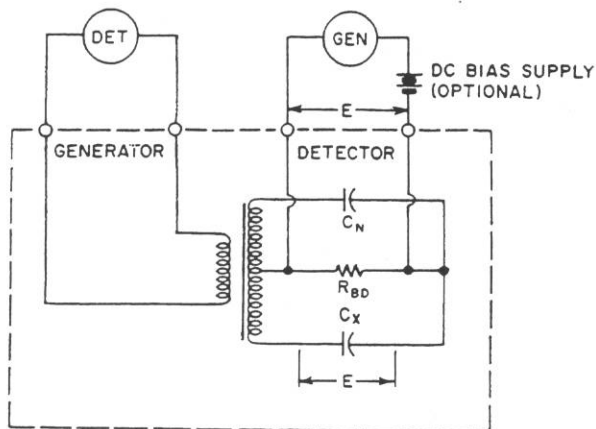


Figure 5-4. Bridge circuit with generator and detector reversed.

TABLE 5-4
CURRENT LIMITS FOR TRANSFORMER-CORE SATURATION

C MAX	I_{max}	TRANSFORMER
1 μ F	0.8 A	T102
0.1 μ F	0.08 A	T102
0.01 μ F	0.08 A	T101
1000, 100, 10 pF	0.008 A	T101

TYPE 1615-A CAPACITANCE BRIDGE

5.5 GENERATOR AND DETECTOR REVERSED.

5.5.1 GENERAL. The bridge may be operated with the generator connected to the bridge DETECTOR terminals and the detector connected to the bridge GENERATOR terminals (see Figure 5-4). Use reversed connection when higher-voltage operation is required and when lower sensitivity can be tolerated.

To apply higher voltage to the unknown capacitor than that permitted by the normal generator connection reverse operation must be used. In normal operation, the maximum voltage across the unknown capacitor is limited by transformer-core saturation and by transformer ratio to

$$E_{MAX} = \frac{30 \times (\text{freq in kc})}{M}$$

The factor M has the values of 10, 100, or 1000 as the C MAX control is changed from 1000 pf to 1 μ f.

In reversed operation, the maximum voltage is limited by power dissipation in bridge resistors, or by insulation breakdown, and depends upon the positions to which the terminal selector and D MAX-G MAX control are set. The maximum voltage, E_{MAX} , that can be applied to the DETECTOR terminals and to the unknown capacitors is given in Table 5-3.

With reversed operation the sensitivity of the

bridge balance is usually lower than that obtained with normal operation, but normal resolution may be retained as a result of the higher generator voltage that can be applied. When the detector is connected to the bridge GENERATOR terminals (hence, to the bridge transformers) the balance sensitivity is generally reduced by the mismatch between the low transformer reactance and the much higher capacitor reactance, particularly for frequencies below 1 kc and for capacitances below 1000 pf. For example, the capacitance unbalance that can be easily seen on the 1232-A Null Detector is of the order of ± 0.01 pF when the bridge is driven with 100 V at 50 Hz and ± 0.0001 pF for 100 V at 1000 Hz.

5.5.2 REVERSE OPERATION. To operate the bridge with reversed generator and detector:

a. Connect the generator to the bridge DETECTOR coaxial terminal. Use Type 874-Q2, or Type 874-Q9 Adaptors, or Type 874-R34 Patch Cord, for easy connection of coaxial terminal to binding posts.

b. Connect detector to bridge GENERATOR binding posts; shielding must be complete. Use Type 874-Q9 Adaptor to connect coaxial lead to binding posts. Type 874-R34 Patch Cord may be used, but the cable should be checked for leaks through the single-braid shield of this coaxial cable. Refer to para. 6.7.3.

c. Use normal procedures in Section 3 for bridge operation.

DIELECTRIC AND PERMITTIVITY REFERENCE MATERIAL

Impedance Measurement APPLICATION NOTE EID-11

A 16-page booklet that describes Dielectric Loss and Permittivity Measurements with GenRad Precision Capacitance Bridges.

The brochure is available at no charge through the GenRad Concord Facility.

