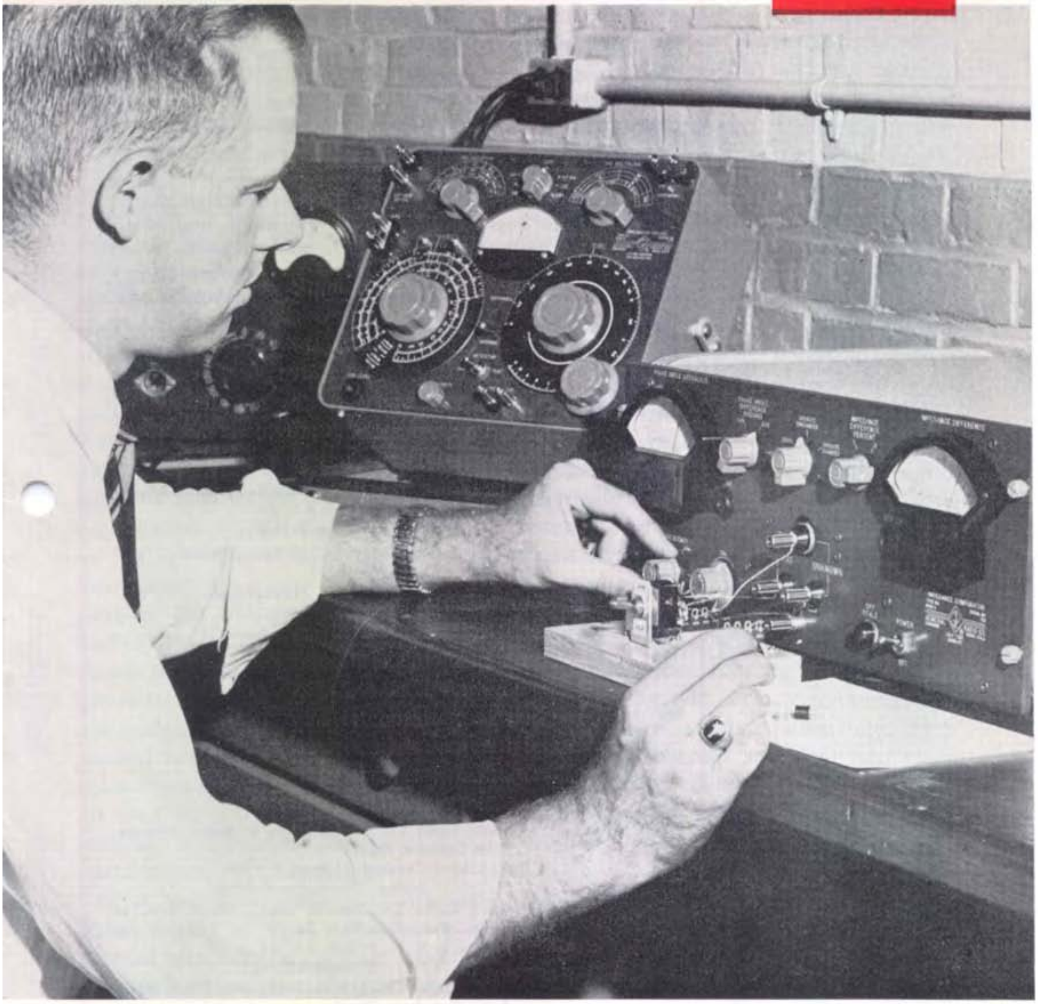
THE GENERAL RADIO
EXPERIMENTER



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Connection Errors in Inductance Measurement

New Inductors and Capacitors

THE GENERAL RADIO

EXPERIMENTER

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GENERAL RADIO COMPANY

West Concord, Massachusetts

Telephone: (Concord) EMerson 9-4400; (Boston) CLearwater 9-8900

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Telephone — N. Y., WOrth 4-2722
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COVER

Measuring the collector-to-base capacitance of transistors with the Type 1605-A Impedance Comparator.

