THE General Radio EXPERIMENTER

VOLUME XXIV No. 2 JULY, 1949

ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

A NEW DECADE INDUCTOR

● **DECADE RESISTANCE UNITS,** as exemplified by the TYPE 510 or 602 series, and decade capacitors, such as the TYPE 380 or 219 series, have long found use as standards in electrical measurements and as components of experimental circuits in the laboratory. General Radio Company now offers a companion set of high-quality decade inductors which cover the range from one millihenry to ten henrys, and are intended primarily for use at audio and the lower ultrasonic frequencies. Each TYPE 940 Decade Inductor Unit consists of four individual inductors having nominal values 1-2-2-5, which are assembled with a TYPE 920-A Switch joining them in series to achieve the ten steps of the decade. The TYPE 1490 Decade Inductors provide a wide range of adjustment by combining three or four TYPE 940 Decades in a single cabinet.

DESIGN CONSIDERATIONS

These inductors possess, to a considerable degree, the most de-

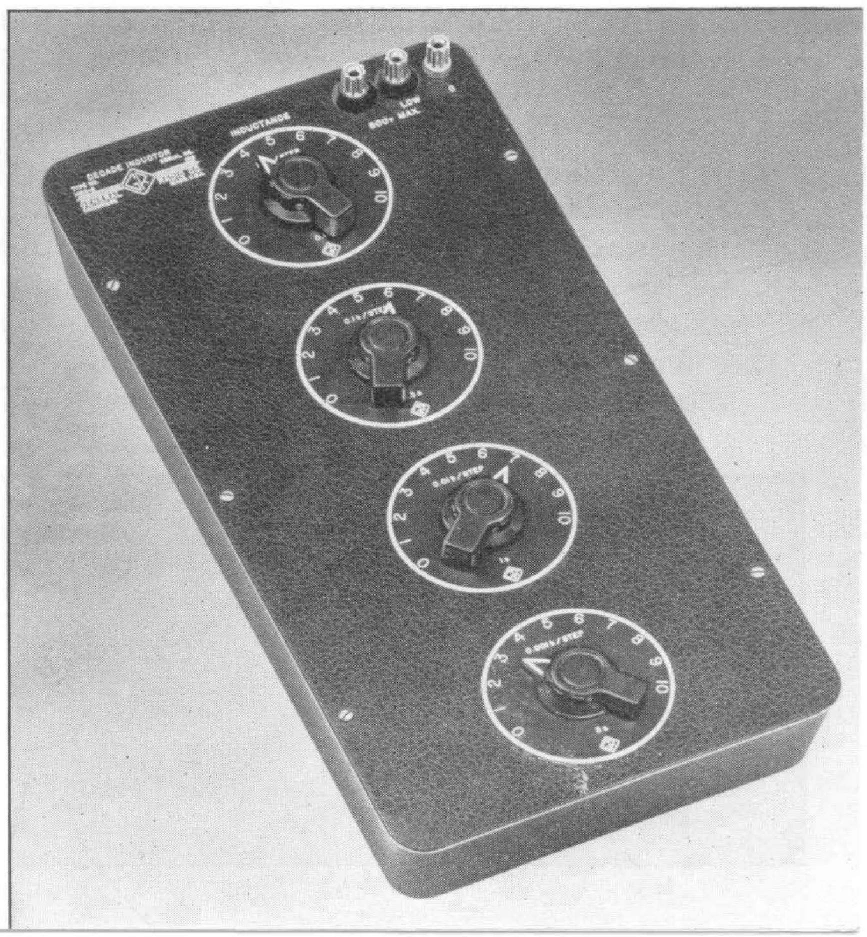


Figure 1. View of a four-dial Type 1490-B Decade Inductor covering a range of 0 to 11.11 h in steps of 0.001 h.

sirable characteristics of a standard inductor. In the first place, in contrast with variometers and solenoid windings, it is important that such inductors be astatic, so that voltages are not induced in them by stray magnetic fields and, correspondingly, they do not create external fields when in use. This is accomplished by winding each individual inductor on a toroidal form with a uniform distribution of its turns around the complete circumference of the toroid. Such a toroidal winding will be astatic except for the equivalent of a single turn loop having the mean circumference of the toroid. These individual inductors may then be stacked in close proximity with a negligible mutual inductance between them.

