DEPARTMENT OF COMMERCE
BUREAU OF STANDARDS
George K. Burgess, Director

TECHNOLOGIC PAPERS OF THE BUREAU OF STANDARDS, No. 330
[Part of Vol. 21]

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OCTOBER 27, 1926

PRICE 5 CENTS
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WASHINGTON
GOVERNMENT PRINTING OFFICE
1926

RESISTANCE OF CONDUCTORS OF VARIOUS TYPES AND SIZES AS WINDINGS OF SINGLE-LAYER COILS AT 150 TO 6,000 KILOCYCLES

By E. L. Hall

ABSTRACT

This paper gives experimental data on the resistance at frequencies between 150 and 6,000 kc of single-layer coils wound with various sizes of solid bare copper wire, litz wire, copper tubing, and an aluminum ribbon. The purpose of these measurements was to obtain data which would aid in the selection of the conductors having the lowest radio-frequency resistance for the coils of a standard frequency meter. The measurements were made by the resistance-variation method. The results are shown in graphs, which are directly comparable because they are plotted for coils having approximately the same inductance. Graphs are also given for two sizes of litz wire showing the increase in radio frequency resistance at one frequency when numbers of strands of wire are removed from the circuit. The graphs are of value in selecting the size of wire of least resistance for a given frequency within the range from 150 to 6,000 kc. At frequencies from 150 to about 1,500 kc the superiority of litz wire of a large number of strands is shown, but above that limit a large size solid copper wire or copper tubing is preferable.

The purpose of the measurements was to obtain data upon single-layer coils of various types and sizes of wire from which the wire having the lowest radio-frequency resistance could be selected for the coils of a new standard frequency meter. The data include the resistances at certain frequencies between 150 and 6,000 kc of windings of various sizes on grooved cylindrical forms of a good quality insulating material. No comprehensive study was made of the effects of changes in coil diameters and winding pitches; the data are, therefore, not as complete as might be desirable, but may be of interest.

The resistance measurements were made in a circuit consisting of the coil under test, a crossed-wire thermoelement, a standard variable air condenser, and the necessary connecting leads, by the resistance-variation method as described in Bureau of Standards Circular No. 74, pages 180 to 182. The resistance of the whole circuit, thus determined, would have been a satisfactory expression of the results of the measurements, because the measuring circuit was very similar to the circuit of the frequency meter. However, to make the data more suitable for general reference purposes, the resistances of the coils alone were calculated by subtracting the d. c. resistance of the thermoelement and connecting leads. The condenser had negligible resistance, and the resistance of the thermoelement and leads was assumed to change negligibly with frequency. The resistances of the coils alone are presented in this paper.

The frequency range covered by these measurements was so great that two coil forms were the minimum number that would cover this range with the three sizes of standard variable air condensers used; that is, 0.0002, 0.001, 0.0035 μf. In order to obtain data on larger sizes of wire at the lower frequencies a third coil form was required having the same diameter as one of the other two forms, but a greater length and smaller number of turns per inch. The inductance of the coil wound on the third form was the same as that of the larger of the first two coils.

The insulating material cylinders were grooved so that one size of wire could be wound on, the measurements made, and the cylinder rewound with the next size of wire. This method gave approximately the same inductance and same length for any size of wire used on the form. The distance between turns was different, for the various sizes of wire, but the pitch of the winding remained the same.

Resistance measurements were made on the following types and sizes of conductors: Solid bare copper wire (AWG) Nos. 30, 24, 18, 14, 10; high-frequency cable or litz 32–38, 48–38, 96–38; a stranded conductor composed of 99 enameled No. 32 wires; two samples of ⅛-inch copper tubing having wall thicknesses of 0.035 inch and 0.01 inch, respectively, and an aluminum ribbon 0.13 inch wide by 0.0003 inch thick. Data were also obtained for 32–38 and 48–38 litz at one frequency, showing the increase in resistance caused by disconnecting strands of wire at one end of the coil.

Figure 1 gives a graphical comparison of the cross-sectional area of the various conductors used for winding the coils. One of the copper tubes had the greatest cross section and the No. 10 wire was next in order. The 96–38 litz and No. 18 copper wire have about the same cross section. A similar equality exists between the 32–38 litz, and the No. 24 wire, and between the aluminum ribbon and the No. 30 wire.

Table 1 is descriptive of the grooved cylinders used to support the wire. The insulating material used for the cylinders was of good quality, but the kind is of no moment, since only comparative values of the conductor resistance were being investigated.

