OPERATING INSTRUCTIONS

TYPE 1632-A

INDUCTANCE BRIDGE

1632

GENERAL RADIO COMPANY

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OPERATING INSTRUCTIONS

TYPE 1632-A

INDUCTANCE BRIDGE

Form 1632-0100-C
September, 1962

GENERAL RADIO COMPANY
WEST CONCORD, MASSACHUSETTS, USA

SPECIFICATIONS

Ranges of Measurement

Inductance: 0.0001 μh to 1111 h.

Conductance: 0.0001 μmho to 1111 mhos.

Accuracy

Inductance: ±0.1%, direct-reading. This accuracy is reduced at the extremes of the inductance, Q, and frequency ranges. The lowest inductance range (0.0001 to 111 μh) has a direct-reading accuracy of ±1%.

When the Q of the unknown is less than unity, the accuracy is reduced to $(+0.05 \pm Q_B)\%/Q_X$. Values of Q_B at 1 kc (the phase angles of the compensated R_B resistors) are given in the table.

Range	a, b, c	d-Low Z	d-High Z e-Low Z	e-High Z f-Low Z	f-High Z g	h
R_B	1 Ω	10 Ω	100 Ω	1kΩ	10 kΩ	100 kΩ
Q_B at 1kc	±.03%	±.005%	±.002%	±.002%	±.02%	±0.1%

For frequencies higher than 1 kc, the error can be determined from the above expression with the Q_B values multiplied by the frequency in kilocycles. There is an additional error of $0.1 \times 10^{-8} f^2\%$ on the lowest inductance range and of $4 \times 10^{-8} f^2\%$ on the highest range.

Two nearly equal inductors can be intercompared to a precision of one part in 10^5 or better.

The bridge adds approximately 1 pf to the capacitance across the inductor.

Conductance: ±1% direct-reading accuracy. This accuracy is reduced at the extremes of the L and G decades, of Q, and of frequency. The C_N capacitor decades are adjusted within ±(1% +2 pf).

When the Q of the unknown is greater than 10, the error, when the bridge reads either series resistance or parallel conductance, is increased to $Q_X(=0.05 \pm Q_B)\%$. See the table for values of Q_B at 1 kc.

For frequencies above 1 kc, the value of Q_B is multiplied by the frequency in kilocycles.

When the bridge reads series resistance, there is an additional error of $0.15\ Q_X\%$ at 1 kc and with the L decades set at one-tenth full scale ($R_N = 10$ kΩ). This error is proportional to frequency (with constant Q_X) and approximately proportional to the resistance (R_N) of the L decades.

Maximum Measurable Q: For series connection, proportional to frequency, 60 at 100 cps. For parallel connection, 80 at 100 cps and R_N of 100,000 ohms, inversely proportional to frequency and to R_N.

Maximum Safe Bridge Input Voltage: One volt on low-inductance ranges to 100 volts on high ranges. Values are engraved on the panel.

Accessories Required: Generator and detector. The Type 1304-B Beat-Frequency Audio Generator or the Type 1311-A Audio Oscillator or the Type 1210-C Unit R-C Oscillator with the Type 1206-B Unit Amplifier and the Type 1232-A Null Detector are recommended.

Accessories Supplied: One Type 274-NL Shielded Patch Cord for connection to generator, one Type 874-R34 Patch Cord for connection to detector, Type 1632-P1 Transformer to match low bridge-input impedances to generators which require a 600-ohm load.

Mounting: Aluminum cabinet and panel with end frames. Can also be relay-rack mounted.

Dimensions: Width 19½, height 16, depth 10½ inch (495 by 410 by 270 mm), over-all; depth behi 8½ inches (230 mm).

Net Weight: 40 pounds (18½ kg).

General Radio Experimenter reference: Volume 33, No. 11, November, 1959

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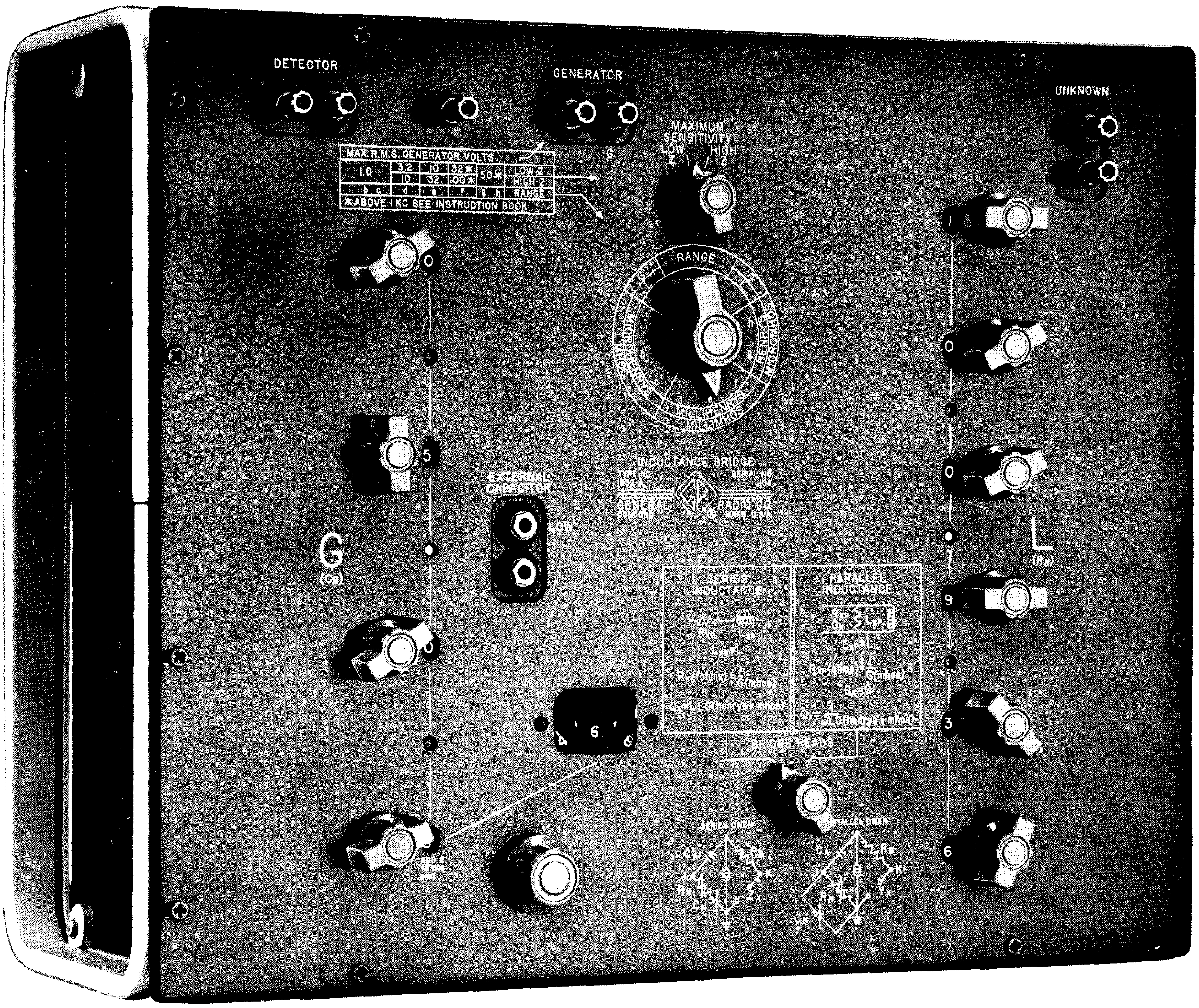

Figure 1. Type 1632-A Inductance Bridge.

TYPE 1632-A

INDUCTANCE BRIDGE

Section 1

INTRODUCTION

1.1 PURPOSE. The Type 1632-A Inductance Bridge (Figure 1) is an Owen impedance bridge designed for the convenient and precise audio-frequency measurements of inductances from 0.0001 microhenry to 1111 henrys. It replaces and in several respects is superior to the older Type 667-A Inductance Bridge.

The Type 1632-A Inductance Bridge is designed to measure the series components (Figure 2) of an unknown inductor: that is, its series inductance, L_{XS}, and its series resistance, R_{XS}, both of which are considered to carry the total current flowing through the inductor. The bridge can also be used to measure the parallel components (Figure 3), which are its parallel inductance, L_{XP}, and its parallel resistance, R_{XP}, or the corresponding conductance, G_X. Each of these parallel components is considered to sustain the full voltage applied to the inductor terminals.

From these data the impedance, Z_X, and the admittance, Y_X, of the unknown inductor can be computed, together with the trigonometric functions of its phase angle, such as its storage factor, Q_X, etc.

With this bridge, the unknown is measured as a two-terminal inductor having one of its terminals grounded.

Measurements of incremental inductance can be made at energy levels limited by permissible heat dissipation in the bridge arms.

SERIES OR PARALLEL INDUCTANCE?

Inductors are almost always described in terms of series inductance, and the BRIDGE READS switch should be set to SERIES INDUCTANCE for most routine measurements of inductance. Parallel inductance is significant in the analysis of ferromagnetic materials, and the PARALLEL INDUCTANCE position is useful in the evaluation of iron-cored inductors and transformers.

With very high- or very low-Q inductors, balance may be possible on only one position of the BRIDGE READS switch. Conversion to the other parameter may then be made by means of the transfer equation on page 8.

1.2 DESCRIPTION. The choice between bridge data for the series or the parallel components of the unknown is made by a three-position BRIDGE READS switch, located in the lower part of the panel, in accordance with the panel legend.

The eight positions of the RANGE switch, designated as a through h, permit a wide range of unknown inductance to be measured (refer to Table 1).

The a position of the switch, marked in orange, has less direct-reading percentage accuracy and is intended only for determining the internal residual

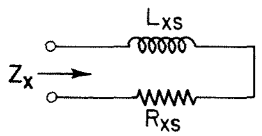

Figure 2. Series Components of an Inductor.

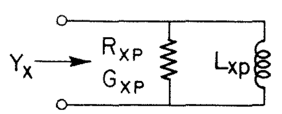

Figure 3. Parallel Components of an Inductor.

TABLE 1

RANGE Selector	Full Value Top L Decade	Full Value Bottom L Decade	Full Value Top G Decade	Full Value Bottom G Dial
a	100 μh	0.001 μh	1000 mhos	100 mmhos
b	1 mh	0.01 μh	100 mhos	10 mmhos
c	10 mh	0.1 μh	10 mhos	1 mmho
d	100 mh	1 μh	1 mho	0.1 mmho
e	1 h	10 μh	0.1 mho	0.01 mmho
f	10 h	100 μh	0.01 mho	0.001 mmho
g	100 h	1 mh	0.001 mho	0.0001 mmho
h	1000 h	10 mh	0.0001 mho	0.00001 mmho

inductance of the bridge or corrections for leads to small-valued inductors.

The bridge can thus indicate directly values of either L_{xs} or L_{xp} that are within the limits of 1111 henrys and 0.1 millimicrohenry. The directly readable values of the bridge conductance, G, are from a maximum of 1111 mhos to a minimum of 0.01 micromho. These are individual ranges, and the L and G extremes cannot be applied concurrently.

The RANGE switch mechanism shifts the decimal points in the L and G read-outs so that the numerical display is given directly, from top to bottom, in the units of the L and G parameters as designated by the RANGE switch legend.

Two independent controls are used for balancing the bridge. On the right-hand side of the panel are six decade switches that constitute the L balance control. Each switch has 11 positions reading consecutively 0, 1, ... 9, and X.

The X position corresponds to 10 units, and is numerically equivalent to one additional unit in the preceding decade. Thus an L balance setting of 8X5.0X3 corresponds to a numerical value of 905.103. When the bridge is balanced, the readings of these L balance controls (which are actually decade resistors) give directly the self-inductance value of the unknown, either L_{xs} or L_{xp}, in the units of inductance indicated by the RANGE selector legend.

The G balance control, on the left-hand side of panel, consists of four decade switches and a continuously adjustable dial (displaced out of line to the right), which is readable, by interpolation, to two digits. These controls are decade capacitors, and are calibrated to indicate directly the balance bridge conductance, G, in units indicated by the RANGE selector legend. The upper four decades of the G control are 11-position switches, reading consecutively, 0, 1, 2, ... 9, and X. The X position corresponds to 10 units, and is numerically equivalent to one additional unit in the preceding decade. The fifth decade is an air capacitor.

The use of the two-position SENSITIVITY switch in the upper center panel is discussed in paragraph 2.4.

Jack-top binding posts are provided for connecting the UNKNOWN inductor, the external ac GENERATOR, and the external null-balance DETECTOR as labeled, the red insulating cone indicating the high terminal of each pair. A single terminal between the GENERATOR and DETECTOR terminals may be used for connecting the bridge chassis to an external ground. Two jacks marked EXTERNAL CAPACITOR permit the upper range of the G balance control to be extended by the addition of an external capacitor. Refer to paragraph 2.7.

1.3 FREQUENCY CHARACTERISTICS OF AN INDUCTOR. It should be realized that any inductor has a certain effective or so-called "distributed" capacitance across its terminals. This means that the inductor itself is a resonant circuit and has a specific resonant or "natural" frequency determined by its two reactive parameters. Accordingly, the effective values of L_{xs} and L_{xp} are not fixed, but are functions of the frequency at which the inductor is energized and may depart substantially from their basic or dc values.

When an inductor is connected to any impedance bridge, the inductor's own distributed capacitance is augmented by the direct capacitance that exists across the unknown terminals of the bridge, plus the capacitance between the two connecting leads. Consequently, the bridge-measured parameters of the unknown may differ appreciably from the true values of the "free" unknown, especially when large inductances are measured at higher frequencies. Considerable care has been taken in the Type 1632-A Inductance Bridge to reduce this bridge-terminal capacitance, which loads the free inductor, to the smallest possible value (about 1.0μμf), and thus to eliminate, or at least minimize, a correction to the bridge-measured data (refer to paragraph 4.1).

When an inductor is energized at a frequency higher than its natural frequency (which may be only a few kilocycles for large values of inductance) it acquires a negative phase angle and functions, in reality, as a capacitor, so that it cannot be measured on an inductance bridge.

The loss parameters, R_{xs}, R_{xp}, and G_x of any inductor are likewise functions of the exciting frequency. At sufficiently low frequencies R_{xs} exceeds the dc resistance by only an insignificant amount, but as the frequency is raised, the effective ac resistance is increased by eddy currents in the winding and dielectric losses in the distributed capacitance. In an iron-cored inductor these losses are further increased by eddy currents and hysteresis in the core material.[1] The manner in which ac resistance increases with frequency causes any inductor to have a maximum phase angle and storage factor, Q_x, at some specific frequency.

1.4 ACCURACY OF MEASUREMENT. The L balance controls are calibrated to a tolerance of ±0.05 percent and the G balance controls are calibrated to ±1.0 percent. The bridge components chosen by the RANGE and SENSITIVITY switches are adjusted so that the

[1] "A New Decade Inductor" Horatio W. Lamson, GENERAL RADIO EXPERIMENTER, Vol 24, No. 2, July 1949.

product of the capacitance in the A arm and the resistance in the B arm has a tolerance of less than ±0.05 percent.

Consequently, for the direct measurement of an unknown inductor, an accuracy of ±0.1 percent may be expected for inductance values, and accuracy of ± 1 percent for resistance values. The tolerance of Q determinations will then be ± 1 percent plus the tolerance with which the operating frequency is known. These specifications are valid up to a frequency of about 5 kc. At higher frequencies the accuracy of direct measurements is reduced because of residual impedances in the bridge (refer to Section 4).

Much smaller tolerances for inductance comparison can be obtained by use of the direct substitution technique (refer to paragraph 2.13).

Section 2

OPERATING PROCEDURE

2.1 AC GENERATOR. Any adjustable ac generator having the desired frequency range and satisfactorily low harmonic waveform distortion may be used. The generator should include a means of adjusting the output voltage. If ac power mains are to be used for measurements at 50 or 60 cycles, an isolation transformer and an adjustable autotransformer, such as a Variac® autotransformer, should be inserted between the line and the bridge.

Adequate generator range and power for most bridge uses can be provided by the Type 1304-B Beat-Frequency Audio Generator, by the combination of Type 1210-C Unit RC Oscillator and Type 1206-B Unit Amplifier, or by the Type 1311-A Audio Oscillator.

Type 1632-P1 Impedance Matching Transformer. When low-valued inductors are measured with the RANGE selector set at positions a, b, c, or d, the input impedance of the bridge may be as low as the 1- or 10-ohm resistance of the ratio arm R_B. To obtain adequate voltage without distortion to drive the bridge from a generator having an output impedance higher than this, an impedance-matching transformer must be connected between the generator output and the bridge input. The Type 1632-P1 is supplied for this purpose and is designed to plug into the generator to keep the magnetic field of the transformer away from the bridge and from the inductor being measured. The OUTPUT terminals of the transformer marked 20:1, when connected by cable to the bridge input, provide an impedance step-up of 400:1, to match the 1 ohm of ranges a, b, or c to the generator. The terminals marked 5:1 provide an impedance ratio of 25:1, to match the 10 ohms of range d (low Z).