CONNECTION ERRORS IN INDUCTANCE MEASUREMENT

As the pursuit of increased accuracy in electrical measurements moves downward into the fractions of microhenrys and of picofarads, the contributions to the measured quantity made by the connections between measured component and measuring instrument become increasingly important. When a capacitor or inductor is used or measured, it is connected to and becomes a part of a complete circuit. The impedance between its terminals therefore depends not only upon its self-impedance, but also upon the mutual impedances between the capacitor or inductor and the rest of the circuit. These mutual inductances and capacitances are usually sufficiently small to impose no appreciable limit on the accuracy of measurement as long as the self-inductance or capacitance is larger than, say, 100 μh or 100 pf. For smaller inductors or capacitors, some care must be taken both in the construction of standards and in the techniques of measurement to insure that the mutual impedances can either be neglected or can be included in the calibrated value without limiting the desired accuracy. A calibration of 100 microhenrys to an accuracy of 0.1% or to ±0.1 microhenry is not of much significance if the connections produce uncertainties of 0.1 microhenry.

The problems introduced into the measurement of small capacitance by mutual capacitances between capacitor terminals and connections have been discussed in an earlier article.[1] It was the purpose of that article to point out that uncertainties of the order of tenths of a picofarad can be introduced by casual connections; that one can reduce the uncertainties by an order of magnitude or more by making the geometry of the connections sufficiently definite, as, for example, by specifying the terminals to be used as the connection; and that still smaller uncertainties can be achieved by the use of the three-terminal capacitors and measuring techniques that exclude the mutual capacitances.

It is the purpose of this article to discuss the analogous problems introduced into the measurement of small inductance by mutual inductances between the inductor and the connections. In such measurements, the uncertainties with ordinary connections and techniques may be as large as tenths of a microhenry. Much smaller uncertainties can again be achieved by methods analogous to those used for capacitors. Most attention will here be given to the reduction of the mutual inductances themselves and to the reduction of their uncertainties by care in the construction and use of the inductors and connections. Although mutuals can be excluded by magnetic shielding and four-terminal measurements, the added cost and complexity of the shielding and special bridges is not yet justified by the need for higher accuracy in measurements of small inductance. This discussion will therefore be limited to methods of reducing errors when the usual two-terminal inductors and bridges are used.

An example of a two-terminal inductor connected to a bridge is shown in Figure 1. To suggest the origin of these components and to simplify the discussion, only a few of the possible inductances of

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

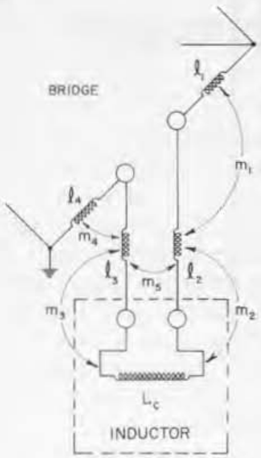


Figure 1. The circuit of an inductor connected to a bridge showing self and mutual inductances which are measured.

wires, l, and the mutuals, m, are shown here, and these are indicated as lumped parameters, although they are actually distributed over the entire circuit. The inductance value obtained by a direct bridge measurement of the components shown would be the sum of the self-inductance, L_c, of the inductor and all the connection inductances, l, and the mutuals, m. This measured value is subject to the uncertainties which can be introduced by accidental changes in the length or orientation of the connecting wires. It is possible to reduce the uncertainties to any desired level if we specify with sufficient precision the geometry of the connections and their environment. A direct measurement, is, however, seldom used when high accuracy is required.