Reference to the dimensions given for the coil forms shows that the two large forms did not have the theoretical relation between diameter and length to give the greatest inductance for a given length of wire. The small form was very close to the condition referred to, which exists for a ratio of diameter to length of coil of

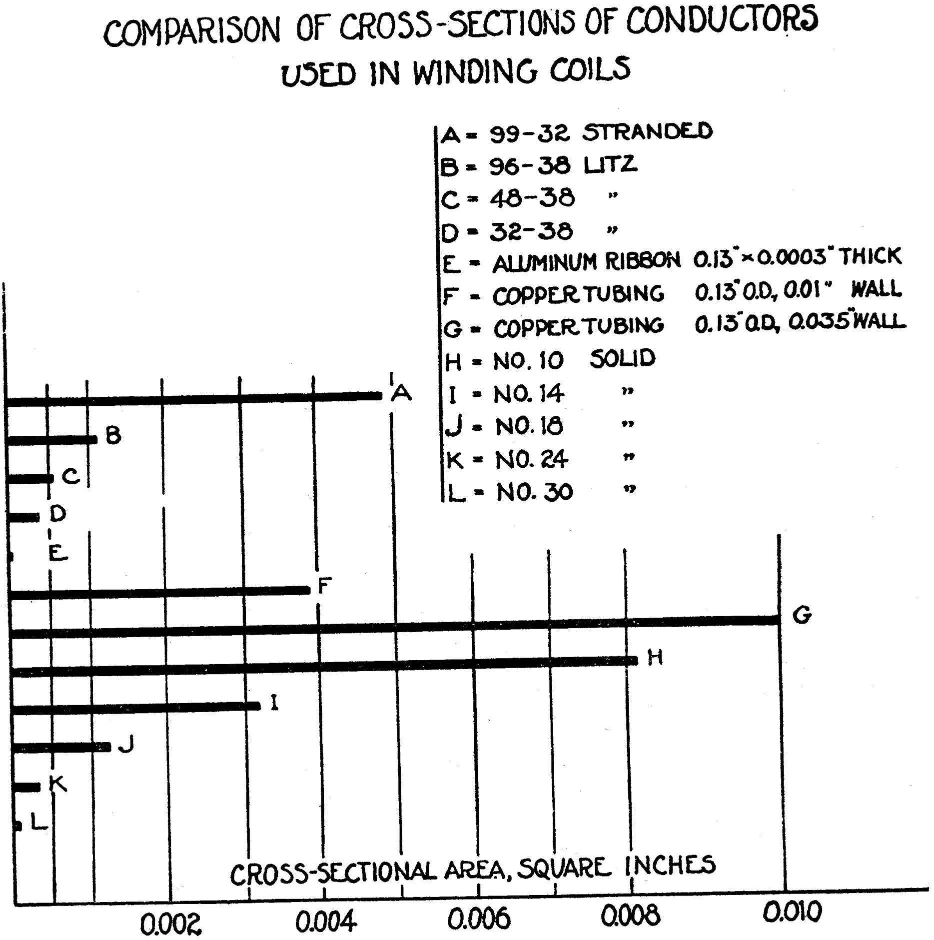

Fig. 1

approximately 2.46. The ratios of the three coils are as follows: Large I, 1.04; large II, 0.75; small, 2.54.

TABLE 1

Form	Diameter	Number of turns per inch	Total number of turns	Approximate inductance	Frequency range of test
	Inches			*Microhenries*	*kc*
Large I	6 5/16	10	61	460	150–911
Large II	6 5/16	8	68	460	150–911
Small	4 1/8	5	8	10	911–6,000

Table 2 gives the frequencies at which measurements were made, together with the sizes of condensers used, and the approximate condenser settings.

TABLE 2

Coil	Frequency	Condenser	Approximate condenser setting
			Degrees
Large I or II	150	0.0035	117
	300	.001	95
	450	.001	38
	600	.0002	90
	750	.0002	40
	911	.0002	14
Small	911	.0035	156
	1,500	.0035	55
	2,000	.001	103
	3,000	.001	42
	4,000	.0002	101
	5,000	.0002	47
	6,000	.0002	20

The results of the measurements at the higher frequencies are not as accurate as the measurements at the lower frequencies. Nevertheless, the data are reliable for the purpose of selecting the wire having the lowest resistance under the conditions of measurement for any frequency within the range given. The pitches of the windings used on these coils are such as may be used on the inductors of a laboratory standard frequency meter. Somewhat different values of resistance would be expected for different diameters and pitches of the winding.

