the GENERAL RADIO

Experimenter

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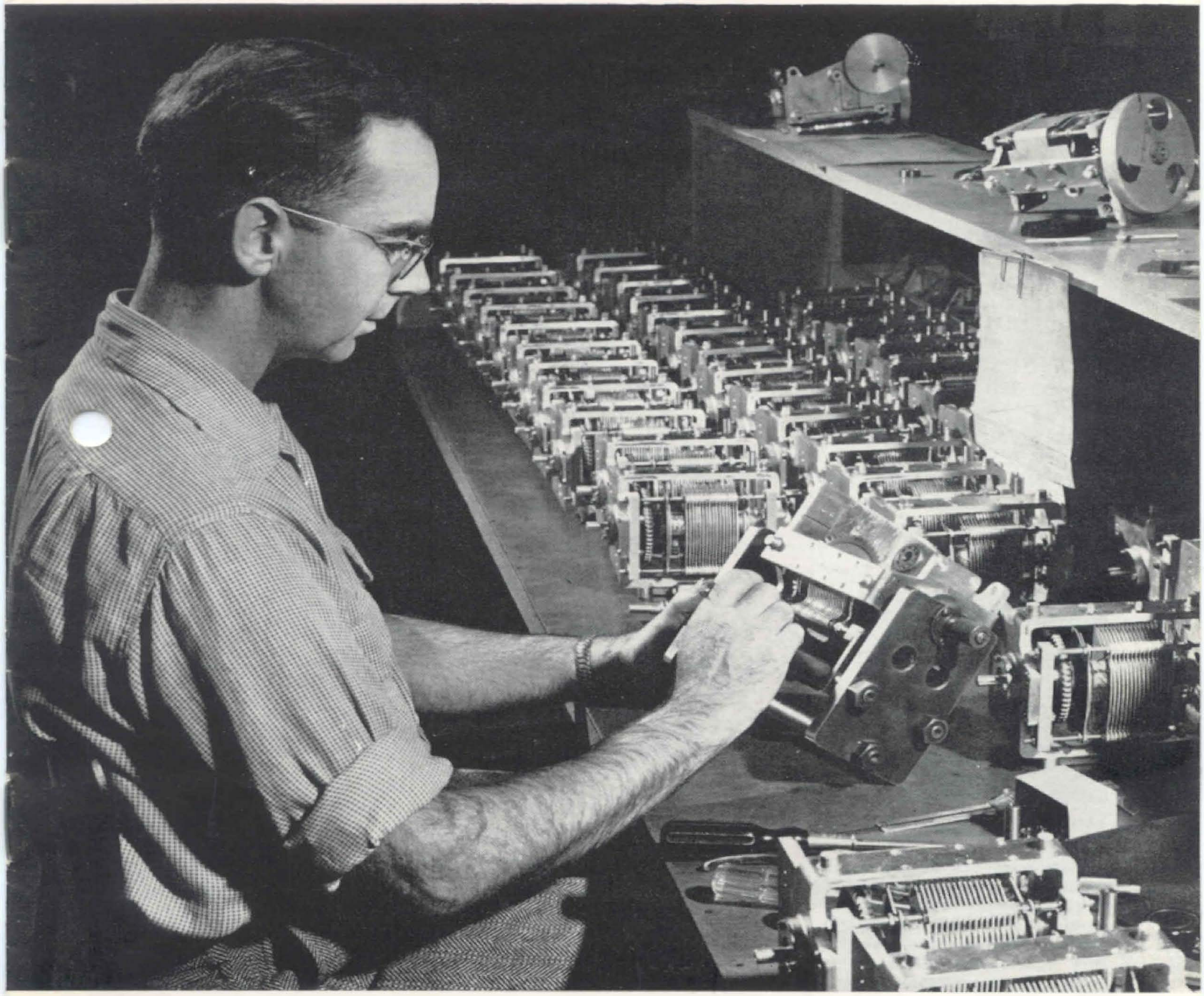

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GENERAL RADIO COMPANY

275 Massachusetts Avenue
Cambridge 39 **Massachusetts**
Telephone: TRowbridge 6-4400

BRANCH ENGINEERING OFFICES

NEW YORK: Broad Avenue at Linden, Ridgefield, New Jersey
Telephone—N. Y., WOrth 4-2722
N. J., WHitney 3-3140

CHICAGO: 920 South Michigan Ave., Chicago 5, Illinois
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Cover

The accuracy of a precision variable air capacitor depends upon the maintenance of close mechanical tolerances—from the fabrication of each part to the final assembly. This photograph shows Type 722 Precision Capacitors undergoing adjustment and alignment in a jig to assure linearity of the capacitance characteristic.