It is usually more convenient to eliminate many of the connection errors by using a substitution rather than a direct measurement. If one measurement is made with the inductor connected as in Figure 1 and then a second measurement is made with the same connections but with the inductor replaced by a shorting link, the difference between the two measured values is independent of the self and mutual inductances, l_1, l_2, l_3, l_4, m_1, m_4, m_5, which appear in both measurements. The difference is still a measure not only of the inductance L_c but of the mutuals, m_2, and m_3, and of the inductance of the shorting link, l_s, and its corresponding mutuals. Although the substitution measurement can remove major portions of the connection impedances and the uncertainties produced by them, the small remaining mutuals must still be considered when small increments, say less than 0.01 microhenry, are significant.

The mutuals m_2 and m_3 represent the magnetic coupling between the inductor and the connecting wires, if it is assumed that the other portions of the bridge circuit are sufficiently remote to have negligible coupling. Their magnitudes change with the form and orientation of inductor and leads, and, hence, they are a source of uncertainty unless the configuration is precisely specified. The need for such precise specification of measurement conditions can be avoided if the coupling is reduced to a negligible value or if the coupling is made invariant with changes in the connecting wires. The coupling can be kept at a minimum by the use of twisted leads for the connecting wires and of toroidal rather than solenoidal coils in the inductor. The coupling can be made independent of connections if that portion of the connecting wires which is closest to the inductor terminals, and which thus contributes most to the coupling between the wires and the inductor or shorting link, is constructed as an integral and unvarying part of the inductor.

The smallest connection errors should, therefore, be obtained from an inductor constructed, as shown in Figure 2, to have both low and constant mutuals.

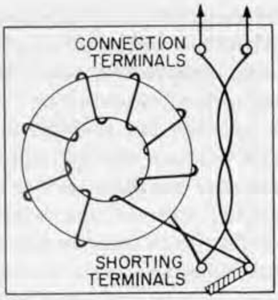


Figure 2. Inductor with separate terminals for connection and for shorting.

This inductor has two sets of terminals. The terminals at the top in Figure 2 are used to connect the inductor into the circuit in which it is measured or used. The terminals on the top are connected to the bottom ones by internal, twisted leads and also to the toroidal coil. The two measurements of the substitution method are made with the bottom right terminals first open and then shorted. The measured difference in inductance should be to a high degree independent of the connections to the inductor as long as they remain constant during the two measurements. Since the connections are made at separate terminals in this inductor, they are not easily disturbed by the application or removal of the shorting link.

The shorting link can, however, introduce error into the inductance measurement in another way. When the shorting link is connected across the inductor, the circuit connected across the bottom terminals of the inductor is that shown in Figure 3. As long as the resistance of the link, R_s, is not zero, there is an equivalent inductance, L', between these terminals, which is

$$L' = L_c \frac{R_s^2}{(R_s + R_c)^2 + \omega^2 L_c^2}$$

This inductance, like that of the link, appears only in the measurement with the inductor shorted and hence is part of the measured difference in inductance. The requirement for accuracy is, therefore, not that this inductance be zero, but that it be reproducible.

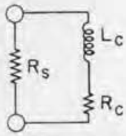


Figure 3. Circuit of shorted inductor.

Since the inductance L' depends upon R_s, any change of the contact resistance of the shorting link with time or with the method of application results in a change in the measured inductance. The relation between the change in the resistance, $\triangle R_s$, and the change in inductance $\triangle L'$ is

$$\triangle L' = 2L_c \triangle R_s \left\{ \frac{R_s}{(R_c + R_s)^2 + \omega^2 L_c^2} - (R_c + R_s) \left[\frac{R_s}{(R_c + R_s)^2 + \omega^2 L_c^2} \right]^2 \right\}$$

As an example of the magnitude of $\triangle L$, consider a standard inductor with L_c = 10 μh and R_c = .02 ohm and a shorting link with R_s = .001 ohm and a variation $\triangle R_s$ = 0.0001 ohm at a frequency of 100 cycles, where $\omega^2 L_c^2$ can be neglected. The uncertainty is $\triangle L'$ = .004 microhenry in an inductance of 10 microhenrys. The variations assumed for $\triangle R_s$ are those of a shorting link in good condition, so the uncertainties could be expected to exceed this figure in practice. The shorting link in parallel with the coil can, therefore, limit the accuracy of the measurement of low inductance at low frequencies.