Figure 2 shows resistance curves for coils of various conductors between frequencies of 150 to 911 kc. These conductors were wound on the "Large I" form. The direct-current resistance values of the coils are indicated in the figure. It will be noticed that the direct-current resistances of the coils wound with the Nos. 24 and 30 solid wire and the three sizes of litz wire are about the same as the resistance values of these wires at 150 kc. In the case of the Nos. 14 and 18 wire the d. c. resistances are much less than the resistances at 150 kc. The advantage of the litz wire is clearly shown for this range of frequencies, the 48–38 and 96–38 litz having the lowest resistances of any of the conductors given in the figure. For the range from 150 to 700 kc the No. 14 solid copper wire has lower resistance than the No. 18 solid wire, but above 700 kc has higher resistance than the No. 18 wire. This result may be due to the greater eddy currents set up in the larger wire at the higher frequencies, because the spacing between turns was very much less for the No. 14 wire than for the No. 18 wire. However, the differences shown for either of these two sizes is not of significance. The smaller sizes of solid copper wire had resistances too high for use on frequency meter coils. The resistance curve of No. 14 bare copper wire in Figure 2 approaches the values obtained on the larger sizes of litz wire at the lower frequencies. It seemed desirable, therefore, to make measurements on a larger size solid wire.

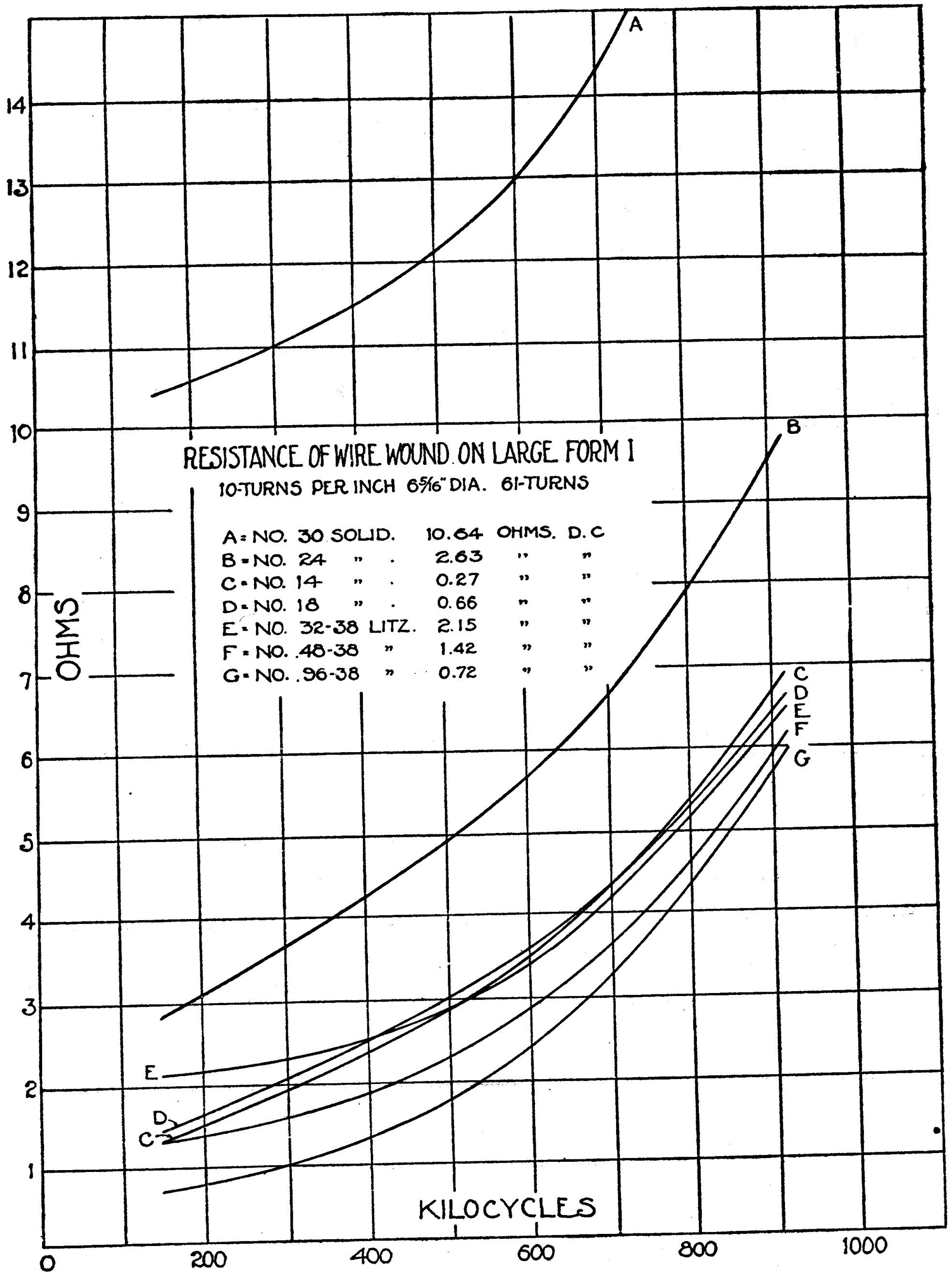

Fig. 2

The "Large II" form was prepared to accommodate the larger wires and have approximately the same inductance as the "Large I" form, with 68 turns wound 8 turns per inch. Figure 3 shows the results obtained on the conductors available for measurement. In general, the 96–38 and 48–38 litz wire had the lowest resistance if the lowest frequencies are not considered. In Figure 3 the conductor referred to as "99–32 stranded" consisted of 99 strands of No. 32 copper wire, each being enameled and twisted in groups of 11 wires and bound together with two servings of silk. The d. c. resistance