2.2 GENERATOR VOLTAGE LIMITATIONS. In order to avoid excessive heating of certain bridge components, it is necessary to stipulate definite maximum values of rms voltage permitted at the bridge GENERATOR terminals when the unknown inductor is connected to the bridge. Then, if the unknown inductor is disconnected, the voltage at the GENERATOR terminals may increase considerably above these specified limits. This is not detrimental to the bridge.

Maximum voltages are specified in a table engraved at the upper left of the bridge panel. This table is reproduced below.

Maximum voltage monitored at the bridge GENERATOR terminals is a function of the positions of both the RANGE selector and SENSITIVITY switches. In operation at a frequency of 1 kc or lower, the limiting rms values are designated by the legend on the panel. In operation above 1 kc, the panel legend also applies if the RANGE selector is in the a, b, c, d, or e position. In operating above 1 kc with the RANGE selector in the f, g, or h position, the maximum rms voltage values should be reduced in accordance with Table 2. Values given in the panel legend and in Table 2 are conservative.

PANEL LEGEND

MAX RMS GENERATOR VOLTS					
1.0	3.2	10	32*	50*	LOW Z
	10	32	100*		HIGH Z
a, b, c	d	e	f	g, h	RANGE
* Above 1 kc, refer to Table 2.					

TABLE 2

Switch Positions		Maximum RMS volts at			
RANGE	SENS	1 kc	5 kc	10 kc	20 kc
f	LOW Z	32	24	15	10
f	HIGH Z	100	74	43	29
g, h	Either	50	24	15	10

2.3 NULL DETECTOR. It is desirable, and imperative with iron-cored inductors, to employ a null detector having abundant selectivity at the chosen operating frequency. The sensitivity required depends on the precision with which it is desired to balance the bridge, i.e., the number of digits required in the unknown L_{xs} or L_{xp} value, subject to the permissible generator voltage. Even if it is logarithmic in its response, the null detector should include a control for monitoring gain so that the detector will not become overloaded when the bridge is badly out of balance. This might cause considerable confusion and render the preliminary bridge balance difficult and uncertain.

The requirements for a detector can be met by the Type 1231-B Amplifier and Null Detector with the Type 1231-P5 Adjustable Filter, followed by a null indicator with additional gain, such as a pair of headphones, an oscilloscope, a millivoltmeter, or another Type 1231-B Null Detector. For measurements requiring only the direct-reading accuracy of ±0.1%, a single Type 1231-B with filter is usually adequate.

A specially shielded transformer, with a step-down turns ratio of 3:1, is interposed between the bridge network and the DETECTOR terminals. This transformer permits direct grounding of the low terminal of the null detector. The capacitance (about 100 μμf) thus introduced across the A arm of the bridge is compensated for in the calibration of C_A. The transformer introduces practically zero residual capacitance across the B arm.

2.4 USE OF THE SENSITIVITY SWITCH. This switch should normally be kept in its LOW-Z position where bridge calibrations are most accurate. If the null detector has a very high (infinite) input impedance, it can be shown that the balance sensitivity of the bridge is maximum when the impedance of the unknown, at the operating frequency, is equal to the resistance, R_B, that constitutes the B arm of the bridge. When this switch is shifted from LOW-Z to HIGH-Z the value of R_B is increased tenfold and the value of the capacitor, C_A, which constitutes the A arm of the bridge, is reduced tenfold, so that the product $R_B C_A$ remains unchanged, except for small calibration errors. With air-cored inductors there will be only negligible changes in the setting of the L and G balance controls when the SENSITIVITY switch is shifted. With iron-cored inductors there may be a large change in the L and G balance settings owing to a change of the actual voltage at the terminals of the unknown.

In the interest of balance sensitivity at higher frequencies, it may occasionally be desirable to employ the larger R_B value obtained with the HIGH-Z position. This SENSITIVITY switch functions only in the midrange values of the RANGE selector, namely in the d, e, and f positions. In positions a, b, c, g, and h no change is made in either R_B or C_A when the SENSITIVITY switch is shifted.

2.5 SETUP OF EQUIPMENT. If the unknown inductor is nonastatic in character, so that it broadcasts a magnetic field when energized, it should be located far enough away from all metal objects, such as the bridge cabinet, to prevent induced currents from reacting on the unknown and giving false data. It must also be far enough away from the generator so that it does not pick up directly any significant magnetic field that might be broadcast from the generator. Extreme precautions should be taken in the measurement of nonastatic inductors at power-line frequencies, since most laboratories are permeated with an appreciable magnetic field at these frequencies. (This may be demonstrated by connection of a tuned null detector across the unknown.) Measurements at power-line frequencies, unless demanded, are best avoided.

Connect the unknown inductor, placed at the right of the bridge, to the UNKNOWN terminals. If one terminal of the unknown is grounded, or if one terminal has an inherently larger capacitance to ground, join this terminal to the UNKNOWN bridge terminal that is in contact with the bridge panel. For small-valued inductors, twisted insulated leads may be used to avoid, or at least minimize, a lead correction. For larger-valued inductors, and certainly for those in excess of 100 mh, nearly parallel bare leads should be used to minimize capacitive loading.

The generator and detector should be positioned so that there is no direct pickup between them. The generator should be placed far enough from the bridge so that, with the generator disconnected and the full-gain detector connected to the bridge, there will be no observable pickup by the (internal) shielded transformer that feeds the detector terminals.

Using the shielded concentric leads supplied, connect the ac generator and the null detector to the appropriate bridge terminals. taking care that the high lead of each goes to the red terminal. Keep the generator voltage at zero until ready to balance the bridge (refer to paragraph 2.8).

If it is desired to connect the whole system to an earth ground, such connection should be made at one point only, namely, at the terminal between the DETECTOR and GENERATOR terminals on the upper edge of the bridge panel. The equipment is now ready for operation.

2.6 USE OF THE RANGE SELECTOR. Whenever the RANGE selector is advanced by one position (for example from c to d), either the value of R_B or the value of C_A is increased tenfold so that the product $R_B C_A$ is increased by a factor of 10. For any given unknown the value of this product must be chosen so that the bridge may be balanced within the available ranges of the L and G balance controls and at the

TABLE 3

Range of L_{xs} or L_{xp} (6 digits)	Use RANGE Switch at
100 to 1000 h	h
10 to 100 h	g
1 to 10 h	f
100 mh to 1 h	e
10 to 100 mh	d
1 to 10 mh	c
100 μh to 1 mh	b
10 to 100 μh	a

same time provide the desired precision of the L balance control.

The settings of the RANGE selector that will permit the maximum precision (six digits) of the L balance readings with different ranges of inductance are indicated in Table 3.

Examination of Tables 1 and 3 reveals that the bridge cannot be balanced for series components if R_{xs} value is so small that R_{xs}/L_{xs} does not exceed a value within the limits of 9 and 90 ohms per henry (see Figure 4) unless the upper range of the G control is extended (refer to paragraph 2.7).

In using Figure 4 for a given inductance L_{xs} (abscissa scale), if the ratio R_{xs}/L_{xs} (ordinate scale) lies above the curve, then the series components (see Figure 2) can be measured directly. If the value of this ratio lies below the curve, the inductor must be measured in terms of its parallel components (see Figure 3). Then the series components may be computed, if desired, as described in paragraph 2.9.4. Note that the series bridge can be used at a given frequency if the ratio ω/Q_x exceeds a value between 9 and 90 ohms per henry; otherwise measurements must be made with the parallel bridge.

Six-digit readings of the L balance control are, of course, considerably beyond the absolute accuracy

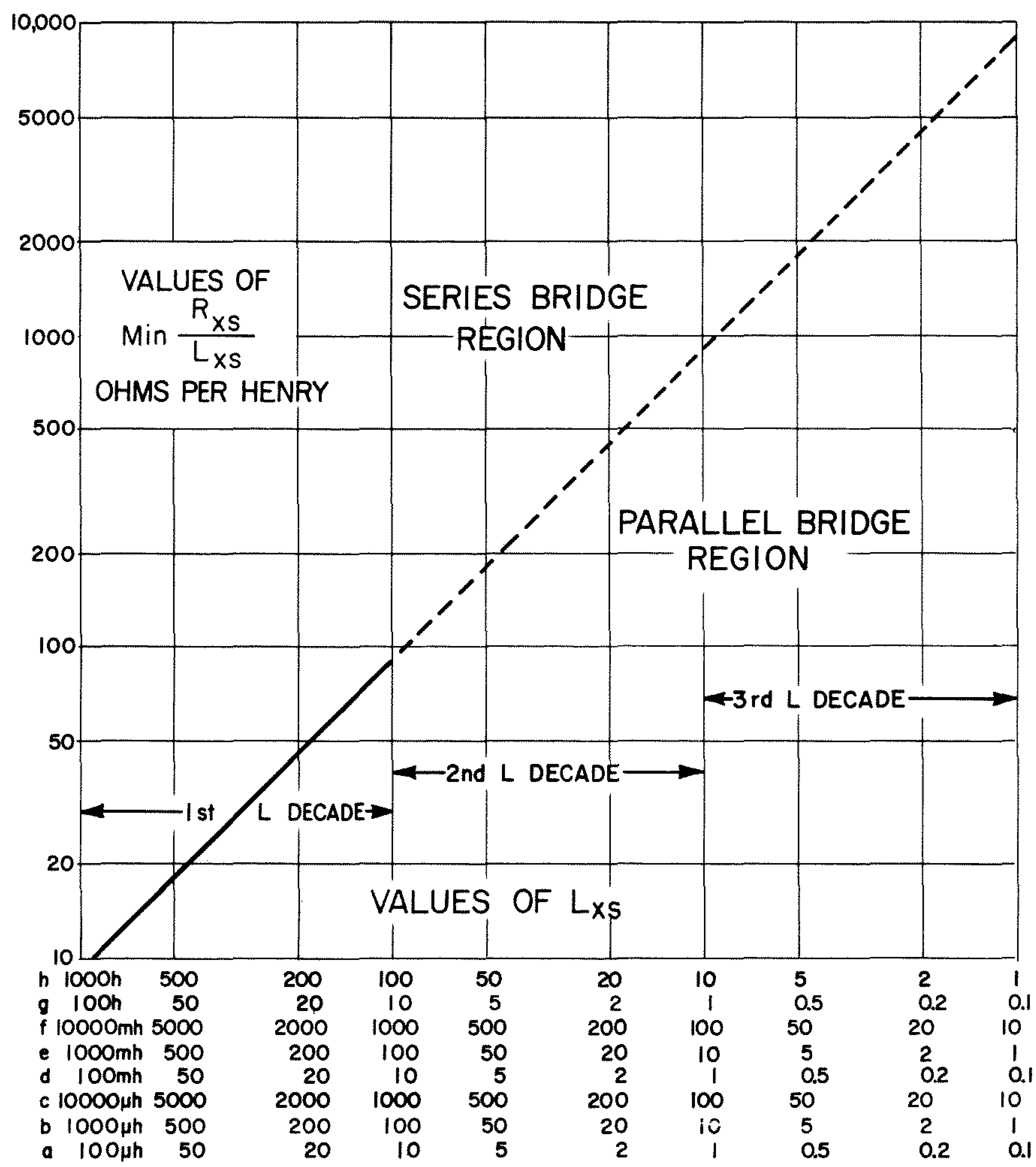

Figure 4. Operating Range of Type 1632-A Inductance Bridge for L_{xs} and L_{xp} Measurements.

of inductance calibration (± 0.1 percent) and thus are of no significance in a direct measurement of an unknown inductor. Readings to six digits may be used for a very precise intercomparison of two nearly equal unknown inductors. (Refer to paragraph 2.13.)

For maximum accuracy in direct L measurements, it is best to select the range which does not require use of the top L decade. Use of the top L decade can be avoided with inductors of less than 100h.

As the RANGE selector is retracted by one position, say from e to d, the first digit in the L balance advances into the next higher L decade, but, at the same time, the first digit in the G balance drops into the next lower G decade. (For instance, an L reading of X0.9364 for the d position becomes 100.936 as the RANGE switch is moved to e. At the same time, the G reading might change from 005.01 to 05.006.) In other words, as the possible precision of the L balance reading is increased, the corresponding precision of the G balance reading (and of the values for R_{XS}, R_{XP}, or G_X) is reduced. While the h position is demanded for inductances in excess of 111h, a compromise is usually desirable whereby the RANGE selector positions of Table 3 are advanced until the last desired digit in the L balance reading is obtained in the bottom L decade.

For example, if five, four, or three digits suffice for the unknown inductance values, the ranges would be given in Table 4.

TABLE 4

RANGES OF L_{XS} OR L_{XP}

RANGE Switch at	5 Digits	4 Digits	3 Digits
h	10 to 100 h	1 to 10 h	100 mh to 1 h
g	1 to 10 h	100 mh to 1 h	10 to 100 mh
f	100 mh to 1 h	10 to 100 mh	1 to 10 mh
e	10 to 100 mh	1 to 10 mh	100 μh to 1 mh
d	1 to 10 mh	100 μh to 1 mh	10 to 100 μh
c	100 μh to 1 mh	10 to 100 μh	1 to 10 μh
b	10 to 100 μh	1 to 10 μh	0.1 to 1 μh
a	1 to 10 μh	0.1 to 1 μh	0.01 to 0.1 μh

2.7 USE OF AN EXTERNAL CAPACITOR. In the measurement of the series components of a relatively low-resistance inductor with the RANGE switch set as directed in Table 4, the required balance value of the G control may exceed the full value of the top G decade. There are three possible remedies for this situation.

a. Retract the setting of the RANGE switch by one step, for example from e to d.

b. Without changing the RANGE switch setting, increase the upper range of the G control by adding a shielded, two-terminal capacitor (0.1μf or larger) across the EXTERNAL CAPACITOR jacks. This capacitor must have a small dissipation factor, as is obtainable with either mica or polystyrene dielectrics. The low terminal of this capacitor should be connected to the LOW jack on the panel. These jacks readily accept General Radio Type 1409 Standard Capacitors. If the value of L_{XS} only, but not of R_{XS} or Q_{XS}, is required, it is not necessary to know the value of the external capacitor. Otherwise the value of the external capacitor must be known, and the total value of the augmented G control must be computed on the basis that the full value of the top G decade (reading X) corresponds to a capacitance, C_N, of 1 μf. For example, suppose that the bridge is balanced with an external capacitor of 0.5002 μf, and with the top four G decades reading 8.547 (C_N = 0.8547 μf). The augmented value of the G control would then be:

8.547
5.002
13.549 units of conductance as designated by the RANGE selector legend.

Again, with an external capacitor of 1.0014 μf and the top four G decades reading 41.93 (C_N = 0.4193 μf), we have:

41.93
100.14
142.07 units of conductance as designated by the RANGE selector legend.

The external capacitor does not affect the L balance, provided that its dissipation factor is sufficiently small. Refer to Section 4.

c. The unknown can be measured in terms of its parallel components, and the series components then computed as described in paragraph 2.9.4. For a given position of the RANGE switch the balance setting of the G control will always be smaller for parallel than for series components, and much smaller for high-Q inductors.

If the setting of the RANGE switch gives too few digits in the G balance setting, the only remedy is to advance the RANGE switch setting (with a corresponding reduction in the available digits in the L balance reading).

2.8 BALANCING THE BRIDGE. It is assumed that the reader is familiar with the general operation of balancing any impedance bridge by the alternate adjustment of two controls to obtain a complete balance, indicated by the lowest obtainable response of the full-gain detector. A distinct advantage of the Owen bridge network (used in the Type 1632-A Bridge) in contrast with certain other inductance bridges, is that the Owen bridge gives basically no "sliding-zero" in its balance. This means that the L and G balance controls are virtually independent of each other, which greatly facilitates the dual balance operation.

With the equipment set up and connected in accordance with paragraph 2.5, proceed as follows:

a. Set the generator voltage to zero.

b. Set the BRIDGE READS switch to measure the series or parallel components of the unknown, as desired.

c. Set the MAXIMUM SENSITIVITY switch to LOW-Z.

d. If the approximate value of the unknown inductor is known, the RANGE switch may be set initially to give directly the desired number of digits in the inductance value in accordance with Table 4.

e. If the value of the inductor is unknown, set the RANGE switch to d or e. Then, if a preliminary balance indicates too few digits in the L balance control, move the RANGE switch until the last desired digit is read on the bottom L decade.