This uncertainty can be eliminated very easily by use of a switch, or the shorting link as a switch, which connects to the terminals *either* the inductance coil *or* the short alone instead of connecting the coil alone or the coil shunted

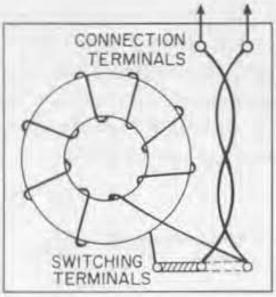


Figure 4. Inductor with shorting link arranged to disconnect coil when short is connected.

by the shorting link. An inductor with such switching is shown in Figure 4. With the shorting link in the position shown, the coil is connected to the connection terminals at the top; with the link moved to the dotted position to connect the right lower pair of terminals, the connection terminals are shorted and the coil is disconnected.

When an inductor having the construction shown in Figure 4 is calibrated in terms of the change in inductance when the shorting link is switched from one position to the other, the calibration accuracy can be very high and the inductance very low before connection errors impose a limit. Since the important section of connecting wires adjacent to the terminals where the change is made are an integral and constant part of the inductor, the form and position of the external connecting wires have negligible effect, provided only that they do not change while the difference is being measured. Since the switching link and its two positions are also an invariant part of the inductor, the self and mutual inductances of the link are both small and definite parts of the calibration. Since the link is not connected in parallel with the inductance coil, the contact resistances of the link have no effect upon the inductance. And, since the inductance coil is toroidal and the connections within the inductor are oriented to minimize the open loops, there is no coupling to external fields or conductors which can vary the inductance. The inductance so calibrated should be sufficiently definite to make the uncertainties less than 0.001 microhenry and to justify a calibration accuracy of 0.1% for inductance as low as 1 microhenry.

To conclude this discussion of connection errors without acknowledgment of the source of much of this information would be a large terminal error. From conversations and correspondence with members of the Resistance and Reactance Section of the National Bureau of Standards in Washington have come knowledge of some of the sources of error in inductance measurements as well as suggestions for their reduction.

— John F. Hersh

NEW STANDARD INDUCTORS
MORE TERMINALS, LESS INDUCTANCE

The General Radio Company recently extended the range of its standard capacitors downward by several decades to 0.01 pf by the introduction of the new Type 1403 Standard Air Capacitors.[1] A parallel, but more modest, step is now being taken to extend the range of our standard inductors downward by the addition of a 50-microhenry unit. In anticipation of future demands for higher accuracy and smaller inductance, the design of this inductor and its two immediate predecessors, the 100-μh and

[1] "New Three-Terminal Capacitors," *General Radio Experimenter*, 33, 8 & 9, August-September, 1959.

200-μh sizes, incorporates the additional terminals and new method of calibration discussed in the preceding article.

The New Inductor

A TYPE 1482 Inductor of 50 microhenrys has for some time been available on special order. The new TYPE 1482-A differs from the earlier models both in having the new six-terminal connections (see below) and in having lower resistance. The coils are now wound with 100/32 Litz wire to have a dc resistance of 0.043 ohms as compared to the 0.200-ohm resistance of previous inductors. An increase in wire size has also been made wherever possible in other inductors, and the low-frequency Q is now more nearly constant throughout the line of inductors.

As in all these inductors, the coil is a uniformly wound toroid on a ceramic core for high stability and low external field. The 50-microhenry coil and the coils up through 500 microhenrys have duplex windings, *i.e.*, their toroids are wound in two equal halves, and the halves are connected in parallel rather than in series, as shown in Figure 1. The duplex winding has two advantages for small inductance coils. For a given inductance, the number of turns is greater with the duplex winding, and the ease and accuracy of adjustment to nominal value are thereby increased. The parallel windings still confine almost all the magnetic field to the torus and, in addition, they can further reduce the small field produced by the equivalent single turn of the conventional toroidal winding. With the leads positioned as shown in Figure 1, the current does not make a complete circle around the circumference of the torus but travels across a diameter on one lead wire and returns in two parallel paths through the two halves of the winding. There are thus two D-shaped loops so phased as to produce very small external field which can contribute to the measurement uncertainties.