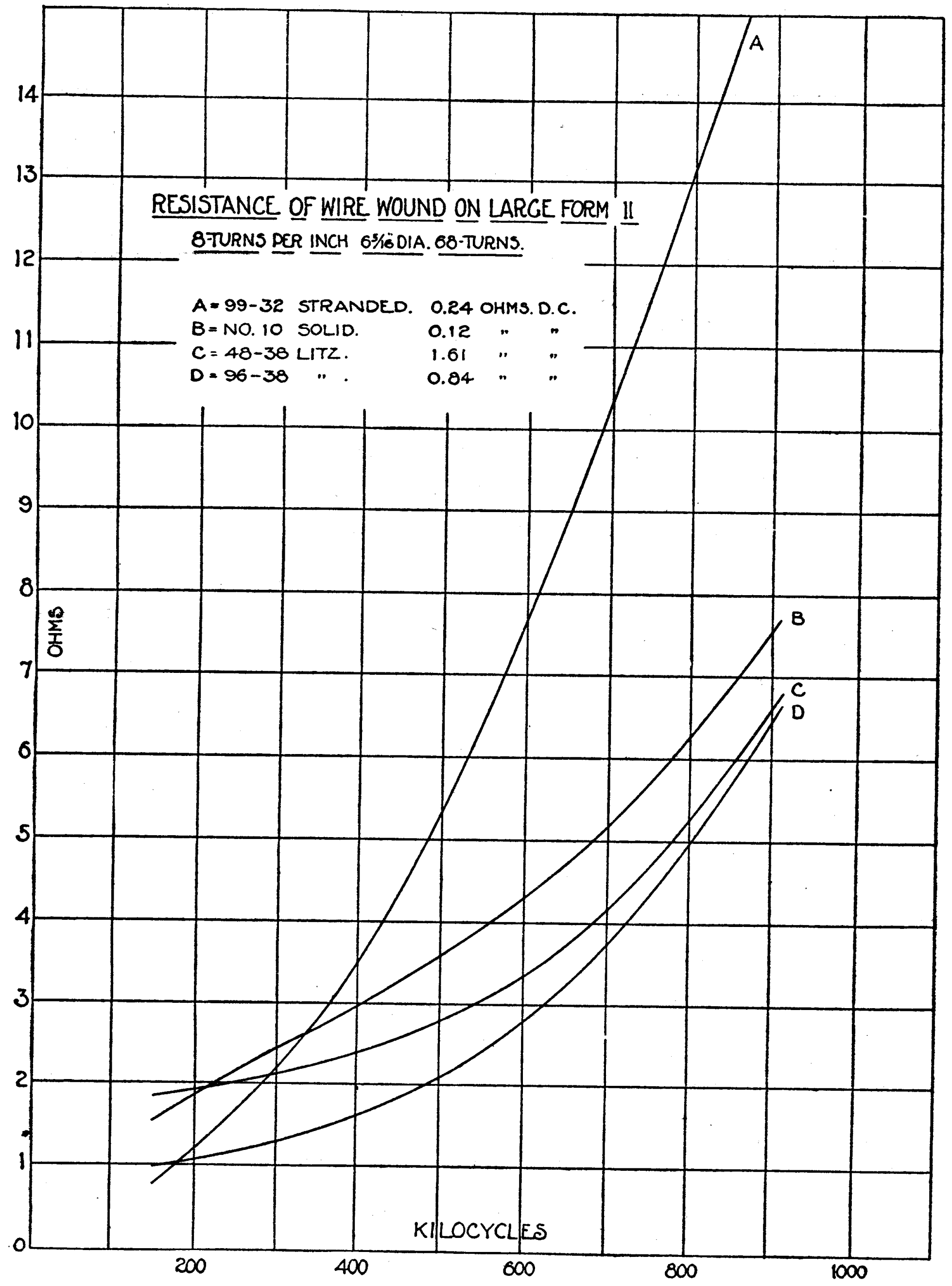

Fig. 3

values of the coils are indicated in the figure. The d. c. resistances of the No. 10 solid copper wire and of the stranded wire are about equal. The stranded wire has the lower resistance of the two wires up to about 330 kc, but above that frequency its resistance rapidly increases to more than twice that of the No. 10 wire. It is of interest to note that although the 96–38 litz wire has almost four times the d. c. resistance of the 99–32 stranded wire, yet the radio-frequency resistance of the litz ranges from about equal at 150 kc to about one-third the resistance of the stranded wire at 900 kc. The superiority of the litz wire at these frequencies is apparent.