GenRad, Inc.
300 Baker Avenue
Concord, Massachusetts U. S. A. 01742

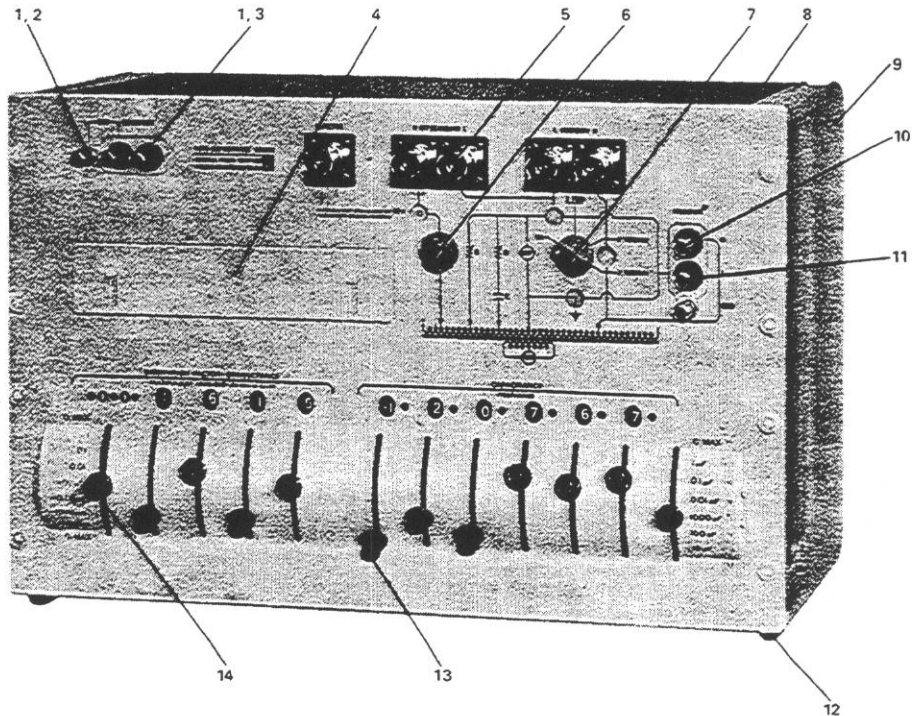
CHASSIS MOUNTED PARTS P/N 1615-3200

REFDES	DESCRIPTION	PART NO.	FMC	MFGR	PART NUMBER
C 100	CAPACITOR ASM	1615-2140	24655	1615-2140	
C 101	CAPACITOR ASM	1615-2150	24655	1615-2150	
C 102	CAPACITOR ASM	1615-2160	24655	1615-2160	
C 103	CAPACITOR ASM	1615-2100	24655	1615-2100	
C 104	TRIMMER CAPACITOR ASM	1615-2120	24655	1615-2120	
C 105	TRIMMER CAPACITOR ASM	1615-2120	24655	1615-2120	
C 106	TRIMMER CAPACITOR ASM	1615-2110	24655	1615-2110	
C 107	TRIMMER CAPACITOR ASM	1615-2110	24655	1615-2110	
C 108	TRIMMER CAPACITOR ASM	1615-2110	24655	1615-2110	
C 109	TRIMMER CAPACITOR ASM	1615-2130	24655	1615-2130	
C 110	TRIMMER CAPACITOR ASM	1615-2130	24655	1615-2130	
C 111	TRIMMER CAPACITOR ASM	1615-2130	24655	1615-2130	
C 201	CAPACITOR .01430 UF	0505-4023	24655	0505-4023	
C 202	CAPACITOR 0.1574 UF	0505-4024	24655	0505-4024	
C 203	CAP MICA 240 PF 5PCT 500V	4700-0521	81349	CM05FD241 JN	
C 204	TRIMMER CAPACITOR ASM	1615-2120	24655	1615-2120	
C 205	FACTORY SELECT				
C 206	FACTORY SELECT				
C 207	CAP CER TRIM 8-50 PF	4910-1170	72982	557-051 E 8-50PF	
J 101	BINDING PCST ASM	0938-3000	24655	0938-3000	
J 102	BINDING PCST ASM	0938-3000	24655	0938-3000	
J 103	BINDING POST ASM	0938-3000	24655	0938-3000	
J 104	OUTER CONDUCTOR ASM	0874-3700	24655	0874-3700	
J 105	PANEL CONNECTOR	0874-4170	24655	0874-4170	
J 106	OUTER CONDUCTOR ASM	0874-3700	24655	0874-3700	
J 107	OUTER CONDUCTOR ASM	0874-3700	24655	0874-3700	
J 108	PANEL CONNECTOR	0874-4170	24655	0874-4170	
J 109	BINDING POST	0938-4000	24655	0938-4000	
J 110	BINDING PCST	0938-4000	24655	0938-4000	
J 111	BINDING POST	0938-4094	24655	0938-4094	