CAUTION

Always reduce the generator voltage to zero before shifting the RANGE selector.

f. Increase the generator voltage at the bridge terminals, keeping well within the limits specified on the panel legend, and make a preliminary balance of the bridge. Be sure that the null detector is not overloaded.

g. Increase the sensitivity of the null detector to maximum, and precisely balance the bridge with the limits of the bottom decades of both L and G controls. It is desirable to use only a minimum of generator voltage to permit a definite determination of the last desired digit in the L balance control. Maximum specified values should not be exceeded.

h. Record numerical readings of the two controls as the values L and G, with decimal points as shown, in the units indicated by the RANGE selector legend. If only the inductance of the unknown is desired, it is not necessary to record the reading of the G control, but both controls should be balanced completely.

i. In direct measurement of the series inductance of small-valued inductors, a correction for the leads to the unknown and/or the residual bridge inductance may be pertinent. To make this correction, short circuit the unknown directly at its terminals by a path of minimum possible length, and rebalance the bridge with the RANGE switch in position a. Subtract the L value so obtained (something in excess of 0.1 microhenry) from the previously measured L_{xs} value of the unknown with its leads. A corresponding correction for lead resistance is not practical.

In the measurement of the temperature coefficient of an unknown inductor, corrections for lead inductance between the bridge and a suitable thermal compartment housing the unknown are ordinarily not necessary, providing that the geometry of the lead path remains unchanged during the test. Thermal variations in the unknown may be determined from measured incremental changes in L_{xs} and corresponding temperature increments evaluated in terms of dc resistance measurements.

2.9 EVALUATION OF THE BASIC BRIDGE DATA.

2.9.1 GENERAL. The bridge is direct-reading in either the series or parallel inductance of the unknown, in the indicated units of inductance:

$$L_{xs} = L \leftarrow \text{(series)} \qquad (1)$$

$$L_{xp} = L \leftarrow \text{(parallel)} \qquad (2)$$

The over-all residual capacitance of the G control (when all five decades are set at zero) is in excess of the full value of the air capacitor, and has been internally augmented to a value corresponding exactly to two steps in the fourth G decade. If, in accordance with the panel legend, the actual reading of this fourth decade is increased by 2 units, the G control becomes direct reading in its true value. For example, with the RANGE selector in position d, an actual G reading of 097.42 has a true value of 97.62 millimhos.

2.9.2 SERIES COMPONENTS. When the series components of the unknown are measured, the series resistance is given by:

$$R_{xs\,(\text{in ohms})} = \frac{10^6}{G_{(\text{in }\mu\text{mhos})}} = \frac{10^3}{G_{(\text{in mmhos})}} = \frac{1}{G_{(\text{in mhos})}} \qquad (3)$$

The storage factor, Q_x, of the unknown inductor, which is defined as the tangent of its phase angle, may be computed as the numerical ratio:

$$Q_x = \tan\theta_x = \frac{\omega L_{xs}}{R_{xs}} = \frac{\omega LG}{10^6} \qquad (4)$$

In (4) use L_{xs} in henrys, R_{xs} in ohms, and ω in radians per second. Note that the last member of (4) gives Q_x directly in terms of the numerical readings of the balance controls with any position of the RANGE switch. Thus at 1 kc, $Q_x = 6.2832\ LG \times 10^{-3}$. For extensive measurements at a specific frequency, a double-entry table may be made to permit the direct evaluation of Q_x over appropriate ranges of L and G values.

2.9.3 PARALLEL COMPONENTS. When the parallel components of the unknown are measured, the unknown conductance is indicated directly in the indicated units of conductance:

$$G_{xp} = G \qquad (5)$$

The parallel resistance of the unknown is given by:

$$R_{xp\,(\text{in ohms})} = \frac{10^6}{G_{(\text{in }\mu\text{mhos})}} = \frac{10^3}{G_{(\text{in mmhos})}} = \frac{1}{G_{(\text{in mhos})}} \quad (6)$$

The storage factor of the unknown inductor may be computed as the numerical ratio:

$$Q_x = \tan\theta_x = \frac{R_{xp}}{\omega L_{xp}} = \frac{10^6}{\omega LG} \quad (7)$$

In (7) use L_{xp} in henrys, R_{xp} in ohms, and ω in radians per second. Note that the last member of (7) gives Q_x directly in terms of the numerical readings of the balance controls with any position of the RANGE selector. Thus at 1 kc, $Q_x = 159.155/LG$.

2.9.4 TRANSFER EQUATIONS. By means of the following transfer equations it is possible to compute the parallel components of the unknown inductor in terms of its measured series components, or vice-versa. It is first necessary to evaluate Q_x from (4) or (7); then:

$$L_{xp} = L_{xs}\left(1 + \frac{1}{Q_x^2}\right) \quad (8)$$

$$R_{xp} = R_{xs}\left(1 + Q_x^2\right) \quad (9)$$

Note that both of the parallel components must exceed the corresponding series components. However, for high-Q inductors (phase angles approaching 90 degrees), L_{xp} is only slightly larger than L_{xs}, but R_{xp} is much larger than R_{xs}.

2.10 MEASUREMENTS OF MUTUAL INDUCTANCE. The mutual inductance, M, which may exist between two inductors having individual series values L_{xs1} and L_{xs2}, or between two windings on a core, may be determined as follows: Connect the two windings in series with each other and measure the series inductance of this combination. Reverse the terminals of either one of these windings, and measure the series inductance of this second combination.

Let L_a be the larger of the two measured values (with the mutual inductance aiding), and let L_o be the smaller of the two measured values (with the mutual inductance opposing). The mutual inductance may then be computed as:

$$M = \frac{L_a - L_o}{4} \quad (10)$$

Obviously, M, L_a, and L_o must all be evaluated in the same unit of inductance.

The coefficient of coupling, K, between the two inductors or windings may then be computed as the ratio of the mutual inductance between them to the geometric mean of their individual self inductances:

$$K = \frac{M}{\sqrt{L_{xs1} L_{xs2}}} \quad (11)$$

2.11 MEASUREMENT OF IRON-CORED INDUCTORS. It should be clearly understood that a specified value of inductance for any inductor having a ferromagnetic (magnetically nonlinear) core is quite meaningless unless one specifies either the concurrent ac voltage across the inductor and the operating frequency, or the alternating current through the inductor. This is because the effective permeability of the core, and the corresponding inductance, may vary considerably with the induction (flux density) in the core. Starting from zero, the inductance will at first increase with rising excitation level to a certain maximum value and subsequently decrease as the induction in the core approaches a saturation value. This over-all variation of inductance will be less pronounced as the effective air gap in the core is increased.

Owing to the odd harmonics that are introduced by the nonlinear core, a high degree of selectivity is required in the null detector to permit precise bridge balance at the fundamental frequency. Leave the MAXIMUM SENSITIVITY switch in the LOW-Z position to minimize these harmonics.

Because of the limited precision with which the operating level can be determined and maintained, measurements of iron-cored inductors to a tolerance of less than 0.1 percent are impractical. The operating frequency must also be stabilized at a known value.

A distinct advantage of this bridge is the fact that, with a low-impedance generator, and a given setting of the RANGE switch, the voltage across the unknown inductor will not change appreciably when the L and G controls are adjusted to balance the bridge. Thus the operating level can be preset to any desired value.

Before measuring any iron-cored inductor, demagnetize the core by advancing the generator voltage to its maximum specified value and then reducing it progressively and slowly (over an interval of about three minutes) to a final zero value.

To determine the operating level, connect a high-impedance electronic voltmeter across the UNKNOWN terminals in parallel with the unknown inductor, to measure the applied voltage, E_x. (Waveform corrections to this measured value may be necessary at high inductions.) Remove this voltmeter while balancing the bridge, and recheck the voltage, E_x, after balance is accomplished.

The current I_x through the unknown inductor may be computed, in terms of its fundamental component, by the equation:

$$I_x = \frac{E_g}{\sqrt{(R_B + R_{xs})^2 + \omega^2 L_{xs}^2}} \qquad (12)$$

where Eg is the voltage measured at the GENERATOR terminals of the bridge and R_B is the existing value of the resistance in the B arm of the bridge (refer to Table 5).

TABLE 5

SENSITIVITY	RANGE	R_B (ohms)	MAX RMS I_x (ma)
LOW Z	b	1	1000
LOW Z	c	1	1000
LOW Z	d	10	300
LOW Z	e	100	100
LOW Z	f	1000	30
LOW Z	g	10,000	10
LOW Z	h	100,000	3

If data are desired for a plot of inductance versus operating level, starting with the demagnetized inductor, measurements should be made with progressively increasing values of E_x or E_g, keeping the same setting of the RANGE switch.

At very low induction levels, designated as the Rayleigh range, a ferromagnetic core has a linear permeability characteristic, so that L_{xs} is a linear function of excitation level. An important and definite parameter of an iron-cored inductor is its initial inductance, i.e., its inductance at zero level. Measurements of initial inductance require a highly sensitive null detector and an electronic voltmeter having the lowest available range and connected to measure E_g. Since harmonic components will be negligible, we may set the MAXIMUM SENSITIVITY switch to HIGH-Z. This will keep the induction in the core as low as possible for a given readable value of E_g.

Starting with a demagnetized core, make three or four measurements of L_{xs} with small and progressively increasing values of E_g, preferably equally spaced. A plot of these L_{xs}-versus-E_g data, to appropriate scales on linear graph paper, should yield a straight-line graph, if within the Rayleigh range. Extrapolation of this graph to a zero value for E_g gives the desired value of initial inductance.

It should be noted that data obtained in this section give the normal parameters L_{xs}, R_{xs}, and Q_x of an iron-cored inductor. To determine the magnetic parameters of the core material certain residuals must be removed as outlined in paragraph 2.14.

The only significant determination of the mutual inductance between two windings on a common ferromagnetic core is that corresponding to initial inductance values. Referring to paragraph 2.10, determine the initial values of L_a, L_o, L_{xs1}, L_{xs2}, and then substitute into equations (10) and (11).

2.12 MEASUREMENT OF INCREMENTAL INDUCTANCE. The Type 1632-A Inductance Bridge may be used to measure the incremental inductance, at low-energy levels, of an inductor having a ferromagnetic core in the presence of a dc polarizing current. It is not adapted to measure heavy-duty chokes at high dc and/or ac excitation levels.

It should be clearly understood that a specified value of incremental inductance is quite meaningless unless the concurrent values of both the ac current (refer to paragraph 2.11) and the dc biasing current flowing through the inductor are stated. Since both of these currents can ordinarily be measured with only limited accuracy, it is impractical to attempt to measure incremental inductance with a tolerance of less than 0.1 percent.

The series bridge should be used with the MAXIMUM SENSITIVITY switch in the LOW-Z position. Two methods will be shown, each of which has certain advantages. In both methods provision must be made so that no dc current can flow through the ac generator. A series-blocking capacitor can be inserted in the circuit between the generator and the red GENERATOR terminal of the bridge. At the operating frequency the reactance of this capacitor should be small compared with the resistance, R_B, of the bridge arm. The detector must have high selectivity.

In method A (see Figure 5), an external biasing circuit is connected across the UNKNOWN terminals in parallel with the unknown inductor. This circuit

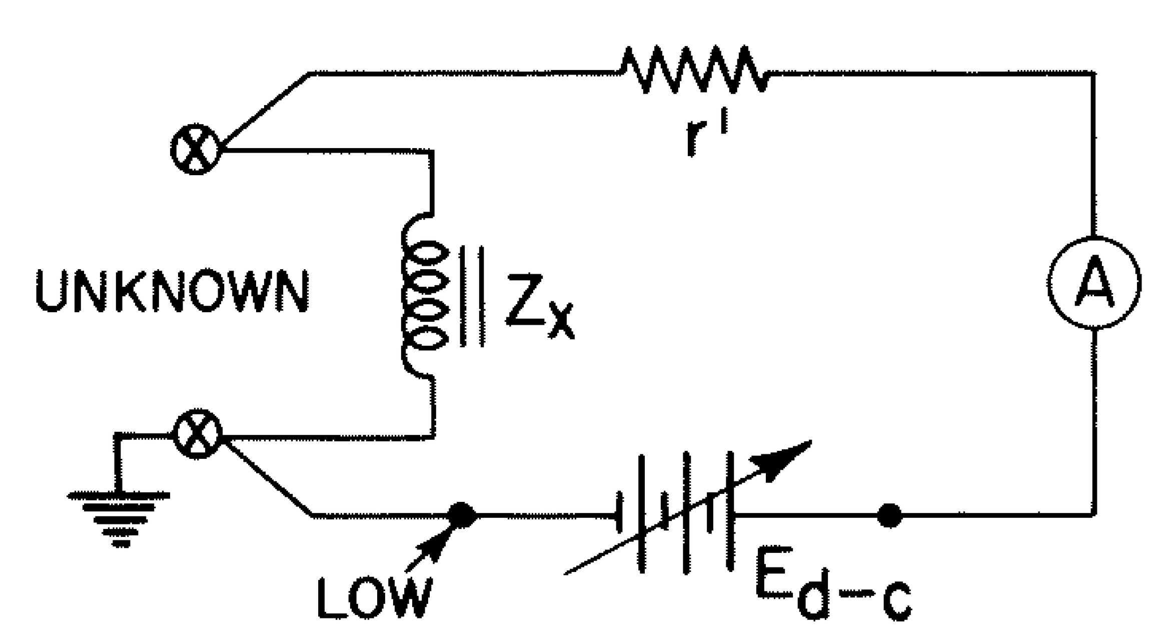

Figure 5. Biasing Circuit for Measuring Incremental Inductance - Method A.

contains a well-filtered adjustable source of dc emf, E_{d-c}, a suitable dc milliameter, A, for measuring the biasing current, and a fixed resistor, r', arranged in the manner shown.

The unknown inductor is thus measured with the biasing circuit shunted across it, so that a correction must be applied to the balanced bridge data to obtain the true incremental inductance of the unknown.

It is assumed that the impedance of the biasing circuit has a value r'+ j0 ohms. Then, if the incremental impedance of the unknown is $Z_X = R_{XS} + j\omega L_{XS}$, and if r' is made large enough so that $Z_X{}^2 \ll r'^2$, it can be shown that:

$$L_{xs} = L'\left(1 + \frac{2R_{xs}}{r'}\right) \tag{13}$$

where L' is the balance reading of the L controls. To evaluate the small correction term in equation (13) it is further assumed that $Z_X{}^2 \ll r'R_{XS}$, which gives:

$$L_{xs} = \frac{L'}{1 - \frac{2}{r'G'}} \tag{14}$$

where G' is the balance reading (in mhos) of the G controls.

In this method the biasing current is limited by the power rating of the resistor r', and the ac voltage applied to the bridge GENERATOR terminals must not exceed the limits specified in paragraph 2.2.

In method B (see Figure 6), the biasing circuit contains a choke coil in series with a suitable milliammeter, A, and a well-filtered, adjustable source of dc emf, E_{d-c}, connected across the GENERATOR terminals in the manner shown. The impedance of this biasing circuit need not be known, but it should be high enough to prevent overloading the ac generator. For a given biasing current, less E_{dc} will be required here than in method A.

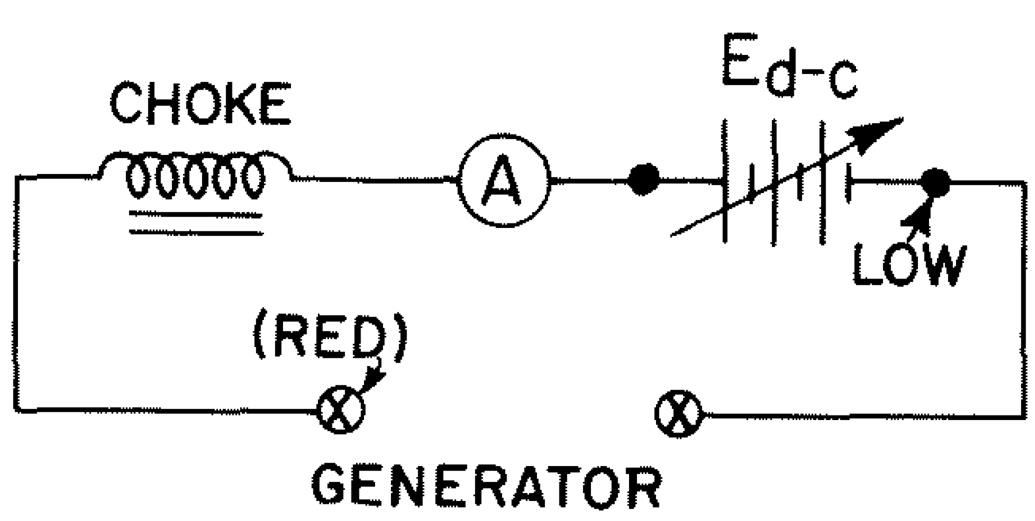

Figure 6. Biasing Circuit for Measuring Incremental Inductance - Method B.

No correction is necessary here, and the incremental inductance of the unknown is given directly by the bridge data at balance.