Figure 4 shows the results obtained between 911 and 6,000 kc on various conductors wound on the "small" form. The d. c. resistances of the coils are indicated in the figure. These windings had very low resistance. This fact, combined with the high fre-

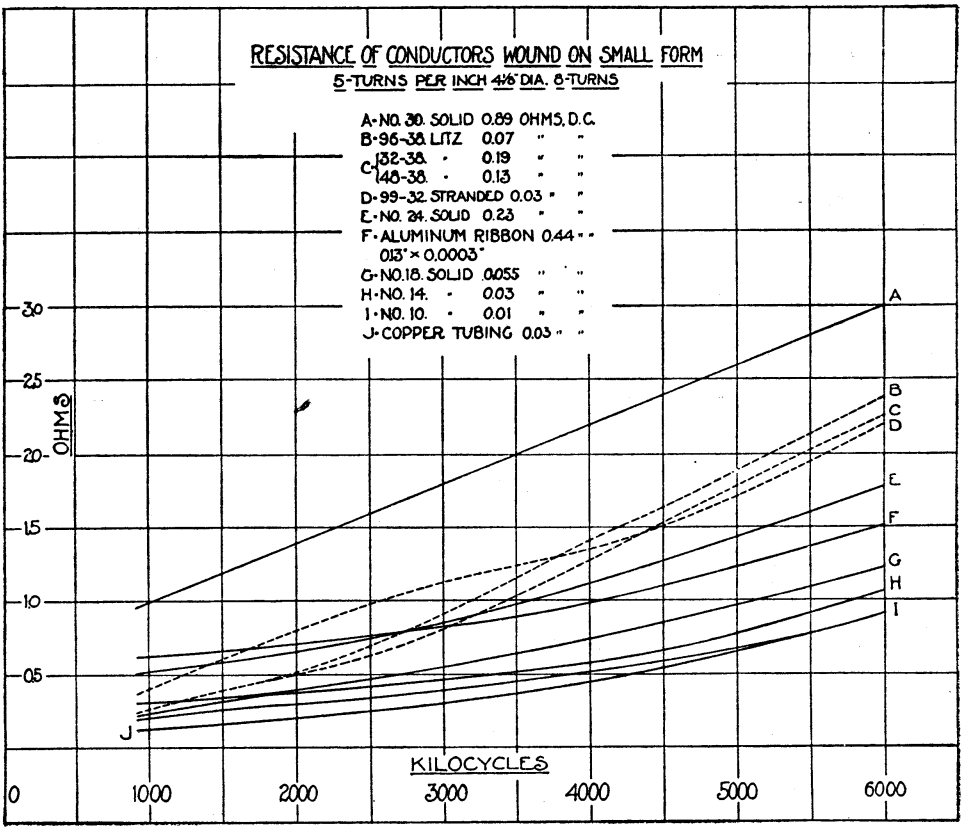

FIG. 4

quencies at which some of the measurements were made, added to the difficulties of measurement. The same sizes of wire tested on the large forms were also tested on the small form and a few other conductors in addition. A No. 10 copper wire was tested both before and after being nickel plated. A curve is not given for the nickel-plated copper wire, since it was similar to the curves given in Figure 4 for the Nos. 10 and 14 wires. At the higher frequencies the nickel-plated wire had about the same resistance as No. 14 copper wire.