To minimize their d-c ohms-per-henry ratios, and thus to increase their low frequency storage factors Q, a multiple layer winding is required. To minimize distributed capacitance and to raise their natural frequency and their high-frequency storage factors, a banked winding, rather than a succession of layers around the toroid, is required. A special toroidal winder was developed for this purpose.

To achieve a high value of maximum Q with a minimum of bulk, and to have this maximum occur within the operating frequency range, required a ferromagnetic core. Since the permeability of a ferromagnetic medium is markedly a function of the flux existing in it, such a core must be diluted with a non-magnetic material to minimize the eddy current losses within the operating frequency range, and should have low hysteresis loss. Finally, for stable calibration, the core should have a minimum temperature coefficient of permeability. A stabilized molybdenum permalloy dust core meets these requirements successfully and, for the first time, permits a satisfactory decade inductor to be constructed which has the operating characteristics described below.

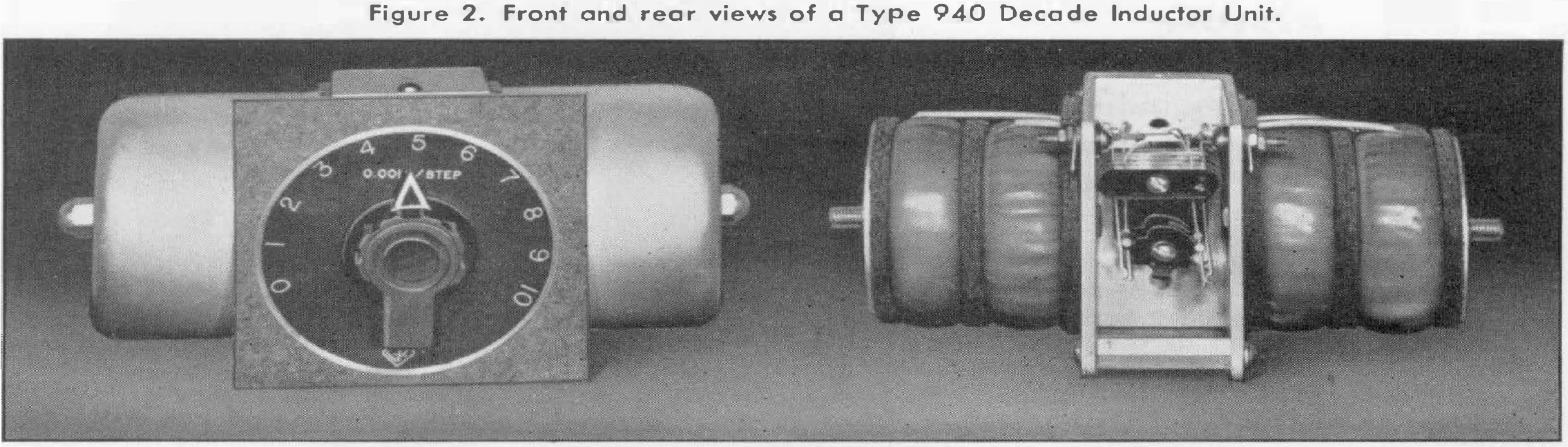
CONSTRUCTION

Molybdenum Permalloy Dust Cores

The Type 940 Inductors are wound on stabilized molybdenum permalloy dust toroids, which were developed by the Bell Telephone Laboratories for loading coils and filter elements, and which are described in a noteworthy paper[1] by Legg and Given. Grain size is 120-mesh, giving a mean diameter of 42 microns and an r-m-s diameter of 50 microns. Quoting their data, the 2-81 molybdenum permalloy (molybdenum 2, nickel 81, iron 17) shows a positive temperature coefficient of permeability of about $180/10^6$ per degree C. To this alloy is added a small quantity of another permalloy containing 12 per cent molybdenum which, having a Curie point slightly above room temperature, shows a large negative coefficient at room temperature. As indicated in Figure 3, the resultant

[1] Bell System Technical Journal, Vol. 19, July, 1940.