THE MEASUREMENT OF CABLE CHARACTERISTICS

Coaxial cables play an important role in today's electronic world. They are vital elements in television, radio communication, radar, blind landing devices, and practically every other electronic device employing high frequencies. The electrical characteristics of the cables used in these applications must meet very rigid specifications,[1] and the problem of accurately measuring the characteristics is important to the cable designer to enable him to check his designs, to the cable manufacturer to inspect the cable being produced, and to the cable user to make it possible for him to determine accurately the properties of the cables with which he is working.

In addition to coaxial cables there are several dual-coaxial and shielded twin-conductor types in fairly common use, and the television industry uses large amounts of unshielded twin-conductor cables. The problem is to select test equipment that will do the job simply, with good accuracy, and at reasonable cost. General Radio Company manufactures equipment which meets all these requirements, and this series of articles will discuss how it can be used to measure attenuation, characteristic impedance, velocity of propagation, capacitance, and other characteristics.

BASIC CABLE CHARACTERISTICS

Conventional transmission line theory starts with the line parameters of shunt capacitance (C) and conductance (G) *between* the conductors, and series inductance (L) and resistance (R) *of* the conductors. Wave equations derived from the theory and worked into a convenient form contain three coefficients that are combinations of these four parameters, namely: characteristic impedance: $Z_o = 10^3 \sqrt{\frac{L}{C}}$ ohms, velocity of propagation: $v = \frac{101.6}{\sqrt{LC}}$ percent of velocity of light in free space, attenuation: $\alpha = 434.3\ (GZ_o + \frac{R}{Z_o})$ decibels per hundred feet[2].

These three coefficients, Z_o, v, and α, are most directly useful for calculations in transmission-line applications, and capacitance (C) is also useful in low-frequency applications and is often needed for the determination of Z_o, which is not always convenient to measure directly. Consequently, the cable characteristics most frequently used are Z_o, α, and C, with v seldom listed,

• This paper, which will be published in several parts, is a revision of an earlier paper by Mr. Thurston that has been available in pamphlet form. Later installments will cover the equipment and procedures used in measuring the significant cable characteristics. When the series is complete, reprints will be available. — Editor

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[1] Joint Army-Navy Specifications, MIL-C-17B, dated Sept. 7, 1955, "Cables, Coaxial and Twin-Conductor for Radio Frequency."

[2] In these equations the units are as follows: C in $\mu\mu$f/ft.; G in mhos/ft.; L in μh/ft.; and R in ohms/ft. Also, it is assumed that the cable losses are small.

probably because it is less frequently used and can, if needed, be found from its simple relation to Z_o and C.[3] It is important to consider the frequency behavior of these characteristics, since this factor greatly influences the choice of measurement methods.

Frequency Behavior of C, G, *L*, and *R*

In cables intended for high-frequency use, the insulating material is generally polyethylene, Teflon, or a combination of one of these materials and air. In any case, the dielectric constant and dissipation factor are essentially constant from audio frequencies to microwave frequencies, a great convenience. Thus, the capacitance (C) is constant, and the conductance (G) is directly proportional to frequency.[4] (Other types of cables, in particular those with rubber-type insulation used at lower frequencies or for high attenuation at high frequencies, are not considered in the simplified presentation of this section. Their capacitance is not constant, so their frequency behavior is more complicated.)

The behavior of inductance (L), shown in Figure 1, is influenced by skin effect, whereby current penetration into a conductor is effectively limited to a depth that decreases as the frequency is raised. At very low frequencies the effective depth of current penetration in metal is large compared to the conductor dimensions, and the current is practically uniformly distributed over the conductor cross sections, as shown by the shaded areas of Figure 2. Magnetic flux, the amount of which per unit current determines the inductance, exists around the current, as indicated by the arrows, and some of this flux is within the conductors, making inductance a maximum.