R 201 thru	RESISTOR UNIT	1615-2290	24655	1615-2290	1 UNIT, 10 SECTIONS
R 210 thru	RESISTOR UNIT	1615-2290	24655	1615-2290	1 UNIT, 10 SECTIONS
R 211 thru	RESISTOR UNIT	1615-2291	24655	1615-2291	1 UNIT, 10 SECTIONS
R 220 thru	RESISTOR UNIT	1615-2291	24655	1615-2291	1 UNIT, 10 SECTIONS
R 221 thru	RESISTOR UNIT	1615-2292	24655	1615-2292	1 UNIT, 10 SECTIONS
R 230 thru	RESISTOR UNIT	1615-2292	24655	1615-2292	1 UNIT, 10 SECTIONS
R 231 thru	RESISTOR UNIT	1615-2293	24655	1615-2293	1 UNIT, 10 SECTIONS
R 240 thru	RESISTOR UNIT	1615-2293	24655	1615-2293	1 UNIT, 10 SECTIONS
R 241	RES CCMP 100 K 5PCT 1/4W	6099-4105	81349	RCR07G104J	
R 242	RES CCMP 1.0 M 5PCT 1/2W	6100-5105	81349	RCR20G105J	
R 243	RES COMP 100 K 5PCT 1/2W	6100-4105	81349	RCR20G104J	
R 244	POT CCMP KNOB 100 OHM 10 PCT LIN	6000-0050	01121	JAIN056S1 01 UZ	
R 245	RES FLX 100K 1/2 PCT 1/4W	6351-3100	81349	RN60D1003D	
R 246	RES FLX 100K 1/2 PCT 1/4W	6351-3100	81349	RN60D1003D	
R 247	FACTORY ADJUST				RESISTANCE WIRE
R 248	FACTORY ADJUST				RESISTANCE WIRE
S 101	SWITCH ROTARY ASM	7890-2800	24655	7890-2800	
S 102	SWITCH ASM	1615-3040	24655	1615-3040	
S 103	SWITCH ASM	1615-3040	24655	1615-3040	
S 104	SWITCH ASM	1615-3040	24655	1615-3040	
S 105	SWITCH ASM	1615-3040	24655	1615-3040	
S 106	SWITCH ASM	1615-3030	24655	1615-3030	
S 107	SWITCH ASM	1615-3030	24655	1615-3030	
S 108	SWITCH ASM	1615-3030	24655	1615-3030	
S 109	SWITCH ASM	1615-3030	24655	1615-3030	
S 110	SWITCH ASM	1615-3030	24655	1615-3030	
S 111	SWITCH ASM	1615-3030	24655	1615-3030	
S 112	SWITCH ROTARY ASM	7890-2810	24655	7890-2810	
S 113	SWITCH ROTARY ASM	7890-2820	24655	7890-2820	
S 114	SWITCH ROTARY ASM	7890-2830	24655	7890-2830	
T 101	TOROID COIL ASM	1615-3100	24655	1615-3100	
T 102	TOROID COIL ASM	1615-3090	24655	1615-3090	