Two sizes of copper tubing having ⅛-inch outside diameter were also tested. The cross-sectional area of one tube was about two and one-half times that of the other. The tubes were but slightly larger in diameter than No. 10 copper wire, had d. c. resistances two and three times that of the No. 10 wire, but had somewhat lower radio-frequency resistance except at the highest frequency where it was nearly the same for the three conductors. The copper tubing having the thinner wall had the lowest resistance at all frequencies, although it was practically the same as the thick-walled tubing and not much lower than the No. 10 solid copper wire.

Measurements were also made on a coil of aluminum strip 0.13 inch wide by 0.0003 inch thick wound flatwise on the form. It is interesting to note that although the aluminum strip had a d. c. resistance from two to six times higher than the majority of the other con-

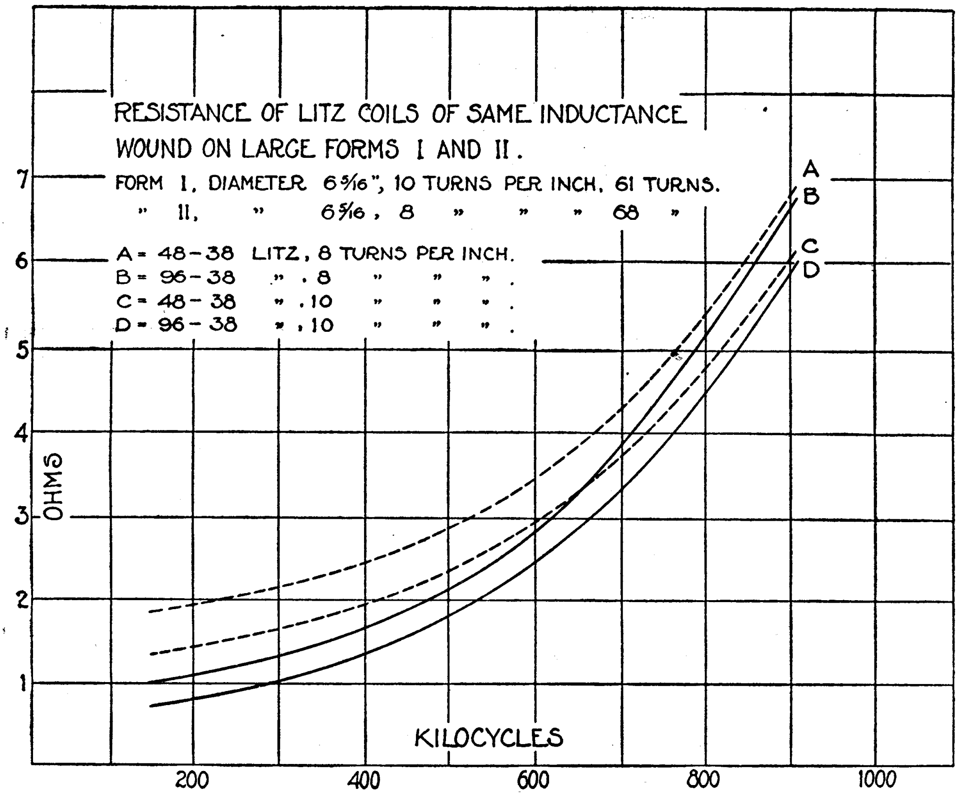

FIG. 5

ductors, its resistance above 3,000 kc was less than that of the No. 24 copper wire or of any litz wire tested.

Figure 4 shows the general similarity between the resistances of litz and solid conductors between 900 and 2,000 kc and the advantage in the use of solid conductors above a frequency of 2,000 kc.

Figure 5 gives the resistances of the coils of litz wire wound on the two large forms. It will be seen here how the three factors—size of wire, spacing, and frequency—combine to affect the resistance. The d. c. resistances of these coils are indicated in the figure. The 96–38 litz wound 10 turns per inch has the lowest resistance of the four coils while the 48–38 litz wound 8 turns per inch has the highest resistance. The wire of the second lowest resistance over the range 150 to 650 kc is the 96–38 coil, wound 8 turns per inch, but over the range 650 to 900 kc the 48–38 coil, wound 10 turns per inch, is the better.