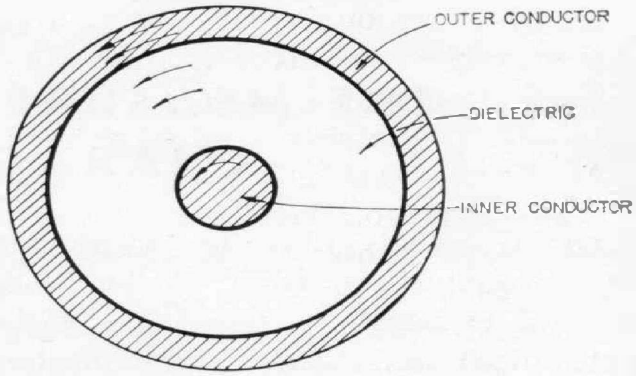

Figure 2. Current distribution in coaxial transmission line.

At very high frequencies, the depth of penetration is negligibly small compared to the cable dimensions, so the current is crowded into the very shallow paths indicated by the black circles in Figure 2. With the same current flowing, the amount of flux *within* the conductors themselves is negligible, yet the flux *between* the conductors (in the dielectric) is unchanged; so the inductance is less than at low frequencies. No further appreciable reduction in flux can occur; thus the inductance is again practically constant and remains so.

The total change of inductance in non-magnetic conductors is readily calculated from conductor dimenions, and, for example, is about 20 per cent for 50-ohm polyethylene-dielectric cables. The frequency range in which the change occurs and the shape of the

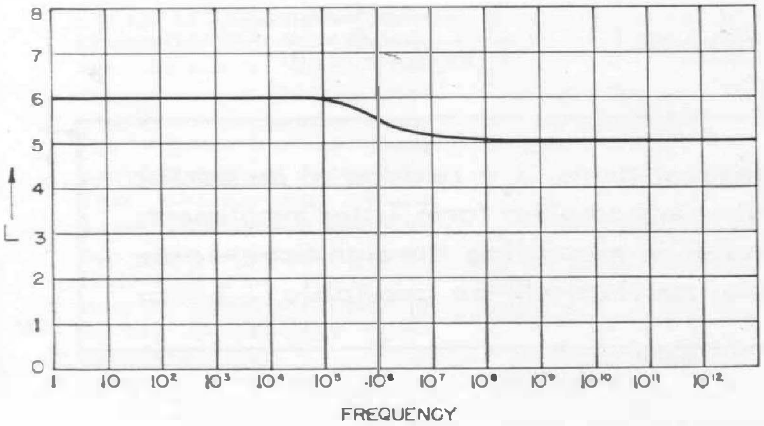

Figure 1. Variation of inductance with frequency (arbitrary units).

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[3] v in per cent $= \dfrac{101{,}600}{(Z_o \text{ in ohms})\,(C \text{ in } \mu\mu f/\text{ft.})}$

[4] $G = 2\pi fCD$, in which f is the frequency and D is the dissipation factor.

curve in this region are dependent upon the size of the cable (the change starts at lower frequencies in larger cables) and upon the way the conductors are made. Skin effect is retarded in stranded conductors as compared to solid conductors, even though the individual strands are not supposed to be insulated from one another, and this fact makes it extremely difficult to calculate the practical frequency limits of the region of inductance change. Furthermore, normal mechanical variations, and possibly electrical inter-strand contact variations, in the cable limit the accuracy with which the inductance curve can be measured. Clearly, the curves of Figures 1 and 3 are idealized. For example, if Type RG-8/U cable had solid conductors, the upper limit[5] of the inductance change region would be about 9 Mc. Because of the stranding of the conductors, the upper limit is higher, possibly 15 or 20 Mc.

The behavior of resistance (R) is determined by skin effect. As the depth of current penetration is reduced, R increases and becomes approximately proportional to the square root of frequency when skin depth becomes very small compared to conductor dimensions. The type, thickness, and quality of plating used on the conductors also influences the high-frequency resistance, and, at extremely high frequencies, a phenomenon called "braid effect" can make attenuation abnormally high.