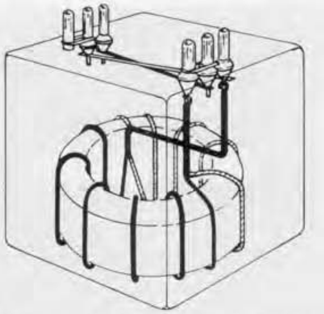


Figure 1. Diagram of duplex winding used for low-inductance standards.

Terminals and Wiring

Arrangement of terminals and wiring for the 50-, 100-, and 200-microhenry inductors is shown in Figure 2. In Figure 3 is shown for comparison the connections formerly used for all of the TYPE 1482 Inductors and still used for inductors of 500 microhenrys and higher. The obvious and significant difference is the addition of three more binding posts at the bottom of the new panel. Two of the new terminals (marked L_0) are connected by internal leads to the two insulated terminals at the top of the panel. The inductance coil is connected to the two outer bottom terminals. When the attached shorting link is connected between the left pair of bottom terminals (marked L), the coil is connected to the top terminals; when the link is moved to the right pair of bottom terminals, the coil is disconnected and the link short-circuits the leads to the top terminals. On both panels the upper left terminal is connected to the inductor case, and the inductor is usually used and calibrated with the adjacent terminal (*LOW*) con-

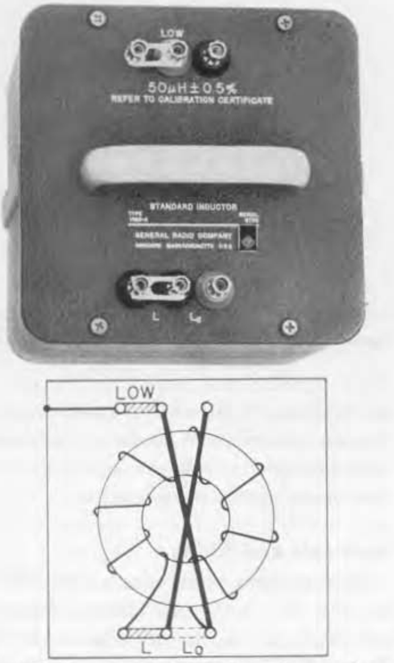


Figure 2. New six-terminal panel and connections.

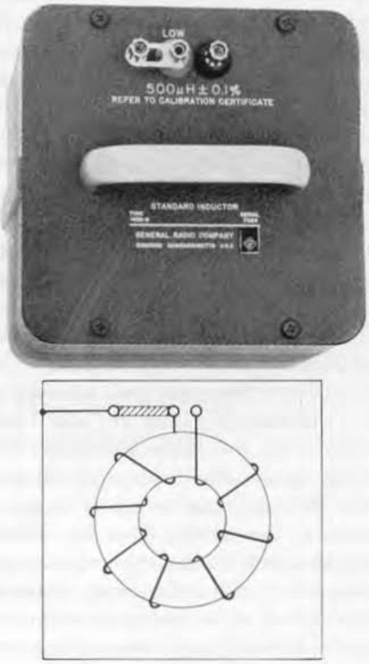
nected by the attached link to this terminal and to the case.