MECHANICAL PARTS LIST

Qty	Fig Ref	Description	Fed Mfg Code	Fed Mfg Code	Mfg Part No.	Fed Stock No.
3	1	Binding post (center part), J101, J102, J103 GND.	0938-3000	24655	0938-3000	5940-075-9617
2	2	Metal spacer for binding post.	7800-0600	24655	7800-0600	
4	3	Insulator for binding post.	0938-7130	24655	0938-7130	
1	4	Access panel (over C-std trimmers).	1615-8030	24655	1615-8030	
5	5	GR 874 connector, J104, DETECTOR; J105 + J106, EXT STANDARD; J107 + J108, UNKNOWN.	0874-4170	24655	0874-4170	
1	6	Knob assembly (includes retainer 5220-5402), MULTIPLY EXT STD BY.	5500-5320	24655	5500-5320	
1	7	Knob assembly (includes retainer 5220-5402), terminal selector.	5500-5321	24655	5500-5321	
1	8	Cabinet (includes 5310-9678). For 1620 see below.*	4180-1708	24655	4180-1708	
		End frame set (includes both end frames and hardware).	5310-9678	24655	5310-9678	
	9	Right end frame (includes feet).	5310-7080	24655	5310-7080	
		Left end frame (includes feet).	5310-7081	24655	5310-7081	
1	10	Binding post (center part), J111, UNKNOWN H.	0938-4094	24655	0938-4094	
2	11	Binding post (center part), J109, UNKNOWN GND; J110, UNKNOWN L.	0938-4000	24655	0938-4000	
4	12	Resilient foot.	5260-0710	24655	5260-0710	
10	13	Switch handle, balance control (gray knob).	1615-0470	24655	1615-0470	
2	14	Switch handle, C MAX; D MAX (black knob).	1615-0471	24655	1615-0471	

# See Figure 1-1	Cabinet for 1620 assembly (includes 1 gasket, 2 filters).	4177-1620	24655	4177-1620
	Gasket (fits rim of front-panel group).	5331-2258	24655	5331-2258
	Filter (fits into vent opening, if any, at handle).	5270-3406	24655	5270-3406



Front view of bridge, showing mechanical replaceable parts.

Type 1615-P1

RANGE-EXTENSION CAPACITOR

(Accessory for the Type 1615-A Capacitance Bridge)



1 DESCRIPTION

The Type 1615-P1 Range-Extension Capacitor contains a hermetically-sealed, silvered-mica, 10,000-pf capacitor, equivalent in quality to the 0.01- μf Type 1409-L Standard Capacitor. Both capacitor terminals are General Radio Type 874 coaxial connectors, insulated from the case; they plug directly into the EXT STANDARD terminals of the Type 1615-A Capacitance Bridge. A variable trimmer capacitor of approximately 30 pf, connected in parallel with the mica capacitor, can be adjusted with a screwdriver, through a hole in the case, to set the capacitance to agree with the bridge standards, for either two- or three-terminal use.

This capacitor extends the range of the Type 1615-A Bridge upward to 11 μf . The bridge, with its largest standard of 1000 pf and largest transformer ratio of 1000:1, can measure unknown capacitors up to

1.11110 μf . When the 10,000-pf Type 1615-P1 capacitor is connected as an external standard, as shown in Figure 1, the range of the bridge is extended continuously through another decade to 11.11110 μf .

When the capacitor is plugged into the bridge EXT STANDARD terminals, the H terminal is connected to the transformer taps through the rotary MULTIPLY EXT STANDARD BY switch to provide a 1- μf -per-step seventh decade of capacitance adjustment above the six decades provided by the lever-switch balance controls. The L terminal of the capacitor is automatically grounded by the bridge to provide a two-terminal external standard when the bridge terminal-selector switch is set to the 2 TERMINAL position.

The Type 1615-P1 capacitor is adjusted at the factory to 10,000 pf ± 1 pf at 23 ± 1 C, when added to a production Type 1615-A bridge as a two-terminal external standard. The capacitance will vary with temperature, typically +35 ± 10 ppm/ $^{\circ}\text{C}$. The two-terminal capacitance may change as much as a few picofarad when used on different Type 1615-A bridges because of variations in bridge-terminal and wiring capacitances. The capacitance can, however, be quickly calibrated or adjusted to high precision for a particular bridge or for a particular temperature by the procedures described below. The three-terminal capacitance will be, typically, 9982 pf when the trimmer has been adjusted for two-terminal use.