Variation in Z_O, v, and α with Frequency

The characteristic impedance, Z_o, varies as $\sqrt{\frac{L}{C}}$; since C is independent of frequency, Z_o varies as $\sqrt{L}$. Therefore, the frequency characteristic of Z_o, shown in Figure 3a, is very similar to that of L (Figure 1) except that the total percentage change of Z_o between low frequencies and high frequencies is about half the percentage change of L. The change in Z_o is nor-

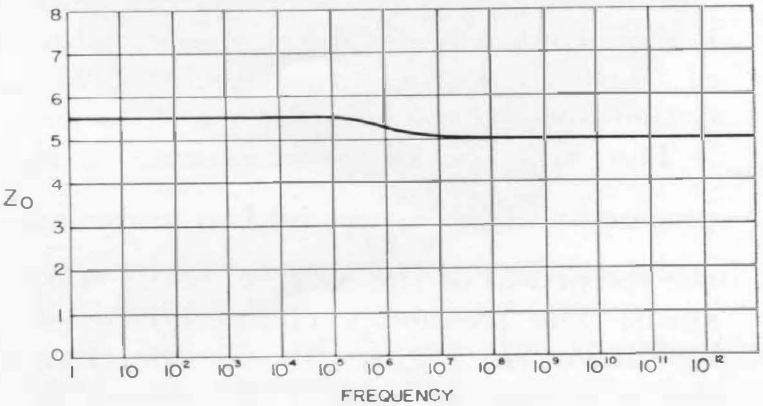

Figure 3a. (above) Variation of characteristic impedance with frequency (arbitrary units).

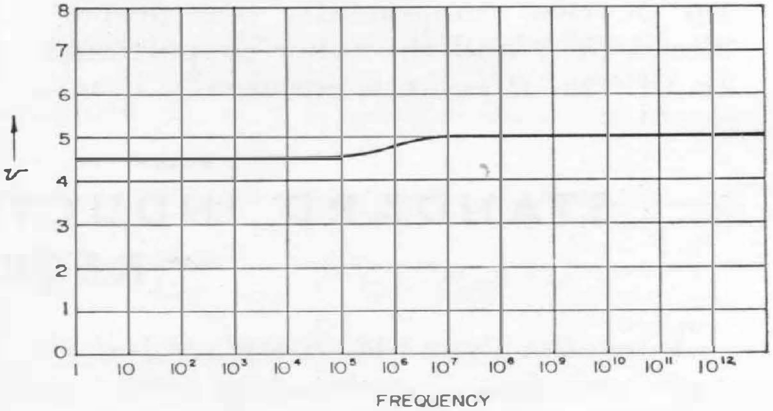

Figure 3b. (above) Variation of velocity of propagation with frequency (arbitrary units).

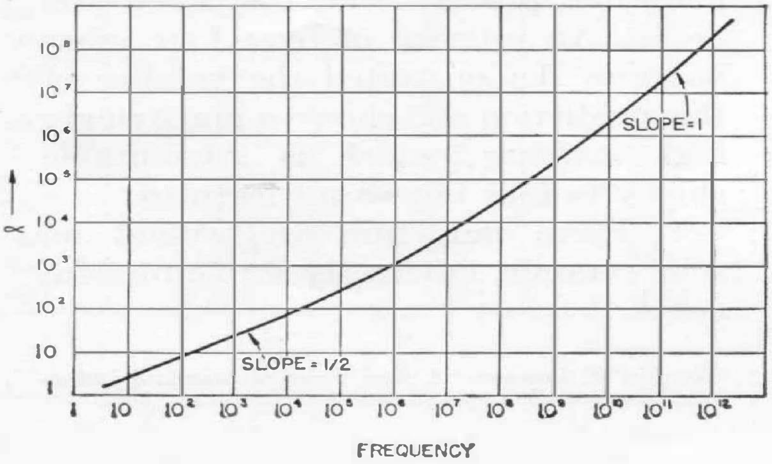

Figure 3c. (right) Simplified version of the variation of attenuation with frequency (arbitrary units).

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[5] Frequency at which the inductance is within 1% of the final, high-frequency value.

mally complete at frequencies sufficiently low so that only the final, high-frequency value need be considered or listed. However, special situations arise in which it must be considered. As an example, it may be convenient for a cable manufacturer to make the test of characteristic impedance at a frequency of 1 Mc. In RG-8/U cable, at this frequency, the characteristic impedance is 4 per cent higher than the high-frequency value of 50 ohms. The target value at 1 Mc is therefore 52 ohms.