However, care must be taken in limiting the combined dc current, read on A, and the ac current, obtained from equation (12), since both currents must here pass through the R_B arm of the bridge, which has a maximum permissible rating of one watt. Thus the total rms value I' of these two currents should not be allowed to exceed the appropriate value shown in Table 5, under MAX RMS I_X. The value of I' may be computed by the equation:

$$I' = \sqrt{I_{dc}{}^2 + I_{ac}{}^2} \tag{15}$$

in which I_{ac} is the rms value of the ac current.

Whichever method is used, the biasing current does not change when the balancing controls are adjusted, which is a desirable feature of this bridge. Both the ac and dc voltage applied to the bridge should be reduced to zero before any change is made in the position of the RANGE switch, or before the unknown inductor is disconnected from the bridge.

Before balancing the bridge, establish the desired biasing current and electrically "shake" the core of the unknown inductor into a stable polarized condition as described in paragraph 2.11. If data are desired at various values of biasing current, i.e., at different points on the normal magnetization curve of the core material, such measurements are best made at ascending values of bias current, after stabilizing the core at each new bias level.

2.13 DIRECT SUBSTITUTION MEASUREMENTS. The accuracy of direct measurements is limited by the calibration accuracy of the bridge components (refer to paragraph 1.4) and by the effects of residual bridge impedances (refer to Section 4). In measurements made by the direct substitution method these errors are largely eliminated, so that two nearly identical inductors may be intercompared in inductance with an accuracy approaching a few parts per million. This is one of the important applications of the Type 1632-A Inductance Bridge.

Precise measurements demand a detector of high sensitivity, and the generator voltage must be kept as low as practical to avoid heating effects, chiefly resistance changes, in the measured inductor. This would produce an annoying drift in the balance settings of the G controls. Use of the top L decade is permissible here if six-digit data are desired.

Let L_{std} be a standard inductor whose absolute value is known accurately at the existing stabilized temperature and specified frequency. Let L_x be the unknown inductor to be calibrated in terms of L_{std}. Measure the small incremental difference between the two inductors as follows.

a. Connect L_{std} to the bridge and obtain a precise balance reading, L_s, on the dials.

b. Replace L_{std} with L_x, keeping exactly the same geometry of the connecting leads. Without changing the RANGE and MAXIMUM SENSITIVITY switch settings, obtain an equally precise second balance setting, L_u.

c. From these two direct measurements the value of the unknown will be:

$$L_x = L_{std} + (L_u - L_s) \tag{16}$$

Bridge errors associated with the product $R_B C_A$ and the unspecified lead inductance thus cancel in the measured differences $L_u - L_s$. It is important that as many as possible of the upper L decade controls remain in the same position for both of the two balances. Assume that the two balance readings were:

L_s = 199.492 mh

L_u = 199.507 mh

The difference, 0.015 mh, would be independent of any systematic calibration errors in the first three decades, but would be influenced by any systematic errors in:

1 step in the 4th decade
9 steps in the 5th decade
5 steps in the 6th decade.

On the other hand, had the two balance readings been:

L_s = 199.492 mh

L_u = 199.4X7 mh

any systematic errors in the first four decades would be eliminated, leaving only the systematic errors of

1 step in the 5th decade
5 steps in the 6th decade

to limit the accuracy of the same incremental difference, 0.015 mh.

Unless individual calibrations of the L decades are available and applied, the uncertainty with which the difference can be determined increases as the two inductors become less equal in their inductance values.

In such precise comparisons the absolute frequency of the generator must be known and maintained precisely, preferably at a value at which the standard inductor has been calibrated.

A further refinement in this substitution technique may be desirable if the two inductors have appreciably different Q values. This would result in different balance settings of the G controls, which would introduce different amounts of residual resistance of the G capacitors as unknown increments of the L controls, thereby reducing the accuracy with which the desired difference, $L_u - L_s$ can be determined. The remedy is to measure both inductors at the same Q level as follows:

aa. Introduce an adjustable resistor, R_s, of constant inductance into the LOW lead between the inductor and the bridge. Precise calibration of R_s is not required.

bb. Set R_s at zero value and measure first the inductor having the larger resistance value, by balancing the bridge with the L and G controls.

cc. With the second inductor replacing the first, make the second bridge balance using only the bridge L controls and advancing the value of R_s as required.

Since the G decade settings remained the same for both balances, their unknown residual resistance does not appear in the difference $L_u - L_s$. The G dial control (alone) may be changed in making the second balance, if desired, without introducing any appreciable error.

This "constant Q" method is employed at General Radio for calibrating the Type 1482 Standard Inductors after they are brought to a stabilized temperature indicated by their dc resistance values. The primary standard inductors have been calibrated in absolute inductance by the National Bureau of Standards. A primary frequency standard, known to closer than one part in 10^6, is used as the generator.

2.14 EVALUATION OF MAGNETIC CORE MATERIALS.

2.14.1 GENERAL. In use of the measured values of L_{xs} and R_{xs} to determine the actual magnetic properties of a ferromagnetic material used as the core of an unknown inductor (refer to paragraph 2.11), allowance must be made for two residual impedances, one representing losses in the winding and the other allowing for leakage inductance due to airborn flux.

It will be assumed that a continuous and homogeneous core having a uniform cross section of A sq cm and an effective flux path length of ℓ_1 cm can be inserted into a winding of N turns. Symbols and nomenclature used in this section concur with those standardized by the American Society for Testing Materials.[2]

First measure the series components of the winding alone, designated as R_w and L_w (ohms and

[2] ASTM PUBLICATION A-346-59: Alternating Current Magnetic Properties of Laminated Core Specimens (Standard Methods of Test).

henrys), in the regular manner. Since no iron is involved, this measurement can be made at any convenient level and at the frequency for which core data are desired. At low frequencies R_W will be only slightly, perhaps negligibly, in excess of the dc resistance value.

Then assemble the core into the winding and measure the series components of the ferromagnetic inductor, R_{XS} and L_{XS} (ohms and henrys), at some desired energy level. Compute the rms exciting current (I in amperes) in the winding from equation (12). This exciting current must not exceed the values specified in Table 5. It is important to use the minimum possible value of R_B to permit maximum exciting currents and to minimize harmonic distortion in the core.

The impedance of the inductor may be represented by Figure 7, where R_C and L_C are the series parameters of the core alone independent of the arbitrary residual parameters R_W and L_W of the winding. The differences of the measured value give:

$$R_c = R_{xs} - R_w \tag{17}$$

$$L_c = L_{xs} - L_w \tag{18}$$

To compute the true magnetic parameters of the core material it is necessary to convert R_C and L_C into their equivalent parallel components, R_1 and L_1, so that the impedance of the inductor is represented by the network of Figure 8.

To make this conversion, first compute the storage factor of the core material:

$$Q_c = \frac{\omega L_c}{R_c} \tag{19}$$

The last members of the following four equations (20 through 23) give approximations which may be valid for high-permeability, low-loss cores for which Q_C^2 is very large compared to unity.

The effective resistance representing losses in the core is:

$$R_1 = R_c(1 + Q_c^2) \approx Q_c^2 R_c \tag{20}$$

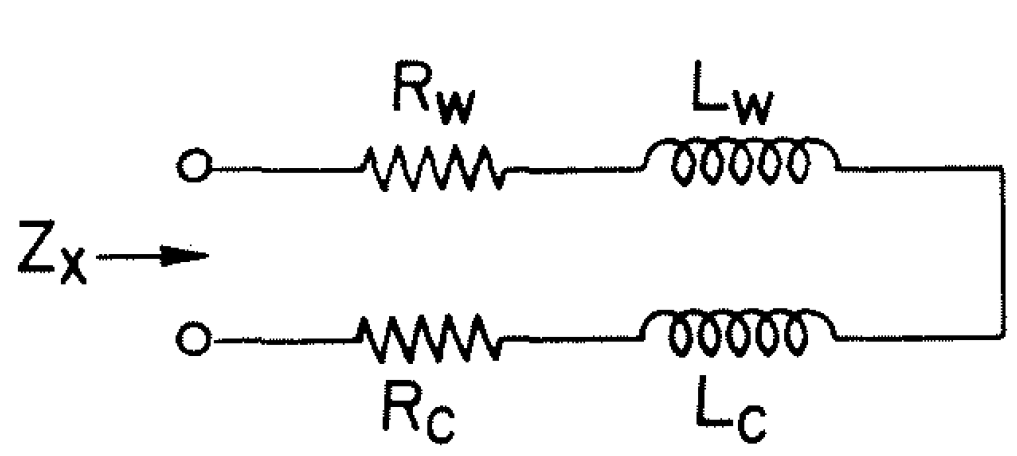

Figure 7. Separation of Winding and Core Parameters.

and the effective inductance due to the intrinsic flux in the core material is:

$$L_1 = L_c\left(1 + \frac{1}{Q_c^2}\right) \approx L_c \tag{21}$$

Note that the exciting current, I, divides into two quadrature components: the core-loss current, I_C, which determines the core losses, and the magnetizing current, I_m, which is responsible for the intrinsic induction in the core material. These two components are computed from the known exciting current as follows:

$$I_c = \frac{I}{\sqrt{1 + Q_c^2}} \approx \frac{I}{Q_c} \tag{22}$$

$$I_m = \frac{I}{\sqrt{1 + \frac{1}{Q_c^2}}} \approx I \tag{23}$$

The ac permeability from parallel inductance in the core material will be:

$$\mu_L = \frac{10^8 L_1 \ell_1}{0.4\pi N^2 A} \tag{24}$$

and the intrinsic peak induction (in gausses) existing in the core material will be:

$$B_i = \frac{L_1 I_m \sqrt{2} \times 10^8}{NA} \tag{25}$$

The corresponding peak magnetizing force in the core material (in oersteds) will be:

$$H = \frac{B_i}{\mu_L} = \frac{0.4\pi N I_m \sqrt{2}}{\ell_1} \tag{26}$$

The effective hysteretic angle of the core material, by which the exciting current leads its magnetizing component, will be:

$$\beta = \text{arc cotan } Q_c \tag{27}$$

The effective phase angle of the core material is the complement of β:

$$\delta = \text{arc tan } Q_c \tag{28}$$

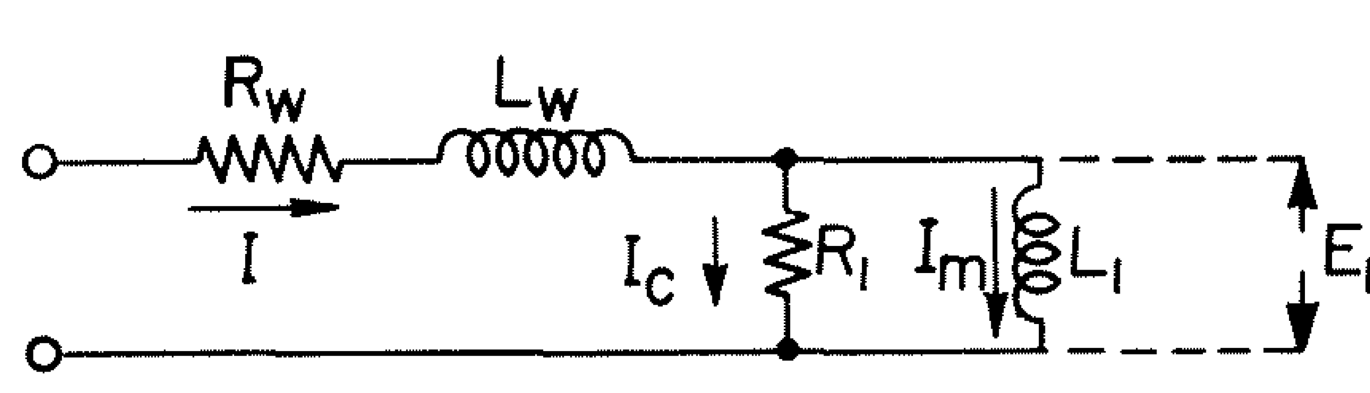

Figure 8. Network for Evaluating Parameters of Ferromagnetic Material.

The core-loss power, in watts, can be computed by:

$$P_c = I^2 R_c = I_c^2 R_1 \tag{29}$$

If the magnetic parameters of the core material are desired at various levels of excitation, the initial measurement of R_W and L_W need not be repeated unless the frequency is changed (refer to paragraph 2.11).

2.14.2 EPSTEIN TEST-FRAME MEASUREMENTS. Laminated electrical steel materials are extensively tested in the 25-centimeter Epstein Test Frame, in which the core is a four-sided assembly of alternately overlapping strips cut to the dimensions 28 cm × 3 cm.[3] The Type 1632-A bridge may be used, as specified above, to measure such Epstein assemblies, subject to excitation levels limited by the rms current specifications of Table 5. The standard Epstein frame has an exciting (primary) winding of 700 turns and an effective ℓ_1 value of 94 cm. Accordingly, the magnetizing current required to produce a specified intrinsic induction in the specimen is given by:

$$I_m = 4.95 \times 10^{-6} \left(\frac{B_i A}{L_1}\right) \tag{30}$$

and the corresponding permeability of the specimen material at this induction will be:

$$\mu_L = 1.528 \times 10^4 \left(\frac{L_1}{A}\right) \tag{31}$$

The cross-section, A, is computed from the measured weight of the sample and its known density. For a one-kilogram sample A is approximately 1.2 sq cm.

The incremental magnetic parameters of the core material can also be obtained, for specified values of ac and dc excitation, by procedures specified above in conjunction with a suitable biasing circuit (refer to paragraph 2.12).

[3]ASTM PUBLICATION A-343-59: Alternating Current Magnetic Properties of Epstein Specimens. (Standard Methods of Test).

Epstein measurements are usually made at prescribed specific levels of induction, B_i. This cannot be done by presetting values of I_m, equation (30), since the corresponding values of L_1 are not known beforehand. To establish a definite peak induction, the Epstein test frame carries a second (secondary) winding of 700 turns, across which is connected a high-impedance flux voltmeter. This voltmeter indicates the open-circuit induced voltage, E_1, independent of winding and core losses, so that E_1 is less than the voltage applied to the terminals of the primary winding. This meter responds to the true average value of the voltage wave, but is calibrated to indicate the rms value of E_1, assuming a form factor of 1.111. Then, with leakage flux considered negligible at higher inductions, the prescribed voltmeter reading for a given B_i is:

$$E_1 = 4.444\, B_i ANF \times 10^{-8} \tag{32}$$

The core-loss power is:

$$P_c = \frac{E_1^2}{R_1} \text{ watts} \tag{33}$$

The reactive power in the core is:

$$P_q = \frac{E_1^2}{\omega L_1} \text{ vars} \tag{34}$$

while the apparent power delivered to the core is:

$$P_a = \sqrt{P_c^2 + P_q^2} = \frac{E_1^2 \sqrt{R_1^2 + \omega^2 L_1^2}}{R_1 \omega L_1} \text{ volt-amperes} \tag{35}$$

At low inductions an air-flux compensator (mutual inductor, not shown) is sometimes used to counteract the component of E_1 that is caused by leakage flux, so that equation (32) gives an indicated value of E_1 that is due solely to the prescribed intrinsic induction, B_i, in the core material.

Persons interested in measuring the magnetic properties of core materials are urged to consult the ASTM Publications cited for a fuller analysis of the problem.

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Section 3
BASIC THEORY OF OPERATION

3.1 EQUATIONS FOR BALANCE.

3.1.1 GENERAL. In development of the basic theory of the Type 1632-A bridge, all residual impedances in the bridge network will be assumed nonexistent. The A arm is thus purely capacitive, $Z_A = 0 - j/\omega C_A$, while the B arm is purely resistive, $Z_B = R_B + j0$. The N and X arms of the bridge contain both resistance and reactance and thus have complex impedance values.

3.1.2 SERIES OWEN. In the series Owen bridge (Figure 9) the impedance of the N arm is $Z_n = R_n - j/\omega C_n$, and the impedance of the unknown inductor is $Z_x = R_{xs} + j\omega L_{xs}$. The complex balance equation $Z_x Z_a = Z_b Z_n$ may be written in the form:

$$R_{xs} + j\omega L_{xs} = \frac{R_B\left(R_N - \frac{j}{\omega C_N}\right)}{0 - \frac{j}{\omega C_A}} \qquad (36)$$

This gives the two simultaneous scalar equations for balance:

$$L_{xs} = R_B C_A R_N \qquad (37)$$

$$R_{xs} = \frac{R_B C_A}{C_N} \qquad (38)$$

3.1.3 PARALLEL OWEN. In the parallel Owen bridge (Figure 10) the admittance of the N arm is $Y_n = \frac{1}{R_n} + j\omega C_n$, and the admittance of the unknown inductor is $Y_x = G_x - j/\omega L_{xp}$.