Calibration

In the initial calibration, usually at the National Bureau of Standards, inductors are calibrated by the substitution method in which two measurements are made: one with the inductor connected to the bridge and the other with the same connecting wires but with the inductor replaced by a short-circuiting bar or link. For an inductor with the three-terminal panel of Figure 3, the first measurement is made with the bridge connected to the pair of insulated terminals, and a short is then either applied to these terminals or the connecting wires are moved to the left pair of terminals which are connected by the link. For an inductor with the new, six-terminal panel of Figure 2, the bridge is still connected to the upper right pair of terminals (connection terminals). The measurement of the inductor is made with the link on the lower terminals in the left or L position to connect the coil. The short is then applied by moving the link to the right or L_0 position on the lower terminals (reference terminals).

The advantages of the new panel and connections are that the mutual inductances between the internal leads, coil, and shorting link are independent of connections and environment because they are an invariant part of the inductor and that the connecting wires are not subject to disturbance when the short is applied at terminals separated from the connections. The connection errors and methods of reducing them have been discussed in detail in the preceding

Figure 3. Three-terminal panel and connections.



article. Since the errors are seldom larger than tenths of a microhenry, the advantages of the six-terminal panel in reducing these errors are appreciable only when the inductance is small. The upper limit of inductance with which the new terminal arrangement is used has been chosen somewhat arbitrarily to be 200 microhenrys, in part because this is also the dividing line between the hand-wound and the machine-wound coils in the TYPE 1482 Inductors.

Calibration by Direct Comparison

The major difference between a calibration with the short circuit at the connection terminals and one with the short at the reference terminals is the inductance of the internal leads between the two sets of terminals. This inductance (the difference between the two calibrations) is about 0.11 microhenry. Its value is important, not only in unintentional misuse of the short, but in a calibration by direct comparison of one of the six-terminal inductors with a three-terminal one of the same nominal value. In many calibrations outside of the National Bureau of Standards, a direct-comparison method is used. The unknown is simply compared to an inductor of almost equal value which has an NBS calibration and the measured difference used to obtain the value of the unknown. The measurement with the short circuit is implicit in this new calibration, however, because the Bureau used a short in their original calibration, and the new calibration is valid only with the short applied at the position used in the original calibration. If, therefore, a new 50-microhenry, TYPE 1482-A Inductor, is calibrated by direct comparison with an older one with an NBS or GR calibration, the calibrated value so obtained is that with the short at the connection terminals. The inductance obtained by a short at the reference terminals will be about 0.11 microhenry less. When accuracy to 0.01 microhenry is important, the lead inductance should be measured by moving the short from connection to reference terminals.

When a calibrated six-terminal inductor is available, the calibration of other inductors can still be influenced by the inductance of the internal leads. If the two inductors are compared in the usual manner by a difference measurement using the same external leads, the measured difference includes not only the difference between the two inductance changes at the reference terminals but also the difference between the two internal lead inductances. Calibration by this method is subject to error unless the differences in internal lead inductance are negligible or are measured. In these new TYPE 1482 Inductors, experience with a small initial sample indicates that in production the lead inductance of 0.11 microhenry may be held constant to better than 0.01 microhenry so that the error in direct comparison of similar inductors should be less than 0.02%.

When lead inductance is not sufficiently constant, its effect can be eliminated by another method of comparison. The two six-terminal inductors can be connected in series to the bridge. A first measurement is made with the short of one inductor in the L position while that of the other is in the L_o position on the reference terminals. A second measurement is then made with both links moved to the opposite position. The measured difference is the difference between the two inductance changes at the reference terminals and is independent of the internal lead inductances because they appear in both measurements and cancel in the difference.

— JOHN F. HERSH

MORE NEW INDUCTORS: FIXED AND DECADE

Type 1481 Inductors

Inductors in the TYPE 1481 series are high-Q units, toroidally wound on molybdenum-permalloy dust cores. Although not as accurately calibrated as the TYPE 1482 Standard Inductors, they have many uses in audio-frequency measurements, both as auxiliary standards and in circuit development.

Four new units have been added recently to this group as listed in the table below. Characteristics are similar to those of other TYPE 1481 Inductors, listed in our current catalog, except that TYPES 1481-AA, -BB, and -CC are wound on lower-permeability cores with corresponding changes in the frequency for Q_{max}, etc.