The velocity of propagation, v, is proportional to $\frac{1}{\sqrt{LC}}$, and so varies as the reciprocal of the $\sqrt{L}$, C being constant. The frequency characteristic of v, shown in Figure 3b, is therefore the reciprocal of that of Z_o, shown in Figure 3a.

The attenuation constant, α, is made up of two components, one proportional to R and the other proportional to G. The R component usually dominates at lower frequencies and varies as the square root of frequency when current penetration is small compared to conductor dimensions. The G component becomes relatively more important at higher frequencies and is directly proportional to frequency. The slope of α versus frequency when plotted on log-log graph paper is ½ if R dominates, 1 if G dominates, and between ½ and 1 if neither one is negligible. A greatly simplified high-frequency attenuation characteristic is shown in Figure 3c; more complicated curves would generally be obtained because of the effects of stranding, braiding, dielectric impurities, and other departures from idealized theory. Normally, for production testing purposes it is sufficient to measure α at a single frequency in the general range of normal use, but if an accurate value is required at some other frequency, it is necessary to make a measurement at that frequency. — W. R. THURSTON

(to be continued)

STANDARD INDUCTORS—A STABILITY RECORD

When the Type 1482 Standard Inductors were first introduced in 1952,* it was expected that they would prove to be more stable and reliable than their long-time predecessors, the TYPE 106 Series. An interval of over four years has now demonstrated the validity of this prediction and shown a gratifyingly high stability, which is attributable chiefly to four important features:

1. These inductors are wound on solid ceramic, inherently stable toroidal cores.

2. They are subjected to an aging process to relieve winding strains and stabilize the winding prior to final calibration.

3. Packed in granulated cork, these toroidal units have essentially a floating support free from any localized points of strain.

4. An effective hermetic sealing eliminates variation in inductance due to ambient humidity.

Two complete sets of these inductors, constructed in the summer of 1952, are kept to serve as our primary standards of inductance, in terms of which all of

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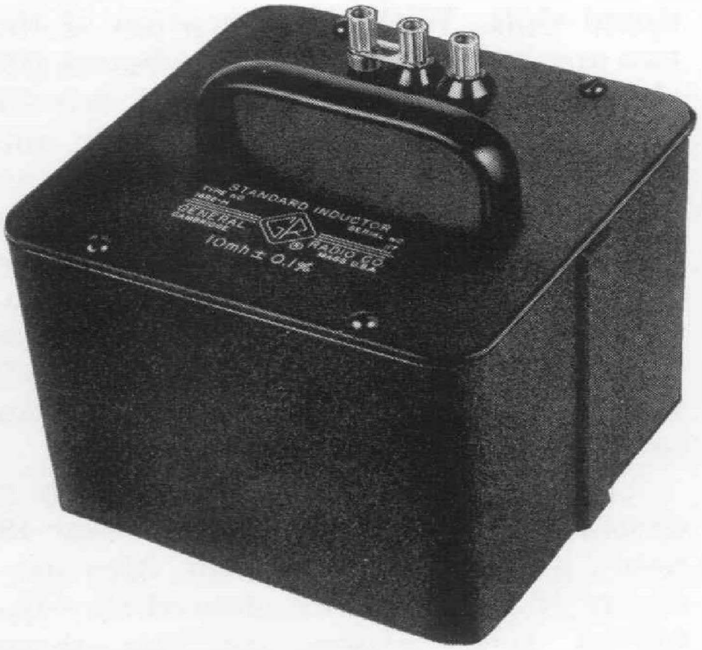
*Horatio W. Lamson, "A New Series of Standard Inductors," General Radio *Experimenter*, November, 1952.

our production units are given their final calibration for our certificate data. One of these sets has been sent to the National Bureau of Standards for calibration on three separate occasions, namely, in September, 1952, July, 1955, and January, 1957. This means that, in addition to 4½ years of extensive laboratory use, these inductors have endured three round trips between Cambridge and Washington.

The Bureau's certified values of self-inductance at 100 cycles offer convincing proof of the stability of these units. The following table shows the differences between certified values on the three measurement dates, as well as the net overall shift since the first measurement. These data are given with more significant figures than correspond to the tolerance limits, ± 0.03%, to which the Bureau certifies absolute inductance.