The complex balance equation: $Y_X Z_B = Z_A Y_N$ may be written in the form:

$$G_x - \frac{j}{\omega L_{xp}} = \frac{-j}{R_B \omega C_A}\left(\frac{1}{R_N} + j\omega C_N\right) \qquad (39)$$

This gives the two simultaneous scalar equations for balance:

$$L_{xp} = R_B C_A R_N \qquad (40)$$

$$G_{xp} = \frac{C_N}{R_B C_A} \qquad (41)$$

and from (41):

$$R_{xp} = \frac{1}{G_{xp}} = \frac{R_B C_A}{C_N} \qquad (42)$$

The fact that only one of the two balance control parameters, R_n or C_n, occurs in each of the equations (37) (38) (40) and (41) shows that both the series and parallel Owen bridges have no sliding zero in their balance.

3.2 PRACTICAL APPLICATION.

Note that the product $R_B C_A$ occurs in each of the five equations (37) (38) (40) (41) and (42). This product is set by the RANGE switch to have the values, in ohm-farads, given in Table 6.

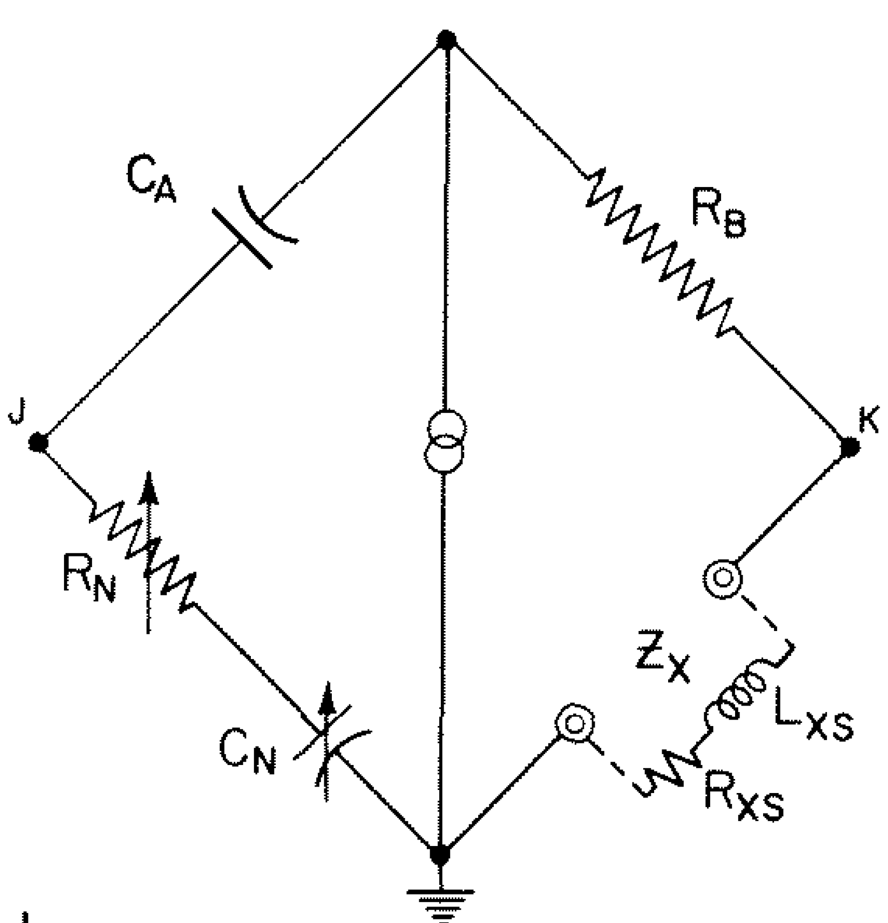


Figure 9.
Series Owen Bridge.

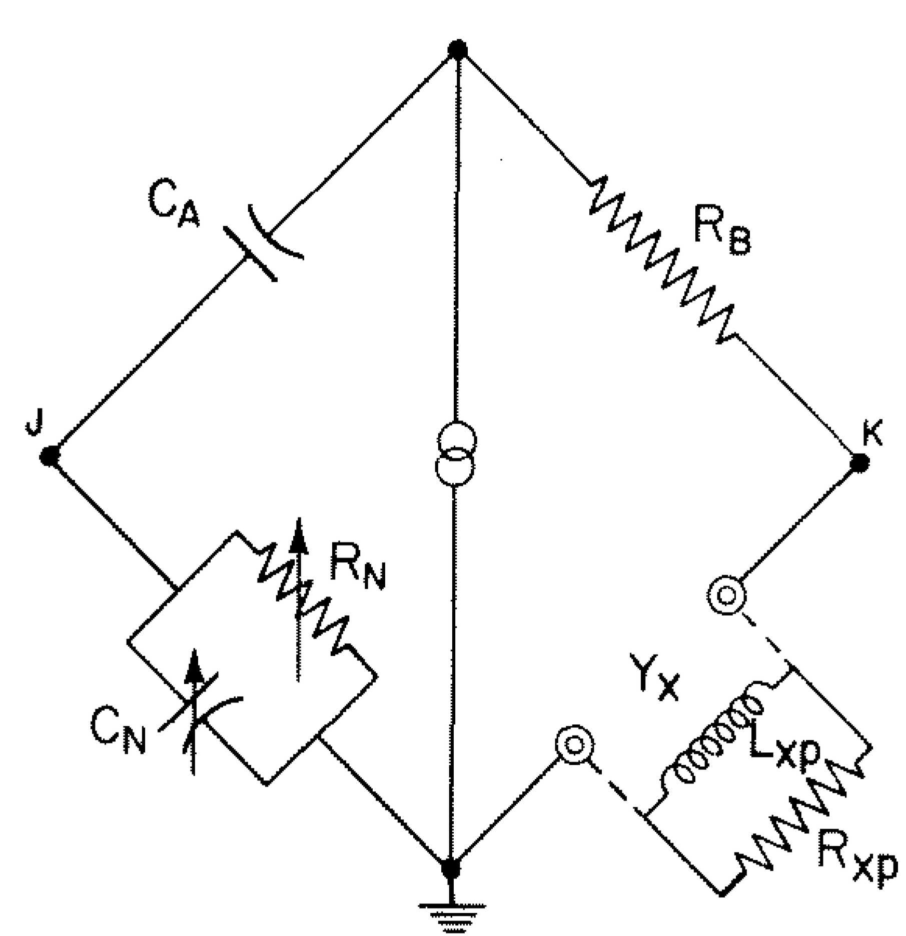


Figure 10.
Parallel Owen Bridge.

TABLE 6

RANGE	MAXIMUM SENSITIVITY	R_B (ohms)	C_A (μf)	$R_B C_A$ (ohm-farads)
a	Either	1	0.001	10^{-9}
b	Either	1	0.01	10^{-8}
c	Either	1	0.1	10^{-7}
d	LOW Z	10	0.1	10^{-6}
	HIGH Z	100	0.01	
e	LOW Z	100	0.1	10^{-5}
	HIGH Z	10^3	0.01	
f	LOW Z	10^3	0.1	10^{-4}
	HIGH Z	10^4	0.01	
g	Either	10^4	0.1	10^{-3}
h	Either	10^5	0.1	10^{-2}

The values of R_N (L controls) and of C_N (G controls) per step in each of the decades are given in Table 7.

When the data in Tables 6 and 7 and the operating range data in Table 1 are applied to equations (37) (38) (40) (41) and (42), the operating equations (1) (2) (3) (5) and (6) are obtained. The bridge parameters at balance, L and G, become direct reading in the units designated by the legend on the RANGE switch, with the decimal points automatically positioned.

For example, with the RANGE selector in position e, suppose that the balance control readings were L = 037.142 millihenrys and G = 19.825 millimhos. The corresponding bridge data would be $R_B C_A = 10^{-5}$, $R_N = 3714.2\,\Omega$ and $C_N = 0.19825 \times 10^{-6}$ farads. Then from equation (37) or (40), the inductance of the unknown would be:

$$L_{xs} \text{ or } L_{xp} = 3714.2 \times 10^{-5} = 37.142 \text{ mh}$$

For the series bridge, from equation (38) the series resistance of the unknown would be:

TABLE 7

DECADE	R_N Ω per step	C_N μf per step
1st	10,000	0.1
2nd	1000	0.01
3rd	100	0.001
4th	10	0.0001
5th	1.0	0.00001
6th	0.1	----

$$R_{xs} = \frac{10^{-5}}{0.19825 \times 10^{-6}} = 50.39\,\Omega$$

or from the working equation (3):

$$R_{xs} = \frac{10^3}{19.825} = 50.39\,\Omega$$

With the same balance data (for a different unknown) measured with the parallel bridge, from equation (41) the conductance of the unknown would be:

$$G_{xp} = \frac{0.19825 \times 10^{-6}}{10^{-5}} = 19.825 \text{ mmhos}$$

or from the working equation (5):

$$G_{xp} = G = 19.825 \text{ mmhos}$$

as indicated directly on the bridge. The corresponding parallel resistance of the unknown, from equation (42) would be:

$$R_{xp} = \frac{10^{-5}}{0.19825 \times 10^{-6}} = 50.39\,\Omega$$

or from the working equation (6):

$$R_{xp} = \frac{10^3}{19.825} = 50.39\,\Omega$$

Section 4

RESIDUAL IMPEDANCES

4.1 GENERAL. In development of the basic equations for the Owen bridges (Section 3), it was assumed that all of the bridge components were pure impedances, i.e., that all resistors had phase angles of exactly zero value and that all capacitors had phase angles of exactly 90 degrees. In practice, these ideal conditions are disturbed by unavoidable existence of certain residual impedances in the bridge network, such as residual capacitance across resistors and losses in capacitors. To allow for such residuals, the correction factors to the basic balance equations will be specified, and the design procedures used to minimize certain of these residual errors in the Type 1632-A Bridge will be described. In the measurement of low-Q inductors, these residuals may introduce a slight amount of sliding zero into the balance of the bridge.

4.2 RESIDUALS IN THE UNKNOWN ARM. Any inductance in the internal wiring of the unknown arm of the bridge becomes a residual component of the measured value of L_{XS}, and might cause appreciable error with small-valued inductors. Making the two UNKNOWN terminals the exact extremities of the unknown arm reduces this residual to the smallest possible value (about 0.1 μh). To check this "zero" inductance of the bridge, short-circuit the UNKNOWN terminals directly and use RANGE switch position a.

Any residual capacitance that is added across the actual unknown inductor will cause an error in the measured values of large inductors at higher frequencies. To reduce residual capacitance across the unknown arm of the bridge to the smallest possible value (about 1.0 μμf), the components of the A and B arms and the detector transformer are enclosed in an internal shield, which is connected to the junction of the two arms. The capacitance to ground (bridge chassis) of this shield is directly across the generator, and thus does not affect bridge balance. This shield covers the part of the "high" unknown terminal passing through the bridge panel. Thus the residual that loads the unknown inductor is reduced to essentially the direct capacitance between the external part of the high terminal post and the bridge panel.

Any pertinent residuals associated with the leads from the bridge to the actual terminals of the unknown inductor must be determined and corrected for (refer to paragraph 2.8).

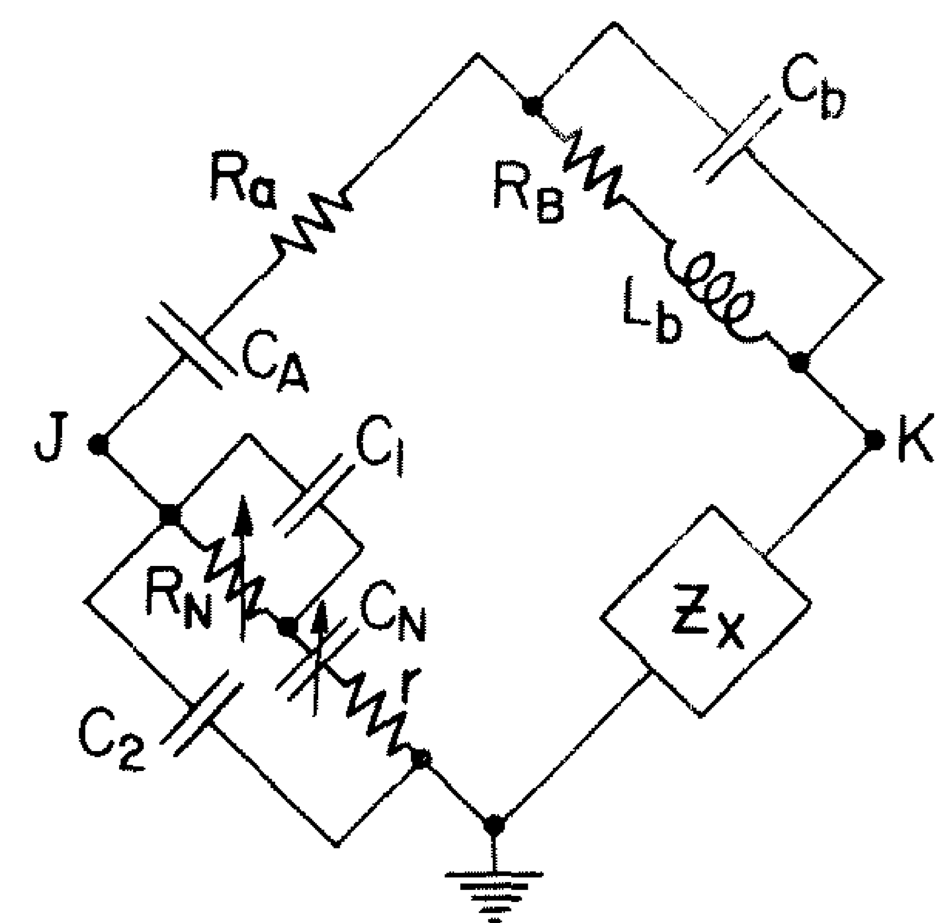


Figure 11. Residual Impedances in the Series Owen Bridge.

4.3 RESIDUALS IN THE SERIES OWEN BRIDGE. Figure 11 indicates six residuals in the other three arms of the series Owen bridge which, under certain conditions can introduce significant errors into high-precision measurements. These six residuals are:

a. Losses in the A arm capacitor represented by the series resistance, R_a, which includes wiring and switch resistance in this arm.

b. Any direct capacitance, C_b, across the B arm of the bridge.

c. Any series inductance L_b in the B arm of the bridge.

d. Losses in the capacitors in the N arm of the bridge (G controls), which can be represented by the series resistance, r.

e. Direct capacitance, C_1, across the resistance decades (L controls) in the N arm.

f. Direct capacitance, C_2, across the entire N arm.

Losses in C_b, C_1, and C_2 are kept to a minimum by the use of high-quality insulating materials. The effects of each of these residuals are functions of frequency. It will be convenient to express the correction factors for the basic equations in terms of corresponding dissipation or storage-factor values which are defined as follows:

a. $D_A = \omega C_A R_a$ (43)

b. and c. $Q_B = \omega C_b R_B - \dfrac{\omega L_b}{R_B}$ (44)

d. $d = \omega C_N r$ (45)

e. $q_1 = \omega C_1 R_N$ (46)

f. $q_2 = \omega C_2 R_N = \dfrac{C_2}{C_N} Q_x$ (47)

The exact expressions for the composite correction factors are quite complicated. For practical purposes, it will be legitimate to consider that each residual is small enough so that the squares and products of each of the five parameters defined by equations 43 through 47 are negligible compared to unity. The corrected values of the unknown (primed symbols) can be obtained with sufficient accuracy by modification of the basic equation (37):

$$L'_{xs} = R_B C_A R_N \left(1 - \frac{D_A + Q_B - d}{Q_x} - \frac{2C_2}{C_N}\right) \quad (48)$$

and by modification of the basic equation (38):

$$R'_{xs} = \frac{R_B C_A}{C_N}\left[1 + Q_x(D_A + Q_B + q_1) + \frac{C_2}{C_N}(Q_x^2 - 1)\right] \quad (49)$$

In equations (47), (48) and (49) the factor Q_x is the storage factor of the unknown:

$$Q_x = \omega C_N R_N = \omega L G \times 10^{-6} \quad (50)$$

computed directly from the bridge values of L and G without correction for any bridge residuals (refer to the basic equation 4).

From equation (48) it will be seen that the basic value of L_{xs} is reduced by each of the three residuals R_a, C_b, and C_2 and is increased by the residuals r and L_b, all in amounts inversely proportional to Q_x, except that the error due to C_2 is independent of frequency. Note that the residual C_1 produces no significant error in the measurement of L_{xs}.

Examination of equation (49) shows that the basic value of R_{xs} is increased by the residuals R_a, C_b, C_1, and also by C_2 if Q_x exceeds unity, and is decreased by L_b. The errors caused by R_a, C_b, L_b and C_1 are directly proportional to Q_x. Note that the residual r produces no significant error in the measurement of R_{xs}.