Figure 6 and 7 show the effect of removing numbers of strands of litz wire up to 50 per cent of the total number, for 32–38 and 48–38 litz, respectively. The abscissas of these two figures represent the number of strands of No. 38 wire in the circuit of the coil. Two or more strands at a time were disconnected from the end of the coil connected to the insulated plates of the condenser, and the resistance of the circuit measured. The results shown are for a frequency of 911 kc. The ordinates of the various curves are radio-frequency

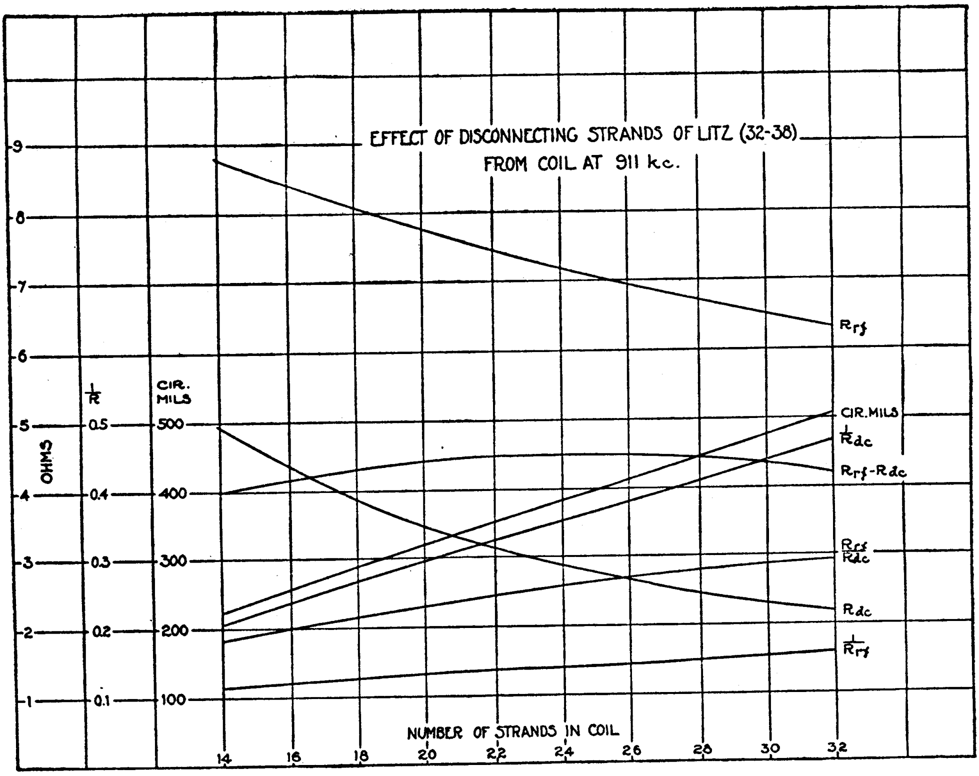

FIG. 6

resistance, direct-current resistance, r. f. resistance minus d. c. resistance, r. f. resistance divided by d. c. resistance, reciprocal of d. c. resistance, reciprocal of r. f. resistance and circular mils cross section.

Referring to Figure 6 the resistance at 911 kc is much higher than the d. c. resistance, but does not increase at as rapid a rate as the latter when strands are removed. The d. c. resistance varies inversely as the cross section of the conductor. This relation is shown by the curves marked "Cir. mils" and "$1/R_{dc}$" which are straight lines. The curve for $1/R_{rf}$ is also a straight line having less slope than the corresponding curve for d. c. values. The curve for r. f. resistance divided by d c resistance shows that the former is between two and three times the latter. The curve for r. f. resistance minus d. c.

resistance shows that this difference remains practically constant as the number of strands is reduced from 32 to 14.

The curves of Figure 7, which are for the case of 48–38 litz, are similar to those of Figure 6. Figures 6 and 7 show that at 911 kc one or two broken strands in 32 or 48 do not increase the resistance very much. Reducing the number of strands in the coil 50 per cent, increases the radiofrequency resistance 33 per cent for the 32–38 litz and 26 per cent for the 48–38 litz.