NOTE

Although the Type 1615-P1 is fitted with the coaxial connectors usually associated with three-terminal capacitors, it is normally used as a two-terminal capacitor when connected to the Type 1615-A bridge to extend the range to 10 μf .

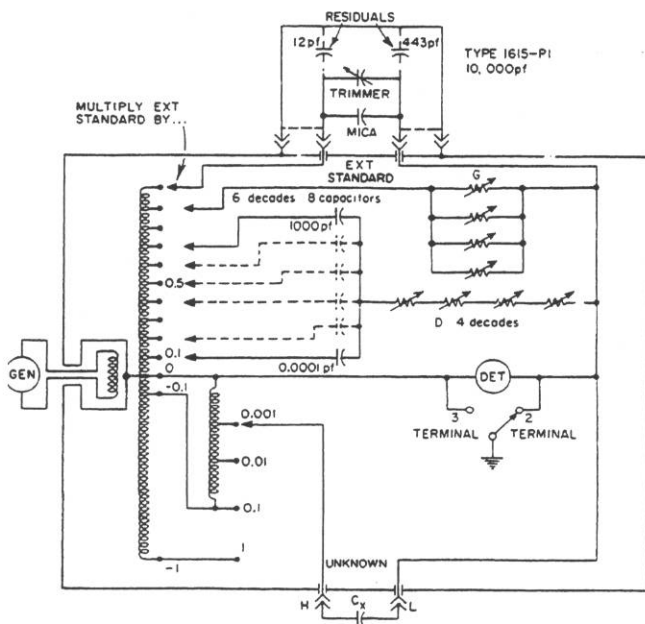


Figure 1. Elementary schematic diagram of Type 1615-A Capacitance Bridge with Type 1615-P1 Range-Extension Capacitor installed for two-terminal measurements.

2 OPERATING PROCEDURES

(Refer to Operating Instructions for Type 1615-A Capacitance Bridge.)

2.1 RANGE EXTENSION ON TYPE 1615-A.

a. Set the Type 1615-A bridge terminal-selector switch to the 2 TERMINAL position.

c. Connect the capacitor to be measured to the H and L UNKNOWN binding posts. (The L post is connected to the GND post.)

d. Balance the bridge.

1. For capacitance:

Set the C MAX control on the appropriate range (usually 1 μf). Adjust the MULTIPLY EXT STANDARD BY. . . switch for the first decade of C balance and the six CAPACITANCE controls for the subsequent decades.

2. For loss:

Set the G MAX control on the appropriate range, + or -. Adjust the four CONDUCTANCE controls for balance.

NOTE

The D MAX ranges may be used for balance in special cases when the G MAX range is not adequate. For computation of C and G when D MAX controls are used, see Type 1615-A bridge operating instructions.

e. Record the bridge readings of C and G.

f. The capacitance and conductance of the unknown are:

1. Capacitance: The unknown capacitance in picofarads is the capacitance of the Type 1615-P1 external standard (multiplied by the reading of the MULTIPLY EXT STANDARD BY. . . dial and by the factor M) plus the capacitance indicated by the six bridge CAPACITANCE readout dials, with decimal point as indicated.

Example: C MAX set at 1 μf (M = 1000)
MULTIPLY EXT STANDARD BY. . . dial reads 0.3
CAPACITANCE dials read 002140. pf
Capacitance of Type 1615-P1 is 10,000.00 pf.

$$C_X = 10\,000.00 (0.3 \times 1000) + 002140. = 3\,002\,140 \text{ pf} = 3.002\,140 \mu\text{f}$$

NOTE

It is convenient and correct to read the figures (0.1, 0.2, etc) in the window of the MULTIPLY EXT STANDARD BY. . . switch as the first digit of 1, 2, . . . etc, μf in the capacitance readout. Care must be taken, however, to interpret the figure 1 in the window as 10 or X in the readout, not as 1.

2. Conductance: The unknown conductance in micromhos is the conductance of the Type

DUCTANCE readout dials (multiplied by the factor M).