Dimensions: Case, (height) 3⅝ x (width) 3⅛ x (depth) 1⅝ inches (92 x 80 x 41 mm); over-all height, including terminals, 4⅝ inches (117 mm).

Net Weight: 14 ounces (0.4 kg).

Type	*Nominal Inductance*	*Accuracy of Adjustment**	*Rms Current for 0.1% increase in L*	*Resonant Frequency*	*Approx. dc Res.*	*Code Word*	*Price*
1481-AA	100 μh	±2 %	120 ma	3000 kc	0.020	INDUCTOMAP	**$37.50**
1481-BB	200 μh	±2	76 ma	2100	0.044	INDUCTOMUG	**37.50**
1481-CC	500 μh	±1	54 ma	1330	0.112	INDUCTOMEN	**37.50**
1481-N	10 h	±0.25	0.24** ma	10	416	INDUCTONAG	**50.00**

*Calibration is at zero frequency and initial permeability. **For 0.25% increase in L.

Type 940-DD Decade-Inductor Unit

Inductors of the 1481 type, the 100-, 200-, and 500- μh sizes are used in the TYPE 940-DD Decade Inductor to provide decade steps of 100 μh, and a total of 1 mh for the decade. Four inductors are used in a 1-2-2-5 series, combinations are connected by the switch to yield successive unit values in the decade sequence.

Accuracy: 2%.

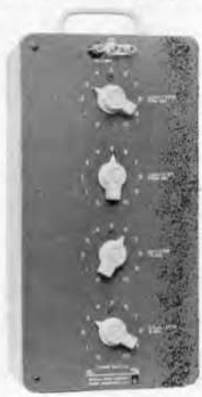
Net Weight: 4 lb. (1.9 kg).

Type		*Code Word*	*Price*
940-DD	**Decade-Inductor Unit 100 μh per step**	INDUCTOCOP	**$110.00**

Type 1490-F Decade Inductor

This four dial decade-inductance box incorporates the new TYPE 940-DD Decade-Inductor Unit together with one each of the TYPE 940-E, -F, and -G units, which have decade steps of 1 mh, 10 mh, and 0.1 h respectively. Total inductance is 1.111 henrys, adjustable in steps of 100 μh above the initial inductance.

Type		*Code Word*	*Price*
1490-F	**Decade Inductor 1.111 h**	FOCUS	**$450.00**



(*Left*) Type 1481-N Inductor; (*center*) Type 940-DD Decade-Inductor Unit; (*right*) Type 1490-F Decade Inductor.

MORE AND BETTER CAPACITORS

Improved Adjustment Accuracy for the Type 1409 Standard

As we constantly improve the stability of our electrical standards, it becomes equally desirable to improve the closeness of their adjustment to nominal values. Two factors influence the selection of this adjustment accuracy: first, the expected stability and, second, the complexity of the adjustment in terms of time and cost.

Recently published eight-year records for our Type 1409 Standard Capacitors,[1] which were introduced for sale only three years ago, indicate that stability can be disregarded as a limiting factor.

The skills acquired from two years' experience in assembling these capacitors impelled the men who build them to suggest that, without appreciable increase in cost, the adjustment could be made to a better nominal accuracy than the then current 0.1%, and, accordingly, a new tolerance of 0.05% was established. During a transition period, the nameplate continued to read 0.1%, and additional labels were affixed to the base, bearing the legend, "Adjustment Accuracy 0.05%." New nameplates now in use bear the 0.05% figure. A certificate, as before, accompanies the capacitor, giving the measured value[2] under stated environmental conditions.

[1] "Stability Records of Standards of Inductance and Capacitance," *General Radio Experimenter*, 34, 4, April, 1960.
[2] I. G. Easton, "Standards and Accuracy," *General Radio Experimenter*, 34, 6, June, 1960.