In the table, all increments are given in parts per million. The third column indicates the assumed precision of the Bureau's measurement, based on a tolerance of ± 1 in the last digit. The last column gives the accuracy to which the Bureau certification was given.

It will be noted that, for the most part, the indicated shifts are random in character and do not greatly exceed the resolution of the Bureau measurements. There is a moderate preponderance of positive shifts, increase of inductance. Only the 2h, 1h, and 200 μh units showed a progressive uni-direc-

Type	*Inductance*	*Precision of Bureau of Standards Measurements*	*Indicated Shifts in Inductance*			*Tolerance of Bureau of Standards Certification of Absolute Inductance*
			Sept. 1952 to July 1955	*July 1955 to Jan. 1957*	*Sept. 1952 to Jan. 1957*	
1482 T	10 h	± 10	− 10	0	− 10	± 300
1482 R	5 h	± 20	0	+ 40	+ 40	± 300
1482 Q	2 h	± 5	+ 50	+ 25	+ 75	± 300
1482 P	1 h	± 10	+ 20	+ 20	+ 40	± 300
1482 N	500 mh	± 20	0	+ 60	+ 60	± 300
1482 M	200 mh	± 5	− 50	+ 10	− 40	± 300
1482 L	100 mh	± 10	− 50	+ 50	0	± 300
1482 K	50 mh	± 20	− 20	+ 20	0	± 300
1482 J	20 mh	± 5	0	− 30	− 30	± 300
1482 H	10 mh	± 10	− 20	+ 40	+ 20	± 300
1482 G	5 mh	± 20	+ 100	0	+ 100	± 300
1482 F	2 mh	± 5	0	+ 20	+ 20	± 300
1482 E	1 mh	± 10	0	0	0	± 300
1482 D	500 μh	± 20	− 100	+ 180	+ 80	± 500
1482 C	200 μh	± 50	+ 200	+ 50	+ 250	± 500
1482 B	100 μh	± 100	+ 800	− 500	+ 300	± 1000
Arithmetic Average (Omitting 200 μh, 100 μh)					37	
Algebraic Mean (Omitting 200 μh, 100 μh)					+ 27	

tional shift. With the exception of the two smallest inductors (200 μh and 100 μh) the overall shifts averaged only 37 and never exceeded 100 parts per million, which is 0.01 per cent. It may or may not be significant that the unit-valued inductors averaged distinctly less in overall shift, 14 parts per million. In all cases, the over-all (4.3 year) shifts indicated by the Bureau data were well within the limits to which the Bureau certified the value of inductance.

The inductors were stabilized in a constant temperature room for over 48 hours prior to measurement. Measurements of d-c resistance showed the stabilized temperatures for the three occasions to be within one degree C. The temperature coefficient of inductance, about $+ 30/10^6$, is of the same order as the precision of the Bureau data.

The average shift, omitting the two smallest inductors, is of the same order as that which would be produced by a one-degree change in temperature.

We believe that the foregoing gives a convincing proof of the high degree of stability exhibited by this set of inductors. Our regular production TYPE 1482 units show a comparable degree of stability. This has been demonstrated on numerous occasions when some of our customers have returned their inductors to us for recalibration in accordance with their own periodic requirements.

Such stable and accurately calibrated inductors can be used with complete confidence in all standardizing laboratories and for the calibration of all types of inductors and bridges, as is done in our own laboratories.

— HORATIO W. LAMSON

AN ENGINEER'S COMPANY

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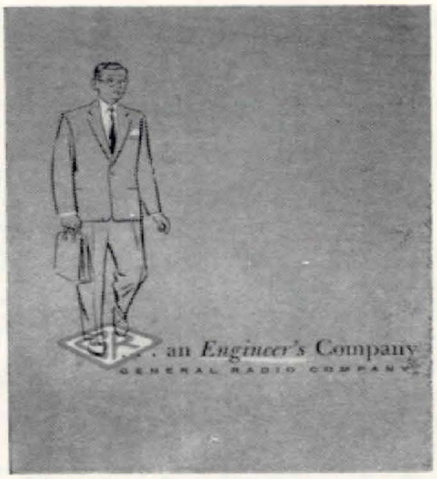

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