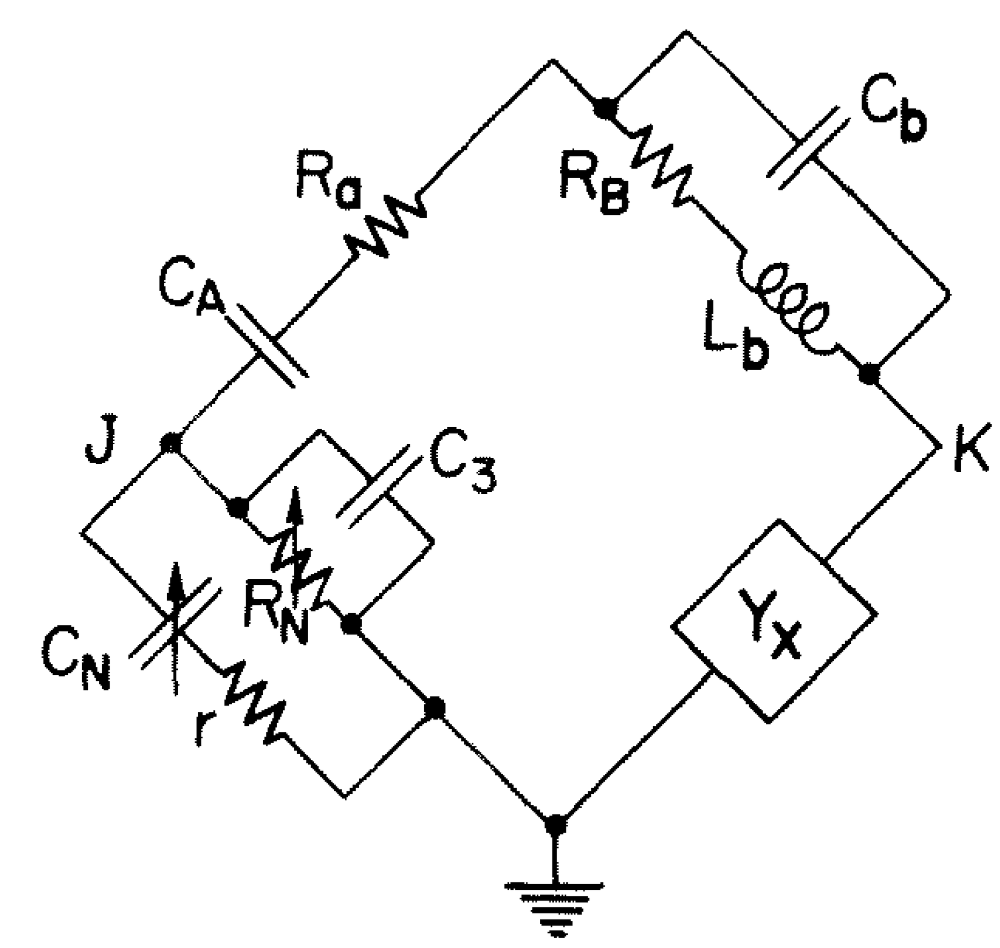


Figure 12. Residual Impedances in the Parallel Owen Bridge.

4.4 RESIDUALS IN THE PARALLEL OWEN BRIDGE. For the parallel Owen bridge, Figure 12 shows the same four residuals, R_a, C_b, L_b, and r resulting in the corresponding values of D_A, Q_B and d, in equations (43), (44), and (45). Here the residuals C_1 and C_2 of the series bridge are replaced by a single direct capacitance, C_3, across the entire N arm, which adds to the decade C_N capacitors to produce an effective capacitance:

$$C'_N = C_N + C_3 \quad (51)$$

Allowance has been made for the residual C_3 in the calibration of the C_N decades for the parallel bridge so that no error is introduced by C_3. The other four residuals result in modifications of the basic equations (40) and (41) of the form:

$$L'_{xp} = R_B C_A R_N \left(1 + \frac{D_A + Q_B - d}{Q_x}\right) \quad (52)$$

$$G'_x = \frac{C_N}{R_B C_A}\left[1 + Q_x(D_A + Q_B)\right] \quad (53)$$

In equations (47), (52), and (53) Q_x is given by:

$$Q_x = \frac{1}{R_N \omega C_N} = \frac{10^6}{\omega L G} \quad (54)$$

Examination of equation (52) shows that the basic value of L_{xp} is increased by the residuals R_a and C_b and is decreased by the residuals r and L_b, each error being inversely proportional to Q_x. Note that the residual C_3 produces no significant error in the measurement of L_{xp}.

Examination of equation (53) shows that the basic value of G_x is increased by the residuals R_a and C_b and is decreased by L_b, each error being directly proportional to Q_x. Note that the residual r produces no significant error in the measurement of G_x.

4.5 REDUCTION OF THE RESIDUAL C_2. To reduce the direct capacitance C_2 to a minimum value (about 1.0 μμf) the L controls are enclosed in an internal shield that is connected to the terminal of R_N which, in the series bridge, is common with the ungrounded side of C_N. This shield increases the direct capacitance, C_1, across R_N somewhat, but this residual does not affect the measurement of L_{xs}.

In the series bridge the capacitance between this shield and the chassis (about 200 μμf) becomes an integral part of C_N and is allowed for in the calibration of the bottom G control dial (this is the "Add 2" referred to on the panel). When a shift is made to the parallel bridge, this shield is grounded to the chassis and C_N is augmented by a separate capacitor of 100 μμf to keep the G controls direct-reading in both bridges.

4.6 REDUCTION OF THE TERM Q_B. Examination of equation (44) for Q_B shows that the residuals C_b and L_b have opposing effects and that Q_B would equal zero at any frequency if:

$$R_B^2 C_b = L_b \tag{55}$$

For any specific value of R_B, if the residual C_b predominates, then Q_B will be positive and the condition (55) could be met if the residual L_b were augmented by an appropriate amount of compensating inductance introduced in series with the R_B resistor. Conversely, if the residual L_b predominates with some other value of R_B, then Q_B will be negative and could be reduced to zero if an appropriate capacitor were added across the R_B resistor to increase the inherent value of C_b and then satisfy equation (55). By these methods the following compensations were made in the 1632-A bridge.

With the RANGE switch in positions using either the 1-, 10- or 100-ohm value of R_B, the B arm has a net residual inductance of about 0.50 μh. To offset this, the 1-ohm resistor is padded with a 0.47-μf capacitor, and a capacitor of 0.0047 μf is connected across the 10-ohm resistor. The inductance of the 100-ohm resistor is compensated by the stray capacitance, so no compensating capacitor is required.

When the 1- and 10-kilohm values of R_B are used, the residual capacitance of about 40 μμf is compensated by inductors of 33 and 3900 microhenrys respectively in series with the resistors. The 1.3- and 57- ohm resistances of these inductors becomes a part of the calibrated R_B value and are small enough so that their variations with temperature and frequency are negligible.

When the 100-kilohm value of R_B is used, the B arm has a net residual capacitance of about 30 μμf. This would require a compensating inductor of 300 mh, an impractically large value. Accordingly, another method was used for canceling this residual capacitance.

The R_B resistor was split into two parts of 50 kilohms each, and the junction of these series components was connected through a capacitor, C11, to the junction of the A and N arms of the bridge. By a T- to - π network transformation, this procedure introduces into the B arm series inductance equal to R_B^2 C11/4. A C11 value equal to 4 C_b, i.e., 150 μμf, was used in this case. This procedure also introduces across the A arm a capacitance C11/2, i.e., 75 μμf, in series with a resistance of 50 kilohms. Since the 100-kilohm value of R_B is used only when C_A is 0.1 μf, this 0.075-percent increase in C_A is compensated for by a decrease in R_B. Also, the initial value of D_A is not changed appreciably by this method.

4.7 CALCULATION OF ERRORS. Although the residuals have been reduced to keep D_A, d, and Q_B as small as possible, the error in the L reading can exceed 0.1%, and the error in the G reading can exceed 1% when the Q has extreme values. The magnitude of the error can be determined from equations (48), (49), (52), and (53) when the magnitudes of the residuals are known. Exact values of these small quantities are not easily determined, however, so that it is seldom practical to use calculated corrections when the errors are large. Knowledge of the magnitude of possible errors can and should be used to avoid large errors and to make necessary corrections for small errors. For these purposes, numerical values of typical residual parameters and of the errors they produce are given below.

The difference between the bridge L reading ($R_B C_A R_N$) and the inductance of the unknown (L'_x) is given in equations (48) and (52). Since D_A, d, and Q_B are multiplied by $\frac{1}{Q_x}$ in these equations, the error in L may be large when Q_x is less than 1. The sign of the error, which depends upon the relative magnitudes of D_A and d and upon the sign of Q_B, varies with range setting and with frequency. When the frequency is 100 cycles or lower, D_A is the predominant term, and the error in series L then makes the bridge read higher than the inductance of the unknown. For example, if D_A = 0.0005 and Q_x = 0.5, the bridge reads 0.1% high. If the relative humidity inside the bridge becomes much greater than 50%, the increased losses in the C_N decade switches and wiring can make d exceed D_A; in this case the sign of the error reverses and the bridge reads low. High humidity inside the bridge can be avoided by the use of desiccants or by use of a light bulb or other heat source to raise the bridge temperature 20°C above ambient.

The error in the bridge reading of R_x or G_x is given by equations (49) and (53). Since D_A, Q_B, and

q_1 are multiplied by Q_X, the error in R or G may be large when Q_X is greater than 10. The sign of the error, which depends upon the sign of Q_B, varies with range setting and with frequency. At frequencies above 1000 cycles, the predominant terms are Q_B and q_1, and the error, $Q_X(Q_B + q_1)$, increases with the square of frequency.

In the measurement of the equivalent series resistance of a high-Q inductor at frequencies above 1000 cycles, the term q_1 (= $\omega C_1 R_N$) can produce considerable error if R_N is about 10 kilohms or more, (i.e., whenever the top L decades are used). As an example, consider the measurement, on the e range at 5000 cycles, of a 100-millihenry inductor with a series resistance of 33 ohms. The bridge is balanced at an L reading of 100.000 millihenrys and a G reading of 82.5 millimhos. The measured series resistance, R_{XS}, is therefore 12 ohms from equation (3). The large difference between 12 and 33 ohms can be explained by equation (49). The measured Q_X is 259, from equation (50). The value of R_N for this reading of the L decades is 10 kilohms and the capacitance C_1 across R_N is about 21.5 µµf, so q_1 = 0.00675. If D_A and Q_B are assumed to be negligible compared with q_1, the error is $Q_X q_1$ = 1.75. From equation (49), the corrected series resistance R'_{XS} is 12 (1 + 1.75) = 33 ohms. The error from q_1 can sometimes be reduced by the reduction of R_N, i.e., by use of a range where the top L decade is not used. In the example above, the 100-millihenry inductor might be measured on the f range, with an L reading of 0100.00 corresponding to R_N = 1 kilohm. The difficulty here, as in many cases, is that the G balance cannot be made on another range without the use of external capacitance, such as the additional 3 µf required to balance 33 ohms on the f range. The error from q_1 can be avoided by measurement of equivalent parallel conductance, G_{xp}, since q_1 does not appear in equation (53). Series resistance, when required, must be calculated from the measured parallel conductance and Q by means of equation (9). The accuracy of frequency is then important because the square of frequency is involved in the parallel-to-series conversion. The usefulness of the parallel equivalent may also be limited if the conductance of high-Q inductors is too small to be measured with sufficient accuracy, if at all, on the lower G dials of the bridge.

Errors in particular measurements can be estimated from the measured values of L and G and from typical values of the residual parameters, D_A, d, Q_B, C_1, and C_2. The D_A values of the mica capacitors, C_A, and the d values of the polystyrene capacitors, C_N (G decades), are functions of both frequency and the magnitudes of the capacitors. Typical values are given in Table 8 and 9. Each R_B resistor is compensated so that its Q_B, defined by equation (44), does not exceed at 1000 cycles the limits given in Table 10. To determine the value of Q_B at a frequency f, multiply the 1-kc value by f/1000.

The capacitance, C_1, that determines q_1 varies with the setting of the R_N decades, and is about 10 µµf for the maximum R_N (100 kilohms), about 20 µµf for an R_N of 10 kilohms, and about 30 µµf for an R_N of 1 kilohm. The capacitance, C_2, (about 1 µµf) may be used in equations (48) and (49) with the value of C_N from Table 7 to determine the contribution of C_2/C_N to the error. The terms in C_2 may be significant when C_N is small, i.e., when only the lowest decade (100 µµf per step) and the variable dial are used in the G balance.

TABLE 8

Dissipation Factor of C_A Capacitors

C_A µf	Ranges	Values of D_A 100 c	Values of D_A 1 kc
0.001	a	0.0008	0.0003
0.01	b d, e, f (High Z)	0.0003	0.0001
0.1	c, g, h d, e, f (Low Z)	0.0002	0.0001

TABLE 9

Dissipation Factor of C_N Capacitors (G Decades)

G Dials	C_N µf	Values of d 100 c	Values of d 1 kc
00000	0.0002	0.0011	0.0006
000X0	0.001	0.0003	0.0002
00X00	0.01	0.0001	0.0001
0X000	0.1	0.0001	0.0001
X0000	1.0	0.0001	0.0001

TABLE 10

Storage Factor of R_B Resistors

R_B ohms	Ranges	Q_B at 1 kc within
1 Ω	a,b,c	±0.03 %
10 Ω	d (Low Z)	±0.005%
100 Ω	d (High Z), e (Low Z)	±0.002%
1 kΩ	e (High Z), f (Low Z)	±0.002%
10 kΩ	f (High Z), g	±0.02 %
100 kΩ	h	±0.1 %

Section 5
SERVICE AND MAINTENANCE

5.1 GENERAL. The two-year warranty given with every General Radio instrument attests the quality of materials and workmanship in our products. When difficulties do occur, our service engineers will assist in any way possible.

In case of difficulties that cannot be eliminated by the use of these service instructions, please write or phone our Service Department, giving full information of the trouble and of steps taken to remedy it. Be sure to mention the serial and the type numbers of the instrument.

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

5.2 TROUBLE-SHOOTING PROCEDURE.

5.2.1 GENERATOR AND DETECTOR. The apparent failure of the bridge to function properly may be caused by a component outside the bridge. If balance cannot be obtained:

a. Check that the generator is applying an ac voltage to the GENERATOR terminals (a level of 1 volt or less is generally safe).

b. Check that the null detector responds to a change in the generator voltage when the bridge is unbalanced (i.e., with the UNKNOWN terminals open), and ascertain that the input is not so large that the detector is overloaded. When a tuned null detector is used, check that the generator frequency is the same as the frequency to which the detector is tuned.

5.2.2 BRIDGE COMPONENTS.

5.2.2.1 General. When both generator and detector function properly but the bridge fails to balance, the components in the bridge can be tested for damage or failure as described below.

5.2.2.2 Generator Terminals. If the generator voltage drops to zero when the generator is connected to the bridge with open UNKNOWN terminals, there is probably a short between the two internal shields connected respectively to the high and low GENERATOR terminals. An ohmmeter should indicate an open circuit between the GENERATOR terminals when the UNKNOWN terminals are open. If the terminal impedance is low under these conditions, remove the bridge from the case (refer to paragraph 5.3.2) and examine the internal shields around the RANGE switch and the high UNKNOWN terminal to see if they are in contact with each other.

5.2.2.3 Detector Terminals. An impedance measurement at the DETECTOR terminals is not very useful in detecting defects in the bridge transformer. To check the transformer for voltage output, apply about 1 volt at 1 kc to the GENERATOR terminals, set the BRIDGE READS switch at its middle (unmarked) position, short the UNKNOWN terminals, set the RANGE switch to e, f, g, or h, and measure the voltage across the DETECTOR terminals. The voltage should be about 1/3 of the GENERATOR voltage.

5.2.2.4 R_B Resistors. To test the six R_B resistors, connect an ohmmeter or Wheatstone bridge between the high (red) GENERATOR terminal and the high (red) UNKNOWN terminal, with the UNKNOWN terminals open. The values of R_B for the RANGE switch settings a to h are tabulated in Table 6.

Note that the resistance measurements at these terminals are not to be used to calibrate the bridge. For the required accuracy of better than ±0.05 percent in R_B calibration, a Kelvin bridge must be used with its potential leads at the exact corners of the bridge.

5.2.2.5 C_A Capacitors. An accurate calibration measurement of the capacitance in the C_A arm cannot be made from the terminals on the bridge panel. Large capacitance defects and shorts can be detected, however. With the BRIDGE READS switch at PARALLEL, the C_A capacitor is connected between the high (red) GENERATOR terminal and the high EXTERNAL CAPACITOR jack. An ohmmeter should indicate an open circuit between these terminals when the UNKNOWN terminals are open.

For a capacitance check, a capacitance bridge (such as the General Radio Type 1650-A Impedance Bridge) can be connected to these terminals. The UNKNOWN terminals should be open, and the L decades (R_N) should be set at maximum value. Connect the low UNKNOWN terminal of the Type 1650-A Bridge to the high (red) GENERATOR terminal of the Type 1632-A Bridge.