Table 3 gives the frequency ranges of the coils used in the frequency meter referred to at the beginning of the paper, the sizes of wire selected for these coils, and other data. The coils of Table 3 have low resistance and have been found to permit very sharp

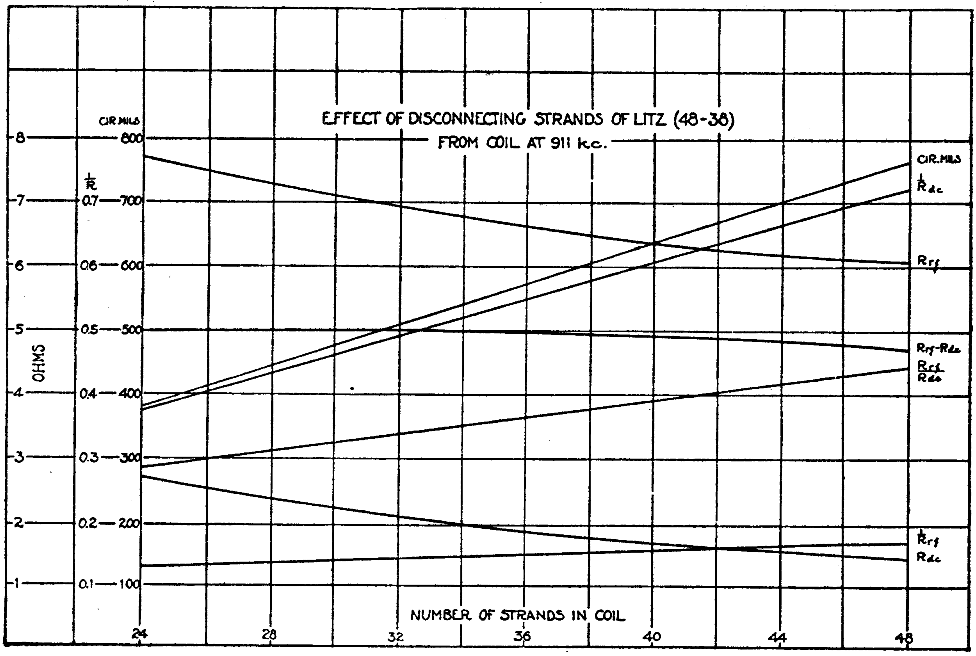

FIG. 7

tuning, changes in frequency of 3 parts in 100,000 being readily measured.

TABLE 3

Coil No.	Frequency range	Diameter	Size of wire	Number of turns per inch	Total number of turns
	kc	*Inches*			
1	170– 235	8.75	96–38 litz	16	109
2	228– 316	8.75	do	16	72
3	308– 427	8.75	do	14	50
4	408– 566	8.75	do	10	38
5	553– 768	6.5	do	12	32
6	736–1,022	6.5	do	9	24
7	1,005–1,395	6.5	No. 10 solid	7	18
8	1,306–1,818	5.0	No. 14 solid	8	15
9	1,740–2,415	5.0	No. 10 solid	5	12
10	2,260–3,155	5.0	⅛-inch copper tube	4	9
11	3,030–4,220	5.0	do	4	6
12	3,860–5,378	5.0	do	2	5

CONCLUSIONS.—The principal results of this work are given in the curves, which present data of value in selecting the size of wire of least resistance under the conditions of test for a given frequency range. The curves of any one of Figures 2, 3, 4, or 5 are directly comparable for the conductors indicated, since each figure gives curves for a coil of approximately the same physical and electrical constants, the size of wire being the chief variable.

The curves presented herewith show, for these test conditions, the desirability of litz wire of a large number of strands for frequencies from 150 to about 1,500 kc. The second choice of wire for this range is No. 14 or No. 18 AWG. The best conductor for frequencies from about 1,500 to 6,000 kc, as shown by these curves, is copper tubing of a diameter about equal to No. 8 wire with a cross-sectional area equal to or less than No. 10 wire. Copper tubing may be difficult to obtain in sufficient lengths so that a wire of large size would probably be preferable. Litz wire should not be used for such coils for frequencies above 1,500 kc, if low coil resistance is desired.

The curves of Figures 6 and 7 show that at a frequency of 911 kc one or two broken strands in litz wire composed of 32 or 48 No. 38 wires do not increase the resistance of the coil appreciably. Reducing the number of strands in the coil connected in the circuit decreases the ratio of radio-frequency resistance to direct-current resistance.

WASHINGTON, July 7, 1926.

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