Example: C MAX set at 1 μf (M = 1000)
MULTIPLY EXT STANDARD BY. . . dial reads 0.3
CONDUCTANCE dials read .00420 μS
Conductance of Type 1615-P1 is .00478 μS

$$G_X = .00478 (0.3 \times 1000) + .00420 (1000) = 5.63 \mu\text{S}$$

3. Dissipation Factor: The dissipation factor can be calculated from the measured C (in farads) and G (in mhos) and the relation $D = G/\omega C$.

Example: For the 3 μf capacitor measured above at 1000 cps

$$D = \frac{5.63 \times 10^{-6}}{6.28 \times 10^3 \times 3.00 \times 10^{-6}} = \frac{5.63}{18.84} \times 10^{-3} = .000\,300$$

3 CALIBRATION OF TYPE 1615-P1

3.1 PROCEDURES FOR MEASUREMENT OF CAPACITANCE AND CONDUCTANCE.

a. Set the Type 1615-A terminal-selector switch to the 2 TERMINAL position.

b. Set the MULTIPLY EXT STANDARD BY. . . switch to 0.

c. Plug the Type 1615-P1 capacitor carefully into the EXT STANDARD coaxial terminals of the bridge, with the H and L terminals of the capacitor connected to the H and L terminals of the bridge, respectively.

d. Connect to the H and L UNKNOWN binding posts of the bridge any capacitor whose capacitance is close enough to 1000 pf (or to 0.01, 0.1, 1.0 μf) to be balanced with the first CAPACITANCE control (extreme left) set in the X position and with the C MAX control set at 1000 pf (or at the 0.01, 0.1, 1 μf position). The Type 1409-F or Type 1401-D, 1000-pf standard capacitors, are convenient to use, since they plug directly into the binding-post UNKNOWN terminals of the bridge.

e. Balance the bridge with the CAPACITANCE and CONDUCTANCE controls and with the appropriate G MAX range. Do not use the D MAX ranges. Use the (-1) position of CAPACITANCE controls when the capacitance of the unknown is less than nominal.

f. After balance has been reached, record the CAPACITANCE and CONDUCTANCE readings.

Example: With a Type 1409-F Capacitor as the unknown,

$$C = X01.054 \text{ pf} \quad G = .000864 \mu\Omega$$

g. Set the MULTIPLY EXT STANDARD BY. . . switch at 0.1 instead of 0. Set the extreme left CAPACITANCE control at 0 instead of X. The bridge should return to a partial balance, because the internal 1000-pf standard has been replaced by 0.1 times the external 10,000-pf standard.

h. To complete the balance:

1. Adjust the bridge CAPACITANCE controls to restore balance. Only the last two or three should need to be moved. The first control lever must be left at 0.
2. Adjust loss with the bridge CONDUCTANCE and G MAX controls.

i. Record the new readings of C and G.

Example: $C = 001.094 \text{ pf} \quad G = .000386 \mu\Omega$

j. The capacitance and conductance values of the Type 1615-P1 are:

1. Capacitance: The capacitance, C_{EXT} , can be calculated from the bridge readings of the unknown capacitance, C_X , (step f) and of the difference, C_B , (step i) between the unknown and the Type 1615-P1. The relation is:
$$C_{EXT} [0.1 \times (M)] + C_B = C_X$$

where M can be 1, 10, 100 or 1000.

Example: $C_{EXT} = (X01.054 - 001.094)/(0.1 \times 1)$
 $= 9\,999.60 \text{ pf}$

NOTE

The external standard C must be multiplied by the reading of the MULTIPLY EXT STANDARD BY. . . dial and by the factor M indicated next to the setting of the C MAX control.

A quick calculation can be made from the usual small changes in bridge readings in the following manner:

When the bridge C reading in step i is not the same as the reading of step f (except for the change from X to 0 in the first figure), the percent change in the bridge reading is the percent deviation of the Type 1615-P1 from exactly 10 times the internal 1000-pf standard. If the reading is high, the capacitance of the Type 1615-P1 is low.