Figure 2. Front and rear views of a Type 940 Decade Inductor Unit.



mixture gives a "stabilized" core which has a negative coefficient of about $24/10^6$ per degree C. (a 7.5 fold reduction) over the range 16–32 degrees C. Below 5 degrees C. and above 50 degrees C. these stabilized cores regain the large positive coefficient of the 2–81 alloy. Legg and Given also show maximum permeability occurring at about 6.5 oersteds and exceeding the initial value by about 2%, and indicate that the effective permeability has dropped to its initial value when H is increased to about 16 oersteds.

Winding and Calibration

Since these inductors are intended primarily for use at audio and somewhat higher frequencies, an available core type having a nominal permeability of 125 was chosen. Each core is initially measured in an eleven-turn jig. The correct number of turns for a specified inductance can then be predetermined within a turn or two. A suitable adjustment of the toroidal winder then insures a full circumferential distribution of the winding. After winding, each inductor is checked against a standard unit with a comparison bridge and is adjusted, if necessary, within prescribed fractional limits. The ultimate limits, obviously, must be broadened as the inductance is reduced. After impregnation a set of four inductors having values 1-2-2-5 is mounted into a decade assembly.

Electrostatic Shielding

Each of the TYPE 940 Decades is electrostatically shielded. As supplied, neither terminal is connected to the chassis. If the terminal marked LOW is grounded to the chassis, a minimum of capacitance is placed across the 5-unit toroid and gives the largest minimum value of natural frequency for the decade. The TYPE 1490 Assemblies are mounted in a metallic cabinet. No point in circuit is internally connected to the chassis. A terminal post, marked G, is mounted on the cabinet panel which, if desired, may be connected to the inductor terminal marked LOW. This will place a minimum of capacitance across the highest-valued decade in the assembly and give the largest minimum value of natural frequency for the entire assembly.

ELECTRICAL CHARACTERISTICS

Variation of Inductance with Applied AC

The Rayleigh[2] equation gives the variation of the permeability μ of a ferromagnetic material from its initial value in terms of the applied magnetizing force H:

$$\mu = \mu_o + \alpha H \qquad (1)$$

This equation holds for diluted cores, provided that the initial value of their effective permeability μ_o is substantially greater than unity.

These TYPE 940 Inductors are calibrated in terms of their initial inductance L_o corresponding to μ_o. In terms of Equation (1) and the core geometry, for

[2] Bell System Technical Journal, Vol. 15, January 1936, page 44.

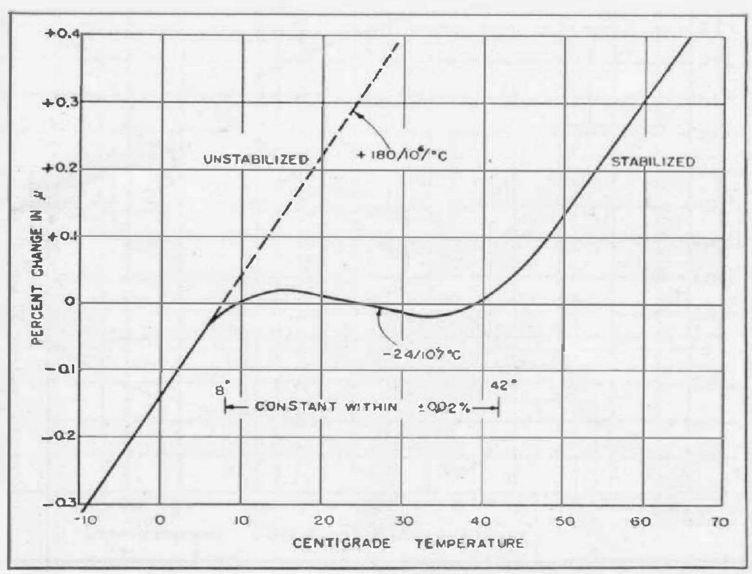


Figure 3. Temperature characteristic of molybdenum permalloy dust core (Courtesy Bell System Technical Journal).