When the RANGE switch is at g or h, or on f with the MAXIMUM SENSITIVITY switch at LOW Z, the 0.1-μf C_A is connected to these terminals for measurement. The Type 1650-A Bridge should indicate that C = 0.101 μf and D = 0.025 on these ranges at 1 kc.

When the RANGE switch is at f with the MAXIMUM SENSITIVITY switch at HIGH Z, the 0.01-µf C_A is connected to these terminals. The Type 1650-A Bridge should indicate that C = 0.0107 µf and D = 0.2 at 1 kc.

When the RANGE switch is at a, the 0.001-µf C_A is connected to the terminals. The Type 1650-A Bridge should indicate that C = 0.00135 µf and D = 1.3 at 1 kc.

Failure of any one of the R_B resistors or C_A capacitors can sometimes be detected by inductance measurements with the Type 1632-A Bridge itself. Since most inductors can be measured on more than one range, and many with either position of the MAXIMUM SENSITIVITY switch, a failure of one R_B or C_A component will appear in only one of the possible conditions of measurement. For example, if a 100-mh inductor can be measured on d - LOW Z and on e - LOW Z but not on d - HIGH Z, an examination of the C_A, R_B values used in these ranges (Table 6) will indicate that the 0.01-µf C_A is probably at fault.

5.2.2.6 Inductance (R_N) Decades. The six decades calibrated in inductance are General Radio Type 510 Decade Resistance Units, having steps of 10 k, 1 k, 100, 10, 1, and 0.1 ohms, from top to bottom. The maximum value is 111,111.0 ohms, occurring when the L dials are set at XXXXXX.

These resistors can be checked with an ohmmeter or Wheatstone Bridge. Set the BRIDGE READS switch to PARALLEL, and measure across the high and low EXTERNAL CAPACITOR terminals. All other dc paths through the bridge arms are blocked by capacitors.

5.2.2.7 Conductance (C_N) Decades. The four decades calibrated in conductance are General Radio Type 1419-A Polystyrene Decade Capacitors, having steps of 0.1, 0.01, 0.001, and 0.0001 µf, from top to bottom. The fifth dial is a continuously variable 130-µµf air capacitor. The zero capacitance is 200 µµf, and the maximum with the dials set at XXXX, 10 is 1.11130 µf.

The capacitors can be checked with a capacitance bridge (such as the General Radio Type 1650-A Impedance Bridge). Set the BRIDGE READS switch to its middle, unmarked, position, between SERIES and PARALLEL. In this position the internal C_N capacitors alone are connected to the EXTERNAL CAPACITOR jacks. Measure across the high and low EXTERNAL CAPACITOR terminals.

5.3 ACCESS TO BRIDGE COMPONENTS.

5.3.1 DECIMAL-POINT DRIVE. Failure of the decimal point to move when the RANGE switch is rotated, or any incorrect positioning of the decimal point, can be caused by a broken or slipping mechanical linkage.

The motion of the decimal points is produced by small black-and-white wheels driven by a bead chain (see Figure 13). This mechanism is accessible after removal of the front panel.

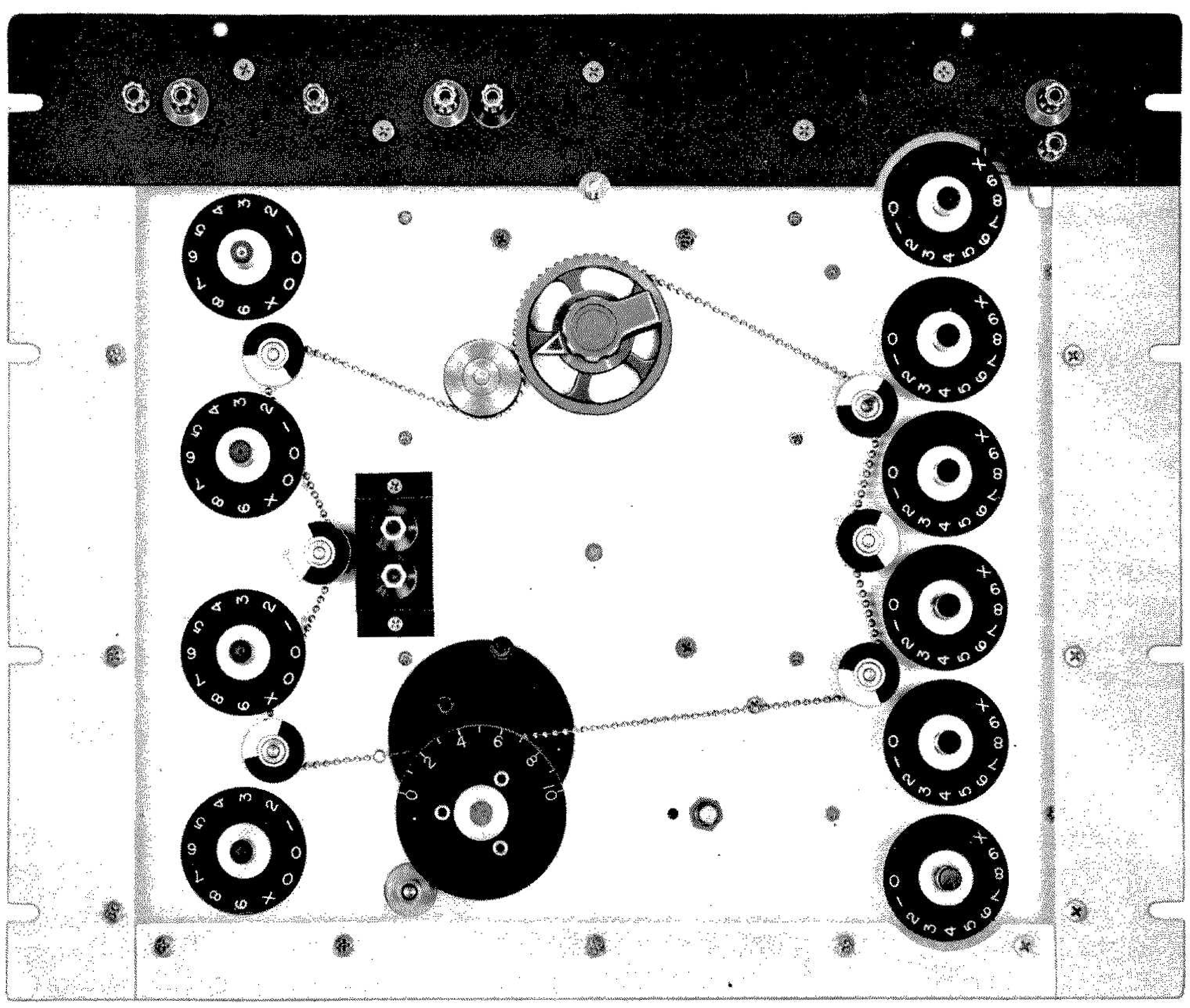


Figure 13.
View with Dress Panel Removed
Showing Decimal-Point Drive
(RANGE switch in b position).

To remove the front panel, first remove the 12 screws at the edges of the panel. The two at the top and two at the bottom hold the panel to the case, and the four at each side hold the panel to the end frames or to a relay rack. Then remove all 14 knobs, and lift the dress panel away from the subpanel (see Figure 13).

The bead chain should be engaged with the drive wheel on the RANGE switch and with the six decimal-point wheels as shown in Figure 13. The white segments of the decimal-point wheels should be oriented as shown in Figure 13 with the RANGE switch set at b, e, or h. The decimal-point wheels are held on their shafts only by the tension of the bead chain, provided by a spring in the chain. The L-shaped aluminum arm floating on each shaft under the decimal-point wheel keeps the chain from jumping out of the decimal-point wheel sockets if the RANGE switch is rotated unusually fast. The short arm of this L, perpendicular to the panel, should lie just outside, but not in contact with, the chain when it is engaged with the wheel.

5.3.2 ELECTRICAL COMPONENTS. The shield, switches, capacitors, resistors, and transformer are mounted on the subpanel and are covered on the rear and sides by the outer case of the bridge. To remove the case, first remove the two screws at the top edge of the dress panel, the two screws at the bottom edge, and either the four screws at each side (which hold the panels to the end frames or to the relay rack) or the four screws at each end (which attach the end frames to the case).

When the case has been removed, the panel with attached components can be supported either on the face or on the panel and shields with the terminal side of the panel facing down. Do not rest the panel on its bottom edge so that weight falls on the bakelite switch of the bottom L decade.

The RANGE and SENSITIVITY switches, transformer, C_A capacitors, and R_B resistors are covered by the shield near the center of the bridge. To remove this shield, remove the screw in the corner next to trimmer capacitor C10 and remove the two screws in the edge of the shield near the panel.

The R_N resistors and switches are covered by a separate shield. To open this shield, remove the 11 screws at its top and sides.

5.4 MAINTENANCE OF DECADE SWITCH CONTACTS. The contact resistance of the switches in the inductance (R_N) decades may increase as the result of dirt accumulation and corrosion. This will cause noisy or erratic detector indications as the bridge is balanced, making the balance difficult, but introducing no error in the result when balance is established.

In normal use the contacts have a self-cleaning action, so deterioration is most evident after the bridge has been idle for an extended period. As a first remedy for noisy contacts, rotate the L decade switches back and forth several times over their full ranges.

If the trouble persists, the switch contacts should be cleaned and lubricated. Remove the bridge case and shield around the R_N decades, as described in paragraph 5.3.2. Be very careful, while cleaning the contacts, not to disturb or damage the resistor cards mounted on the switches. Remove the old lubricant and dirt, using a cloth moistened with any clean solvent (alcohol, naphtha, trichlorethylene, etc), and wipe the contacts with a clean cloth or tissue. Remove corrosion from the contacts with crocus cloth or with a very fine grade of steel wool. Do not use sand or emery paper. Clean again with solvent and carefully remove all residue of the abrasive. Lubricate the contacts liberally with a noncorrosive lubricant, such as Lubrico H-101 (Master Lubricant Co., Philadelphia, Pa.). Vaseline or a mixture of vaseline and clock oil can also be used, but this lubricant does not last as long.

The conductance (C_N) decades have enclosed switches of a different type, which should introduce no noise and require no cleaning.

5.5 BRIDGE ADJUSTMENTS. The only adjustments of bridge components that can be made without special equipment are those of the trimmer capacitors (C9 and C10) across the 0.1- and 0.01-µf C_A capacitors. These air trimmers can be adjusted by a screw driver through the holes marked C9 and C10 in the shield around the range switch and ratio arms, after the case has been removed (refer to paragraph 5.3.2).

Adjustment of C9 and C10 should seldom be required, and should be made only by users skilled in precision inductance measurements. Calibrated standard inductors of better than ±0.1 percent accuracy are required. The bridge has been calibrated at General Radio with a 100-mh General Radio Type 1482-L Standard Inductor, certified to ±0.03 percent. In this calibration, the standard inductor is connected across the UNKNOWN terminals, with leads of known inductance, and the bridge is balanced at 1 kc. The RANGE switch is set at e, the MAXIMUM SENSITIVITY switch is at LOW Z, and C10, across the 0.1-µf C_A, is adjusted to make the error in the bridge inductance reading less than ±0.1 percent. To adjust the 0.01-µf C_A capacitor, another balance is made on the e range with the MAXIMUM SENSITIVITY switch at HIGH Z, and C9 is adjusted to make the error in inductance reading less than ±0.1 percent.

There is no trimmer across the 0.001-µf C_6, used only on the a range. A factory adjustment to ± 1 percent is made by means of small, fixed, mica padding capacitors.

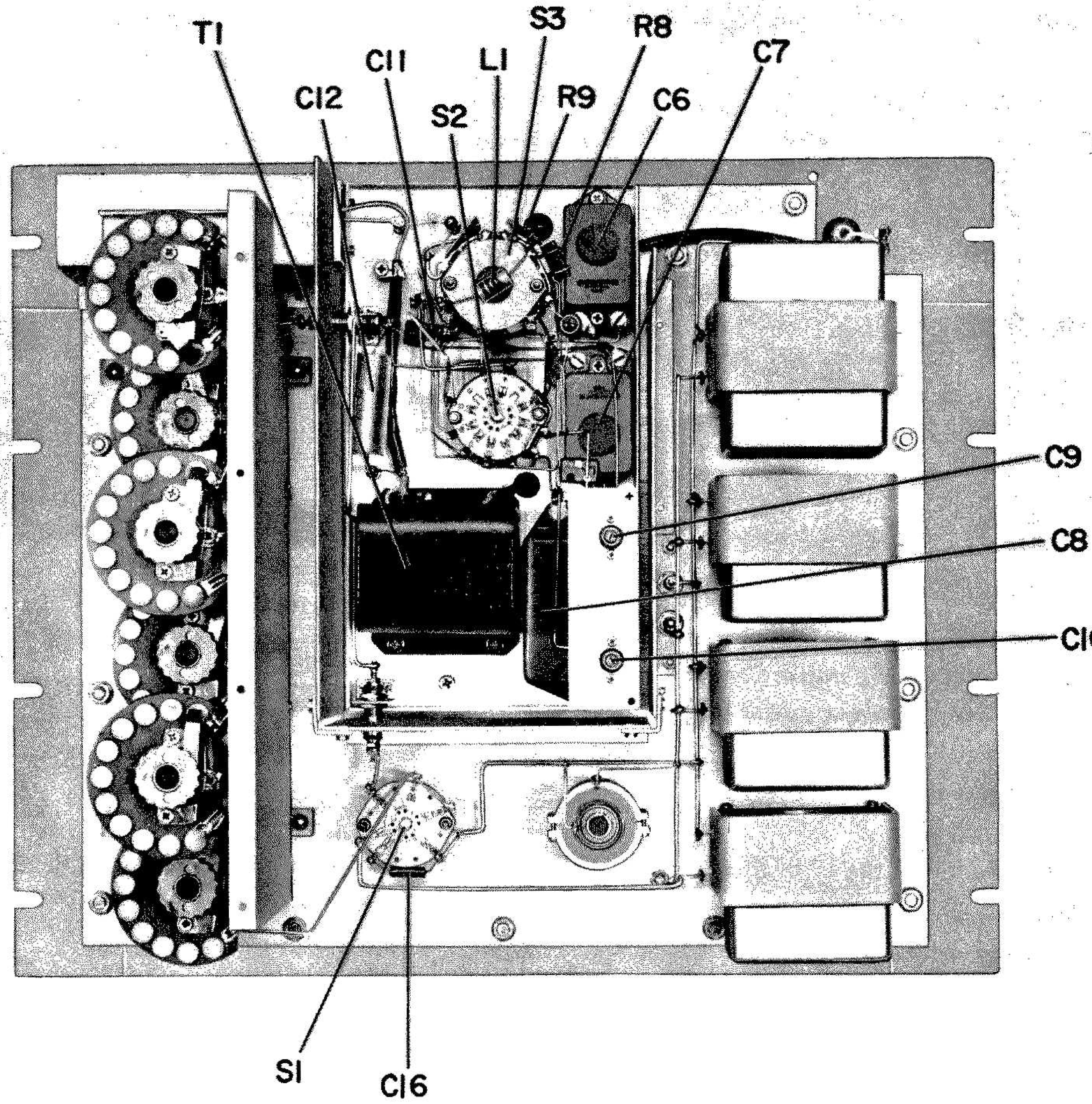
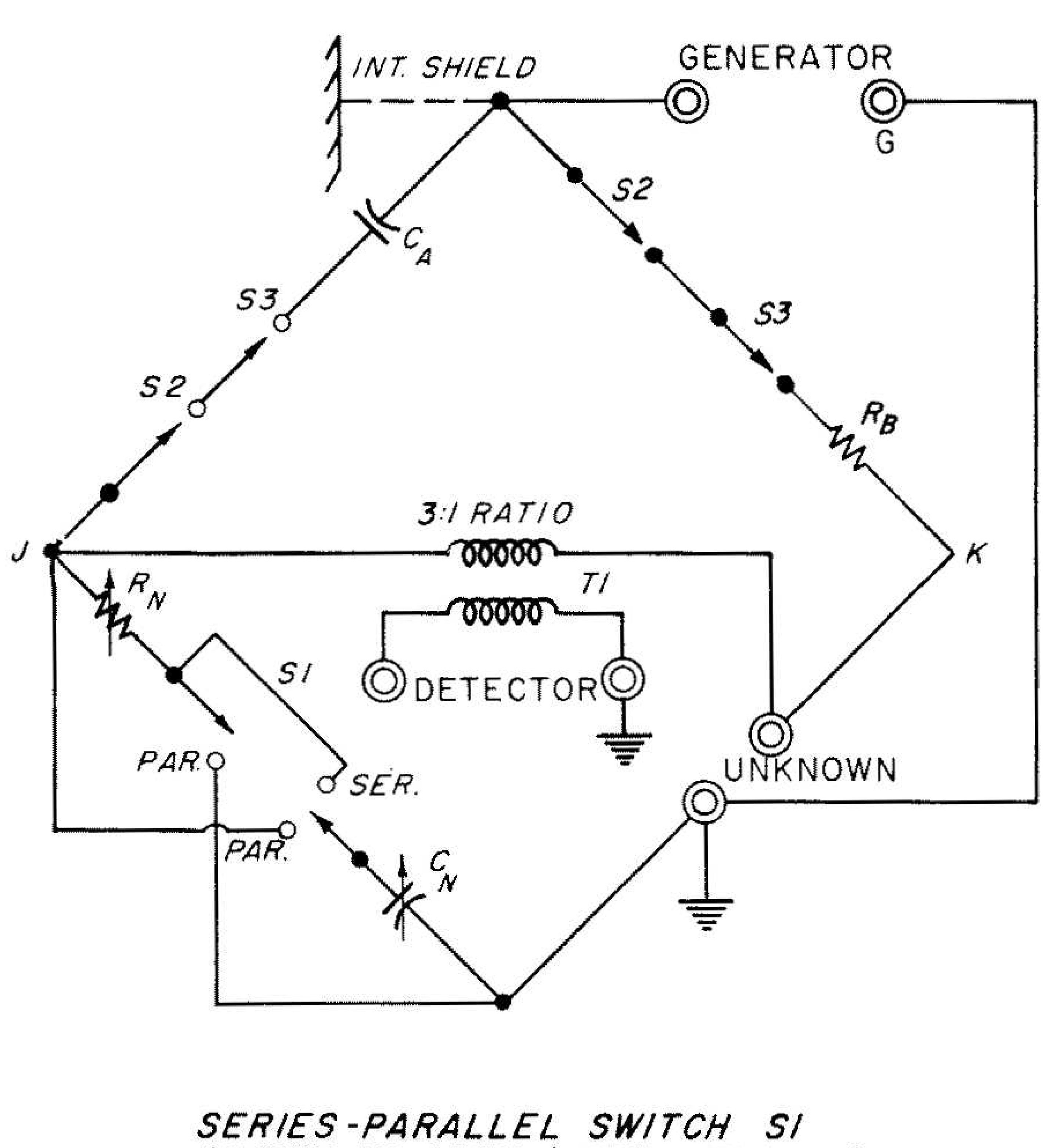


Figure 14. Rear Interior View.