Example: The bridge reads high by (001.094 - 001.054)/1000 = 40 ppm. The capacitance of the Type 1615-P1 is low by 40 ppm; hence

$$C_{EXT} = 9\,999.60 \text{ pf.}$$

2. Conductance: The conductance can be calculated from the conductance readings ob-

tained in step f for the unknown capacitor, G_X , and in step i for the difference between the unknown and the Type 1615-P1, G_B . The relation is:

$$G_{EXT} [0.1 \times (M)] + G_B = G_X$$

Example: $G_{EXT} = (.000864 - .000386)/(.1 \times 1)$
 $= 0.004\,78 \mu\Omega$

NOTE

The external standard G must be multiplied by the reading of the MULTIPLY EXT STANDARD BY. . . dial and by the factor M, indicated next to the setting of the C MAX control.

3. Dissipation Factor: The dissipation factor can, if needed, be calculated from the measured C and G using the relation $D = G/\omega C$.

Example: With the C and G measured above at 1000 cps

$$D = 0.000\,076$$

3.2 CALIBRATION EVALUATION.

From the calibrated value of capacitance and its difference from 10,000.00 pf, the value to be used for the bridge external standard capacitance can be chosen as follows:

a. If the error in the capacitance is small compared with the desired accuracy of the bridge measurement to be made with the Type 1615-P1, use the nominal capacitance of 10,000.00 pf in the calculation of unknown capacitance. In the example in step j of paragraph 3.1, the error of 40 ppm can be neglected when the measurement accuracy required is 0.1%, or even 0.01%. The dial of the MULTIPLY EXT STANDARD BY. . . switch can then be read directly as the first capacitance decade of 1 μf per step.

b. If the error is too large to neglect:

1. Use the measured value of the Type 1615-P1 capacitance in the calculation of the capacitance of the unknown. In the example above, use 9 999.60. . . pf.
2. Adjust the trimmer of the Type 1615-P1 to make the capacitance as close as desired to 10 000.00 pf and reduce the error to a negligible value. See paragraph 3.3 for adjustment procedure.

3.3 ADJUSTMENT OF TYPE 1615-P1.

a. Follow procedure of steps a through g of paragraph 3.1.

b. To complete the balance:

1. Adjust the capacitance with the trimmer of the Type 1615-P1 Capacitor. Remove the

snap-button at the end of the can and rotate with a screwdriver the exposed slotted shaft of the trimmer capacitor. The screwdriver does not have to be insulated, since the shaft is grounded. DO NOT change the setting of the bridge CAPACITANCE controls.

2. Adjust the loss with the bridge CONDUCTANCE and G MAX controls.

c. Record the new reading of G; the C reading must be the same, except for the change from X to 0 in the first figure.

Example: C = 001.054 pf G = .000386 $\mu\Omega$

d. The calibrated values of the type 1615-P1 are:

1. Capacitance: The capacitance has been adjusted to 10 times the capacitance of the 1000-pf standard in the bridge and has the same accuracy, nominally $\pm 0.01\%$, as that standard; hence

$$C_{EXT} = 10\,000 \text{ pf } \pm 0.01\%$$

2. Conductance: The conductance calculation is the same as in step j(2) of paragraph 3.1.

3. Dissipation Factor: The dissipation-factor is the same as in step j(3) of paragraph 3.1.

Type 1615-P2

COAXIAL ADAPTOR, GR900 TO BINDING POSTS

1615-P2 Coaxial Adaptor converts 2-terminal binding-post connection on 1615 bridge to GR900 Precision Coaxial Connector for highly repeatable connections; enables measurements with adaptor to be direct-reading by compensating for terminal capacitance.