any individual L_o (absolute henrys) carrying any r-m-s current (amperes) the corrected value will be given by:

$$L = L_O(1 + \beta I\sqrt{L_O}) \qquad (2)$$

or in terms of the r-m-s applied volts and the frequency:

$$L = L_O\left(1 + \frac{\beta E}{\omega\sqrt{L_O}}\right) \qquad (3)$$

It was found that the initial values of α and β are 0.84 and 2.03. These numerical coefficients hold *constant* (Rayleigh's law) up to an H of about 300 millioersteds, corresponding to a value 0.0010 for the product $I\sqrt{L_O}$ and an increase of 0.20 per cent above the initial inductance. The variation of β at higher values of $I\sqrt{L_O}$ is shown in Fig. 4. When the correction factors in (2) and (3) are used they must be applied individually to the toroids actually in circuit and the results added. Ordinarily it is necessary to do this only to the larger units of a series. Further data are given in the specifications below.

Incremental Inductance

To a close approximation, when a d-c biasing current I_b is passed through these inductors, their initial inductance is reduced in a degree proportional to I_b if the product $I_b\sqrt{L_O}$ in amperes and henrys remains less than 0.010. The equation for this correction can be written:

$$L = L_O(1 - \gamma I_b\sqrt{L_O}) \qquad (4)$$

The coefficient γ will vary somewhat with the simultaneous a-c excitation, but a typical value of 1.4 can be used. The increase of γ with higher biasing levels is indicated in Fig. 4.

Frequency Correction

Any inductor possesses a certain distributed capacitance, which resonates it at its natural frequency and raises its effective inductance at any lower frequency. These TYPE 940 Decade Inductors have been calibrated at their minimum or zero frequency values. If necessary, their effective inductance at any operating frequency may be computed from the equation:

$$L = \frac{L_O}{1 - \omega^2 L_O C_O} \qquad (5)$$

Appropriate values for the distributed capacitance C_O are indicated in the specifications below.