SERIES-PARALLEL SWITCH S1
SHOWN IN OPEN (INTERMEDIATE)
POSITION HERE.

OPERATION OF SWITCHES S2 AND S3

S2 = RANGE SWITCH (8 positions)
S3 = SENSITIVITY SWITCH (2 positions)

POSITIONS S2	POSITIONS S3	R_B ohms	C_A µf	$R_B C_A$ ohm-farads	FULL SCALE L	
a	Either	1	0.001	10^{-9}	100	µh
b	Either	1	0.01	10^{-8}	1000	
c	Either	1	0.1	10^{-7}	10,000	
d	L	10	0.1	10^{-6}	100	mh
d	H	100	0.01	10^{-6}	100	
e	L	100	0.1	10^{-5}	1000	
e	H	10^3	0.01	10^{-5}	1000	
f	L	10^3	0.1	10^{-4}	10,000	
f	H	10^4	0.01	10^{-4}	10,000	
g	Either	10^4	0.1	10^{-3}	100	h
h	Either	10^5	0.1	10^{-2}	1000	

L_X (henrys) $= (R_B C_A) R_N$

Figure 15. Elementary Schematic Diagram.

Section 6
INDEX

6.1 SYMBOLS USED IN THIS TEXT.

A - Effective cross-section of a ferromagnetic core (sq cm)

B_i - Intrinsic induction (peak value) in a ferromagnetic core (gausses)

C_A - Capacitance in A arm of the bridge

C_N - Capacitance in N arm of the bridge (G controls)

C_b - Residual capacitance across B arm of the bridge

C_1 - Residual capacitance across R_N in the series bridge

C_2 - Residual capacitance across N arm in the series bridge

C_3 - Residual capacitance across N arm in the parallel bridge

D_A - Dissipation factor of A arm of the bridge

d - Dissipation factor of C_N

E_{dc} - Bias source voltage for incremental measurements

E_g - Rms voltage applied to generator terminals of the bridge

E_x - Rms voltage impressed upon the unknown inductor

E_1 - Rms induced voltage due to I_m

f - Cyclic frequency (cycles per second)

G - Balance reading of G controls (numeric)

G' - Value of G in incremental measurements (method A)

G_x - Conductance of unknown inductor

G'_x - Value of G_x corrected for bridge residuals

H - Magnetizing force (peak value in oersteds)

I - Rms ac exciting current carried by unknown inductor in normal measurements

I_c - Component of I responsible for core losses

I_m - Component of I responsible for induction in the core

I' - Total rms value of current in unknown inductor for incremental measurements

I_{ac} - Ac component of I'

I_{dc} - Biasing component of I'

I_x - Rms current in an inductor computed from E_g

K - Coupling coefficient between two windings (numeric)

L - Balance reading of L controls (numeric)

L' - Value of L in incremental measurements (method A)

L_{xs} - Series inductance of the unknown inductor

L'_{xs} - Value of L_{xs} corrected for bridge residuals

L_{xs1}, L_{xs2} - Individual self-inductances of two windings having mutual inductance

L_a - Inductance of two windings in series aiding

L_o - Inductance of two windings in series opposing

L_{xp} - Parallel inductance of the unknown inductor

L'_{xp} - Value of L_{xp} corrected for bridge residuals

L_b - Residual series inductance in B arm of the bridge

L_{std}, L_x - Values of standard and unknown inductors in substitution measurements

L_s, L_u - Bridge measured values of L_{std} and L_x

L_w - Series inductance due to air flux

L_c - Series inductance due to intrinsic induction in a ferromagnetic core

L_1 - Parallel equivalent of L_c

ℓ_1 - Effective length of flux path in core

M - Mutual inductance between two windings

N - Number of winding turns

P_a - Apparent power (volt amperes) delivered to ferromagnetic core

P_c - Real power (watts) consumed by a ferromagnetic core

P_q - Reactive power (vars) taken by a ferromagnetic core

Q_x - Storage factor of unknown inductor

Q_B - Storage factor of B arm of the bridge

Q_c - Storage factor of a ferromagnetic core

q_1 - Storage factor due to C_1

q_2 - Storage factor due to C_2

R_{xs} - Series resistance of unknown inductor

R'_{xs} - Value of R_{xs} corrected for bridge residuals

R_{xp} - Parallel resistance of unknown inductor

R'_{xp} - $(=\frac{1}{G'_x})$ Value of R_{xp} corrected for bridge residuals

R_B - Resistance of B arm of the bridge

R_N - Resistance of N arm of the bridge (L controls)

R_s - Adjustable resistor of constant inductance

R_a - Residual resistance in A arm of bridge

r - Residual series resistance of C_N capacitors

r' - Fixed resistor used in incremental measurements (method A)

R_w - Series winding resistance of a ferromagnetic inductor

R_c - Series resistance representing core losses

R_1 - Parallel equivalent of R_c

Y_x - Complex admittance of the unknown inductor

Y_N - Complex admittance of N arm of the bridge

Z_x - Complex impedance of the unknown inductor

Z_A - Complex impedance of A arm of the bridge

Z_B - Complex impedance of B arm of the bridge
Z_N - Complex impedance of N arm of the bridge
π - The numeric 3.1416
$\omega (=2\pi f)$ - Angular frequency (radians per second)
θ_x - Phase angle of unknown inductor
β - Hysteretic angle of core material
δ - Phase angle of core material
μ_L - Ac permeability of core material in terms of L_1

NOTE: All E values are in volts, I values are in amperes. All capacitance values are in farads, resistance and impedance values are in ohms, and all admittance values are in mhos. Inductance and conductance values are in units indicated. Storage and dissipation factors are numerics.

PARTS LIST

RESISTORS (All resistances in ohms except k = kilohms.)

R1	0.1		510-431
R2	1		510-432
R3	10		510-433
R4	100		510-434
R5	1k		510-435
R6	10k		510-436
R7	0.993-0.995		510-439
R8	9.99	±0.02%	510-439
R9	100	+0.01-0.03%	510-439-2
R10	999	±0.02%	510-390
R11	9950	±0.02%	510-390
R12	49,970	±0.02%	510-390
R13	49,970	±0.02%	510-390

CAPACITORS (Capacitances 1 and less in µf, over 1 in µµf.) See NOTE.

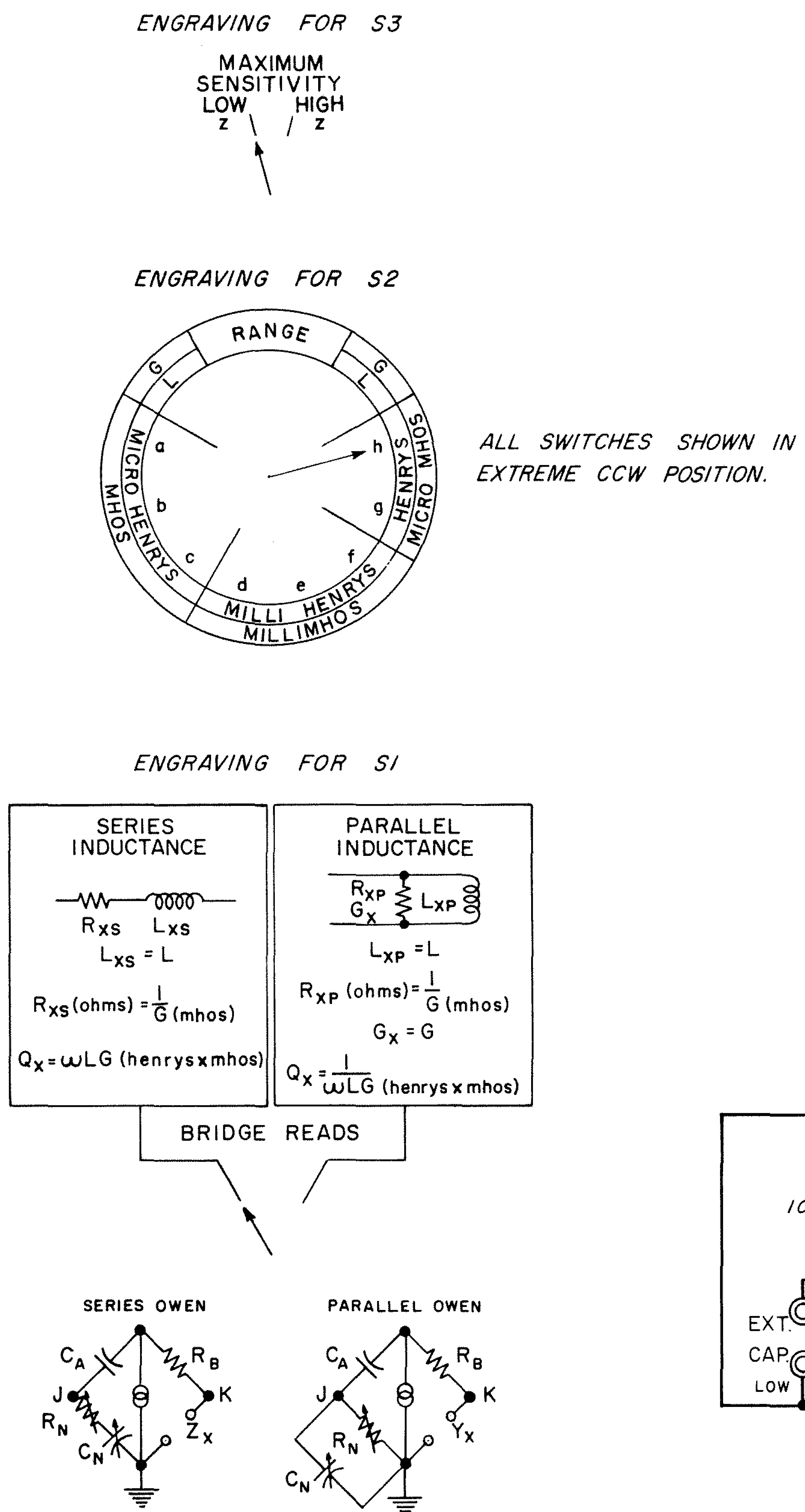
C1	0-130		1420-411
C2	100		980-412
C3	0.001		980-413
C4	0.01		980-414
C5	0.1		980-415
C6	0.001		505-496
C7	0.01		505-497
C8	0.1		505-498
C9	7-140		COA-5
C10	7-140		COA-5L
C11	150	±5%	COM-20D
C12	1		COW-16
C13	50	±10%	COM-20B
C14	0.47		COW-17
C15	0.0047		COW-17
C16	100	±2%	COM-20E

MISCELLANEOUS

L1	INDUCTOR, 3900µh	CHM-7
L2	INDUCTOR, 33µh	CHM-2
S1	SWITCH	SWRW-169
S2	SWITCH	SWRW-170
S3	SWITCH	SWRW-171
T1	TRANSFORMER	578-404

NOTE:

COA - Capacitor, air
COM - Capacitor, mica
COW - Capacitor, wax



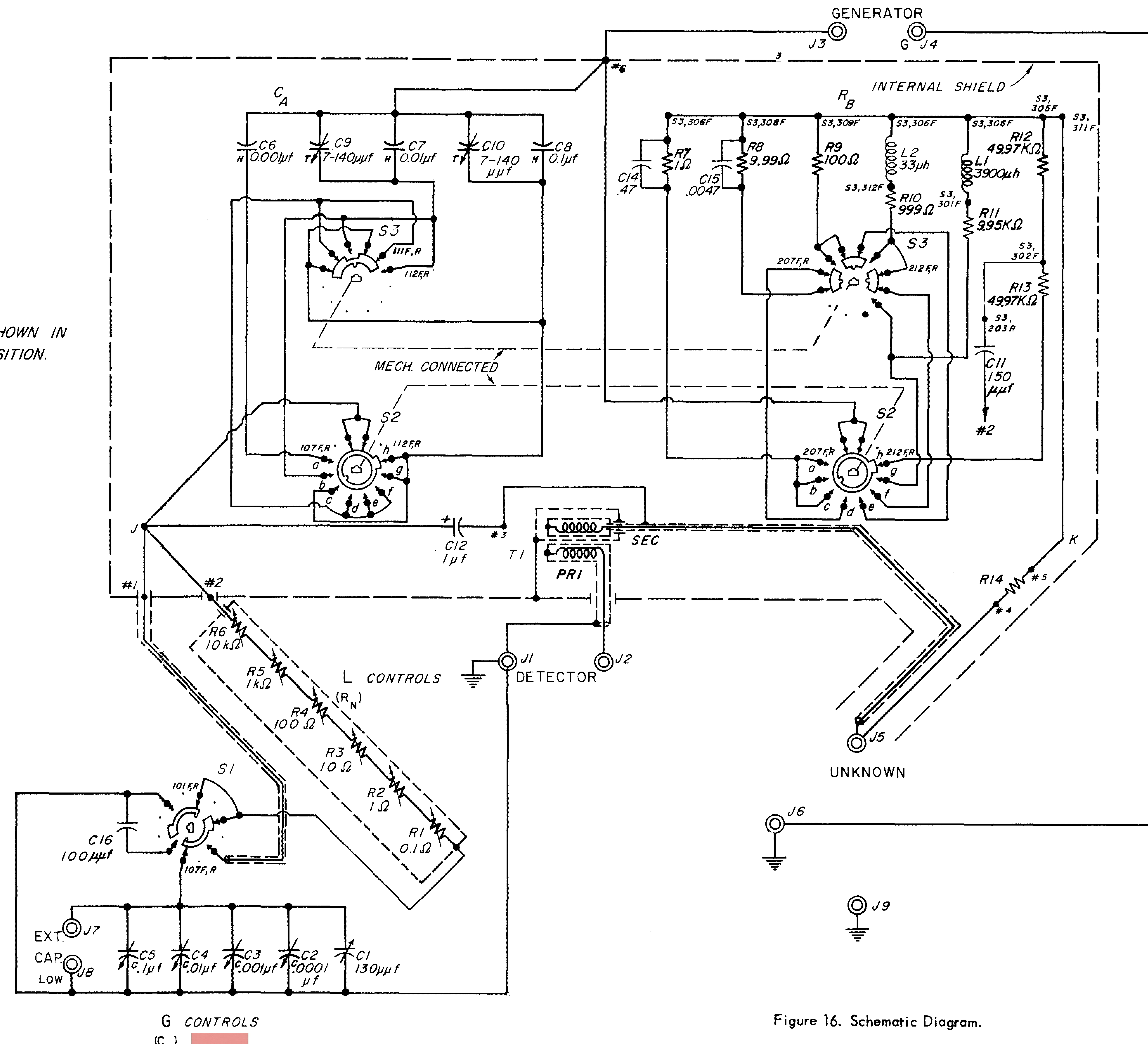


Figure 16. Schematic Diagram.

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