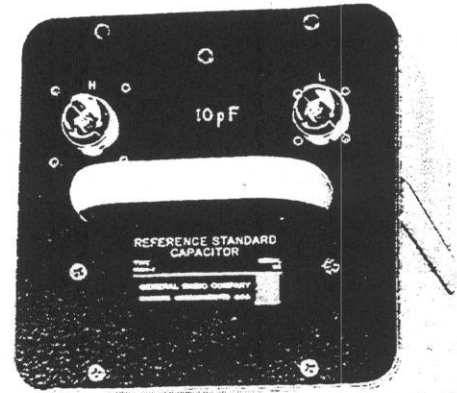
Catalog Number	Description
1615-9602	1615-P2 Coaxial Adaptor, GR900 to binding posts



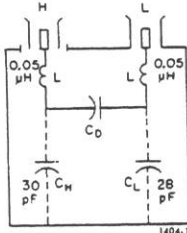
1615-P2

Type 1404

REFERENCE STANDARD CAPACITOR



These capacitors have been designed as primary reference standards of capacitance with which working standards can be compared. The 1615-A Capacitance Bridge is particularly well suited for this purpose and can be conveniently used to calibrate accurately a wide range of working standards in terms of a 1404 Reference Standard Capacitor. A single 1000- or 100-picofarad standard is also the only standard necessary to calibrate the bridge itself.



Equivalent circuit showing direct capacitance, C_0 , and average values of residual inductance, L , and terminal capacitances, C_H and C_L . $C_0 = 1000$ pF for 1404-A, 100 pF for 1404-B, and 10 pF for 1404-C.

In combination with an accurately known external resistor, this capacitor becomes a standard of dissipation factor.

All critical parts of the plate assembly are made of Invar for stability and low temperature coefficient. After heat cycling and adjustment, the assembly is mounted in a heavy brass container, which, after evacuation, is filled with dry nitrogen under pressure slightly above atmospheric and sealed. The container is mounted on an aluminum panel and protected by an outer aluminum case. Each capacitor is subjected to a series of temperature cycles to determine hysteresis and temperature coefficients and to stabilize the capacitance.

Two locking GR874 Coaxial Connectors are used as terminals. The outer shell of one is connected to the case, but the outer shell of the other is left unconnected to permit the capacitor to be used with an external resistor as a dissipation-factor standard.

— See *GR Experimenter* for Aug 1963 and Aug 1966.

Specifications

Calibration: A certificate of calibration is supplied with each capacitor, giving the measured direct capacitance at 1 kHz and at $23^\circ \pm 1^\circ\text{C}$. The measured value is obtained by a comparison to a precision better than ± 1 ppm with working standards whose absolute values are known to an accuracy of ± 20 ppm, determined and maintained in terms of reference standards periodically measured by the National Bureau of Standards.

Adjustment Accuracy: The capacitance is adjusted before calibration with an accuracy of ± 5 ppm to a capacitance about 5 ppm above the nominal value relative to the capacitance unit maintained by the General Radio reference standards.

Stability: Long-term drift is less than 20 parts per million per year. Maximum change with orientation is 10 ppm and is completely reversible.

Temperature Coefficient of Capacitance: 2 ± 2 ppm/ $^\circ\text{C}$ for 1404-A and -B, 5 ± 2 ppm/ $^\circ\text{C}$ for 1404-C, from -20°C to $+65^\circ\text{C}$. A measured value with an accuracy of ± 1 ppm/ $^\circ\text{C}$ is given on the certificate.

Temperature Cycling: For temperature cycling over range from -20°C to $+65^\circ\text{C}$, hysteresis (retraceable) is less than 20 ppm at 23°C .

Dissipation Factor: Less than 10^{-5} at 1 kHz.

Residual Impedances: See equivalent circuit for typical values of internal series inductances and terminal capacitances.

Max Voltage: 750 V.

Terminals: Two locking GR874 coaxial connectors; easily convertible to other types of connectors by attachment of locking adaptors. Outer shell of one connector is ungrounded to permit capacitor to be used with external resistor as a dissipation-factor standard.

Accessories Required: For connection to 1615-A Capacitance Bridge, 2 Type 874-R20A or 874-R22LA Patch Cords.

Dimensions (width x height x depth): $6\frac{3}{4} \times 6\frac{5}{8} \times 8$ in. (175 x 170 x 205 mm).

Weight: Net, $8\frac{1}{2}$ lb (3.9 kg); shipping, 14 lb (6.5 kg).

Catalog Number	Description
	Reference Standard Capacitor
1404-9701	1404-A, 1000 pF
1404-9702	1404-B, 100 pF
1404-9703	1404-C, 10 pF