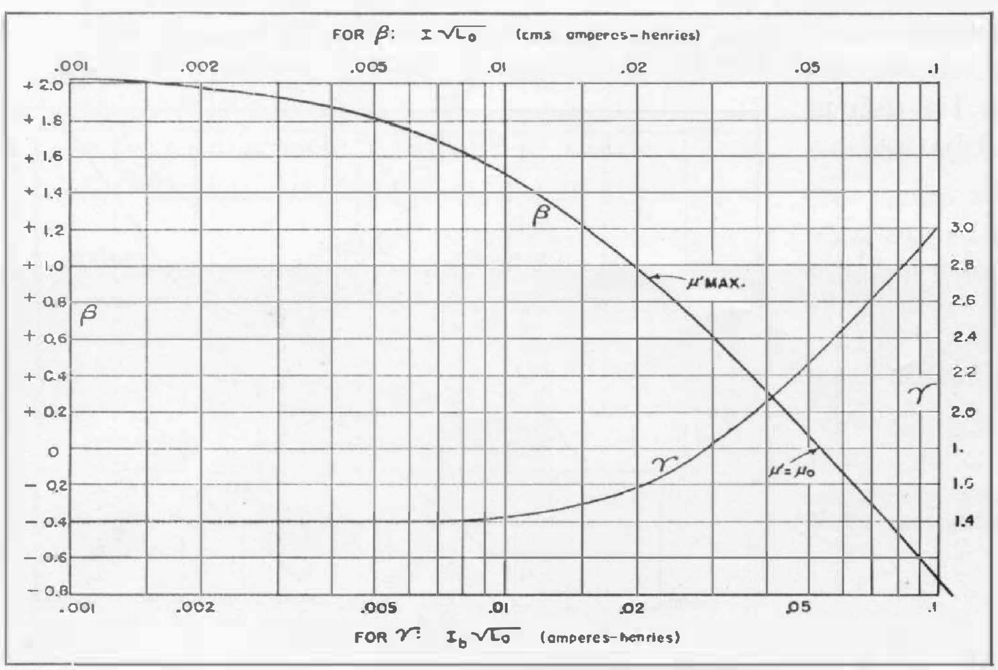


Figure 4. Variation of the coefficients β and γ used in Equations 2, 3, and 4.

D-C Resistance and Zero Inductance Values

Each of the toroidal inductors was wound with the minimum resistance practicable. The 1, 2, and 5 millihenry toroids, as wound, have about 60 ohms per henry, while the higher values have about 44 ohms per henry. The switch and connector resistance of each Type 940 Decade is about 30 milliohms, of which only 4 milliohms is actual contact resistance and subject to possible variation. These 30 milliohms are insignificant in the higher decade units, but they do appreciably reduce the low frequency Q values of the Type 940-A Decade, especially when this lowest decade is used *alone* in the Type 1490 Assemblies. The zero-setting resistance of either Type 1490 Assembly amounts to 30 milliohms per decade plus 30 milliohms for the internal wiring.

Each Type 940 Decade has a zero-setting inductance of 0.13 microhenrys; the zero-setting inductance of the Type 1490 Assemblies is 0.31 microhenrys per decade.

Storage and Dissipation Factors — Basic Theory

The utility of an inductor at any frequency and operating level is established by its storage factor Q, or by its dissipation factor D, which is the reciprocal of Q. The following analysis is an expansion of an earlier paper[3] by two of the author's colleagues. In an inductor having a ferromagnetic core, the magnitudes of Q and D are dependent upon two fundamental types of internal loss — core or magnetic loss, which is a function solely of the core used, and winding loss, which depends solely on the winding applied to the core. Magnetic loss, in turn, has three components — residual loss, hysteresis loss, and eddy current loss. Winding loss, likewise, has three components — copper loss, dielectric loss in the insulation of the windings and its environs, and skin-effect loss due to eddy currents induced in the windings. It can be shown that these six component losses may best be combined in terms of the sum of the corresponding dissipation factors:

$$D = D_m + D_w = (D_r + D_h + D_e) + (D_c + D_d + D_s) \qquad (6)$$

The residual dissipation factor D_r is proportional to the effective permeability μ' of the core and is independent of the frequency. At low induction levels where Rayleigh's law holds and α in Equation (1) is constant, the hysteresis factor D_h is independent of the frequency f and is proportional to H. The eddy current factor D_e is proportional to the product $\mu' f$.

The copper-loss dissipation factor D_c is defined as the ratio of the d-c resistance R' to the reactance of the inductor and is, therefore, inversely proportional to f and becomes the predominant component of D_w at low frequencies. The dielectric loss factor D_d is the major component of D_w at high frequencies, since it is proportional to the square of

[3]McElroy and Field, "How Good is an Iron-cored Coil?" *General Radio Experimenter*, March, 1942.