(*Left*) Type 1409-T Standard Capacitor; (*right*) Type 980-J Decade-Capacitor Unit.

Type 980-J Added, 100 pf per step

For most of the life of the Type 980 Decade-Capacitor Units and their predecessors, the Type 380's, only three capacitance ranges were available, regardless of the dielectric used, and which had, respectively, 0.1, 0.01, and 0.001 μf per step. In our current Catalog P we now list a decade-capacitor unit having 100 pf per step, the Type 980-D. The favorable response accorded this decade unit, which has polystyrene dielectric, has resulted in the introduction of the Type 980-J Decade Capacitor, having silvered-mica dielectric and nominal capacitance increments of 100 pf per step. The capacitance increments from zero position are within $\pm(\frac{1}{2}\% + 2 \text{ pf})$ of the indicated value for any setting for two-terminal connection and within $+0, -(2\% + 8 \text{ pf})$ for three-terminal connection. The differences between these adjustment-accuracy figures and those for the companion Type 980-F, -G, and -H are caused by the switch capacitance (which varies from position to position) and by the wider percentage adjustment tolerance of the low-valued capacitors. Similarly, the dissipation factor figure of <0.0006 is simply determined by the dissipation factor of the 100-pf capacitor.

New Three-Decade Capacitor, Type 1419-M, Replaces Type 219-M

The Type 219-M Decade Capacitor, our "economy" decade capacitance box, has been replaced by a new and improved model, the Type 1419-M. Mechanical changes bring the construction

(*Left*) Type 1419 Decade Capacitor; (*right*) Type 980-L Decade-Capacitor Unit.

and appearance into line with the other Type 1419 units, which have previously replaced equivalent Type 219 models.

The individual mica-dielectric capacitors used in the 0.01-μf-per-step and 0.001-μf-per-step decades remain unchanged. The Type 980-L paper-dielectric decade, 0.1 μf per step, uses firecracker-shaped, sealed, foil-and-paper capacitors having a viscous impregnant. These capacitors have the following improved characteristics:

1. Adjustment accuracy of capacitance increments from zero position is changed to ±1.5% (from ±2%) of the indicated value for any setting.
2. Dissipation factor is reduced to less than 0.005 (from less than 0.01).
3. Insulation resistance is increased to $>10^{10}$ ohms (from 10^8) at 100 v, 25°C, 50% RH, and after 5 minutes' electrification time.
4. Temperature coefficient is +180 ppm/°C nominal.
5. Maximum operating voltage (dc or peak) is raised to 500 (from 300).
6. Frequency limit for maximum voltage is up to 2 kc (from 1 kc).
7. Maximum operating temperature is up to 90°C (from 65°C).
8. The stability of all characteristics is considerably improved.

The use of the sealed firecracker units prevents increase of both capacitance and dissipation factor, which would result from moisture contamination. Further, the use of the viscous impregnant (rather than a liquid one), immobile at operating temperatures, improves capacitance stability since the relative positions of conductors and insulation will not change appreciably as a result of shock, vibration, change of position, or temperature variations.

— P. K. McElroy

Type		*Code Word*	*Price*
1419-M	**Decade Capacitor**	FORAY	**$145.00**
980-J	**Decade-Capacitor Unit, 100 pf per step**	ADIEU	**48.00**

Dimension drawings of all Type 980 Decade-Capacitor Units are available on request.

NEREM — 1960

Boston, Massachusetts — November 15-18, 1960

Come to NEREM, and when you do, drop in at Booths 9 and 10 at the exhibits in the Commonwealth Armory. Our engineers will welcome your call and will be glad to show you the new instruments that we shall have on display, among them:

An electronic frequency meter, direct reading to an accuracy of 0.1% and capable of measuring incidental fm to 1 part in 10^6.

A calibrator for accelerometers and other vibration pickups.

The Type 1531-A Strobotac®, described in the September *Experimenter*

plus

many other instruments displayed in interesting and significant uses.

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