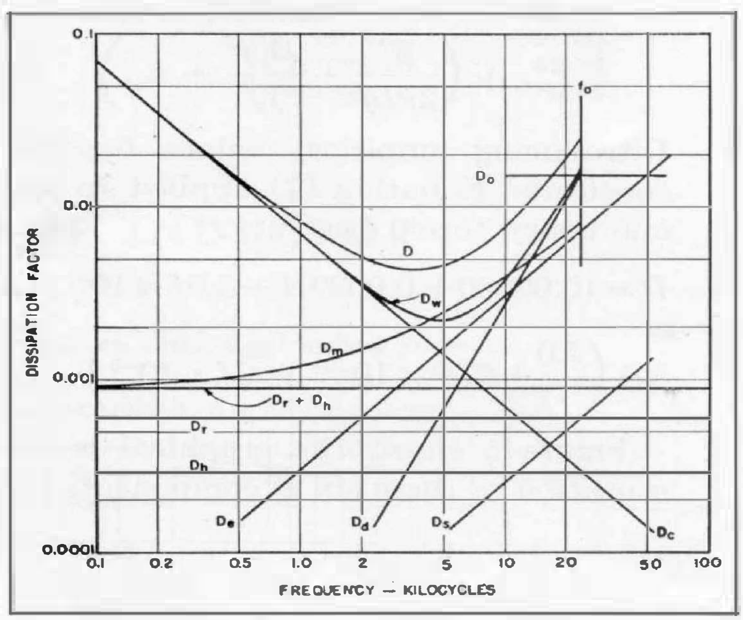


Figure 5. Evolution of the D curve for one henry toroid energized at 100 millioersteds.

To obtain D_m curve add ordinates of lines D_r, D_h and D_e.

To obtain D_w curve add ordinates of lines D_c, D_d and D_s.

To obtain final D curve add ordinates of D_m and D_w curves.

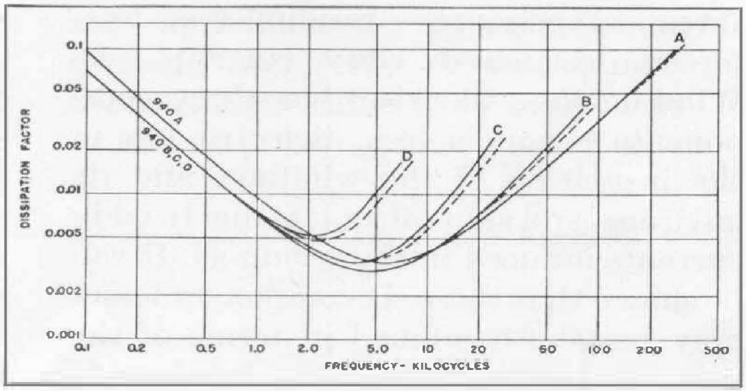


Figure 6. D curves for the full value of each Type 940 Inductor taken at initial μ. Dashed curves correspond to use with chassis floating.

the frequency. D_d can be evaluated in terms of the natural frequency f_o and D_o, which is the value of D_d at f_o. (D_o, in turn, can be considered to be independent of the operating frequency.) Finally, the dissipation factor D_s due to skin effect is proportional to the frequency and usually can be made insignificant by replacing large diameter wire with litz wire (with some increase in D_c). This was done in the 1, 2, and 5 millihenry toroids.

Substituting these six factors, in sequence, into (6), we have Equation (7) in which c, b, k_1, and k_2 are appropriate constants. Note that only D_h depends directly on the operating level and hence vanishes at initial permeability.

$$D = \left(\frac{c\mu}{2\pi} + bH + k_1\mu' f\right) + \left(\frac{R'}{2\pi Lf} + \frac{D_o f^2}{{f_o}^2} + k_2 f\right) \quad (7)$$

Introducing empirical values for the constants, Equation (7) applied to the one henry toroid becomes:

$$D = (0.00060 + 0.0029H + 3.0f \times 10^{-7}) + \left(\frac{7.0}{f} + 27f^2 \times 10^{-12} + 25f \times 10^{-9}\right) \quad (8)$$

Figure 5 shows the graphical representation of these six D components for the one henry toroid and their progressive summation in terms of D_m and D_w. D_h was evaluated at an arbitrary level of 100 millioersteds produced by a current of 330 microamperes.

We thus see that the reduction of eddy currents by a fine subdivision of the ferromagnetic material, together with its small hysteresis loss, permits the low dissipation factors indicated in Figure 6 to be obtained in these high quality inductors. These Figure 6 data were obtained close to initial permeability, where D_h becomes negligible, and show clearly the effect of displacing the D_d line to the left as the values of inductance are increased.

Safe Operating Limits

On the assumption that one of these toroidal windings can dissipate two watts without detrimental temperature rise, the r-m-s current values designated as I_2 in the specifications below were obtained. Such currents, however, would materially lower the inductance below initial values. To avoid any possible "magnetic memory" modification of L_o, large currents should be reduced progressively, rather than by a sudden interruption of the circuit.

In addition, it should be borne in mind that, if these high Q inductors are resonated by tuning with external series capacitance, the voltages developed across them may substantially exceed that of the circuit generator. A safe limit may be taken as 500 volts rms for any fixed position of the inductor switch. To prevent detrimental arcing at the switch contacts, the voltage on any decade unit should not exceed 150 volts rms when the switches are manipulated.

Mr. R. F. Field collaborated in securing the data quoted in this article.

— Horatio W. Lamson

TYPE 940 DECADE INDUCTOR UNIT

SPECIFICATIONS

Accuracy: Each unit is adjusted so that its inductance at zero frequency and initial permeability will be the nominal value within the accuracy tolerance given in the following table:

Inductance per step	1 mh	10 mh	100 mh	1 h
Accuracy	±2%	±1%	±0.5%	±0.25%

Frequency Characteristics: See "Frequency Correction," page 4. Typical values for the distributed capacitance C_0 of the TYPE 940-A Decade Inductor Unit are as follows:

Step	1	2	3	4	5	6	7	8	9	10
C_0 ($\mu\mu$f); Chassis tied to Low Terminal	90	60	50	50	50	45	40	37	35	35
C_0 ($\mu\mu$f); Chassis Floating	45	45	35	35	50	40	35	32	30	25

For the TYPES 940-B, -C, and -D the above values should be multiplied by the factors 1.1, 1.25, and 1.5 respectively.

Dissipation Factor: Figure 4 shows the variation of the dissipation factor $D = 1/Q$ with frequency for the full value of each inductor. It will be seen that maximum storage factor Q values between 200 and 330 are obtained at frequencies between 2 and 5 kc.

Temperature Coefficient: The temperature coefficient of inductance is about −24 parts per million per degree Centigrade. See Figure 3.

Maximum Voltage: The maximum r-m-s voltage for which the units are insulated is 500 volts. The switch will break the circuit at 500 volts if turned rapidly to the new setting, but voltages above 150 may cause destructive arcing if the switch is set between detent positions.

Current Characteristics and Maximum Current Ratings: The core permeability and the inductance value of each toroid are raised 0.1% by the application of 1.22 ampere turns. The corresponding r-m-s current values I_1 for each of the toroids are listed below, together with the r-m-s current values I_2 corresponding to a safe heat dissipation of two watts per toroid.

Inductor	*Toroid*	I_1 (ma) for 0.1% increase	I_2 (amp)
940-A	1 mh	15.6	7.2
940-A	2 mh	11.0	5.2
940-A	5 mh	7.0	3.0
940-B	10 mh	4.9	2.3
940-B	20 mh	3.5	1.7
940-B	50 mh	2.2	1.0
940-C	100 mh	1.56	0.72
940-C	200 mh	1.10	0.52
940-C	500 mh	0.70	0.30
940-D	1 h	0.49	0.23
940-D	2 h	0.35	0.17
940-D	5 h	0.22	0.10

Currents of twice the I_1 values will produce 0.2% increase in inductance; 5.4 I_1 gives 0.5% increase in inductance; 14.6 I_1 gives 1% increase in inductance; while 43.4 I_1 gives a maximum increase (2%) in inductance. Still larger currents will decrease the inductance progressively, the error being zero at about 108 I_1 and negative at larger values.

Terminals: Soldering lugs are provided.

Mounting: Each decade is complete with dial plate, knob, and mounting screws.

Dimensions: (Width) 7¼ x (height) 3½ x (depth behind panel) 3¼ inches, over-all.

Net Weight: 3½ pounds.

Type	*Inductance*	*Code Word*	*Price*
940-A	**0.01 h in 0.001 h steps**	INDUCTOANT	**$62.00**
940-B	**0.1 h in 0.01 h steps**	INDUCTOBOY	**56.00**
940-C	**1 h in 0.1 h steps**	INDUCTOCAT	**62.00**
940-D	**10 h in 1 h steps**	INDUCTODOG	**70.00**

TYPE 1490 DECADE INDUCTOR

SPECIFICATIONS

Frequency Characteristics: In determining the correction factor w^2C_0L use the C_0 value corresponding to the largest decade unit actually in circuit. For each larger decade unit not in circuit add 100$\mu\mu$f if the inductor is grounded to the panel or add 20$\mu\mu$f if the inductor is not grounded to the panel.

Terminals: Jack-top binding posts.

Mounting: The decades are mounted on an aluminum panel in a metal cabinet.

Dimensions: 1490-A 12¾ x 7¾ x 5½ inches overall height; 1490-B 16½ x 7¾ x 5½ inches overall height.

Net Weight: TYPE 1490-A, 15 pounds; TYPE 1490-B, 19 pounds.

Other specifications are identical with those for the TYPE 940 Decade Inductor Units.

Type	*Inductance*	*Code Word*	*Price*
1490-A	1.11 h, total, in steps of 0.001 h	CLUMP	$220.00
1490-B	11.11 h, total, in steps of 0.001 h	COACH	285.00

MISCELLANY

RECENT VISITORS to our laboratories:

From England: Mr. R. L. Smith-Rose, Superintendent, Radio Division, Department of Scientific and Industrial Research, London; Mr. J. F. Coales, Director, Research Laboratories, Elliot Brothers (London) Ltd., London; and Mr. R. G. Clark, Consulting Engineer, Epsom, Surrey.

From Spain: Dr. A. Gurvis, Technical Manager, and Mr. Domenech, Commercial Manager, both of Iberia Radio, Barcelona; and Dr. A. A. Pascucci, Research Section Director, Radio Hispano Suiza, Barcelona.

From France: Mr. Paul Fabricant, of Radiophon, Paris, Distributors of General Radio products in France and the French Possessions.

From Denmark: Mr. O. Lund, Communication Laboratory, Royal Technical College, Copenhagen; Mr. Viggo Kjaer, Manager, Brüel and Kjaer, Copenhagen.

From China: Mr. F. C. Chien, Chief Engineer, Central Broadcasting Station, Nanking.

From Italy: Professor Valentino Zerbini, Chief of Magnetic Section, Institute Elettrotecnico Nazionale "G. Ferraris," Torino.

From Canada: Professor B. de F. Bayly, of the University of Toronto. Professor Bayly is head of Bayly Engineering, Ltd., Oshawa, Ontario, who handle repairs of General Radio instruments in Canada.

VACATION — During the weeks of July 25 and August 1 most of our employees will be vacationing. Manufacturing departments will be closed, and other departments will be manned by a skeleton staff. Every effort will be made to take care of urgent business, but repairs cannot be made, except in hardship cases. Our Service Department requests that shipments of material to be repaired be either scheduled to reach us well before this vacation period or delayed until afterward.

GENERAL RADIO COMPANY
275 MASSACHUSETTS AVENUE
CAMBRIDGE 39 MASSACHUSETTS
TELEPHONE: TRowbridge 6-4400

BRANCH ENGINEERING OFFICES

NEW YORK 6, NEW YORK
90 WEST STREET
TEL.—WOrth 2-5837

LOS ANGELES 38, CALIFORNIA
1000 NORTH SEWARD STREET
TEL.—HOllywood 9-6201

CHICAGO 5, ILLINOIS
920 SOUTH MICHIGAN AVENUE
TEL.—WAbash 2-3820

PRINTED IN U.S.A.