THE USE OF SERPENTINE IN STANDARDS OF INDUCTANCE.

By Edward B. Rosa and Frederick W. Grover.

1. CONSTRUCTION OF THE STANDARDS.

In 1896 Wien described[a] the construction of a very convenient and permanent form of inductance standard and gave measurements of several such standards by one of his own methods. Spools were turned out of serpentine and wound with insulated copper wire. They were then boiled in paraffin, which completely filled the spaces between the wires, and when cold made a solid mass which preserves its shape permanently. This form of inductance standard has since been manufactured by several of the German instrument makers, and the Bureau of Standards has purchased from Siemens & Halske, R. Franke & Co., and Hartmann & Braun a considerable number of them having values of 1.0, 0.1, 0.01, and 0.001 henry. Coils obtained from different makers agree with one another very closely. Coils of different denominations are reasonably consistent with one another and their values are nearly correct, showing that the makers have accurate standards and adjust the inductances carefully.

In attempting measurements of high precision on these coils, however, we found discrepancies that were difficult to understand until we discovered recently that the serpentine was slightly magnetic and its permeability variable, thus making the inductance of a coil a function of the current passing through it. It happened that the current employed in making the measurements did not ordinarily vary greatly, and hence the discrepancies due to the variation in the permeability of the serpentine were quite small. The small differences noted we first attributed to errors of measurement, but when we undertook a systematic search for the source of these discrepancies we traced it to the coils themselves, and then quickly located it in the varying permeability due to magnetic impurities in the serpentine. Coils wound on mahogany spools show no such effects and, of course, pure marble

[a] Wied. Ann. 58, p. 553.

would be free from it. The question is of so much importance that we give in this paper a considerable number of our tests and measurements in order to show the character of the effects produced and the magnitude of the variations of the inductances.

2. MEASUREMENTS OF INDUCTANCES USING DIFFERENT CURRENTS.

Having noticed that the inductance found varied when the resistances of the bridge were changed, we made a series of measurements on the three inductance coils F, C, and S, of one henry each, having a nearly constant voltage on the Anderson bridge, and giving the resist-

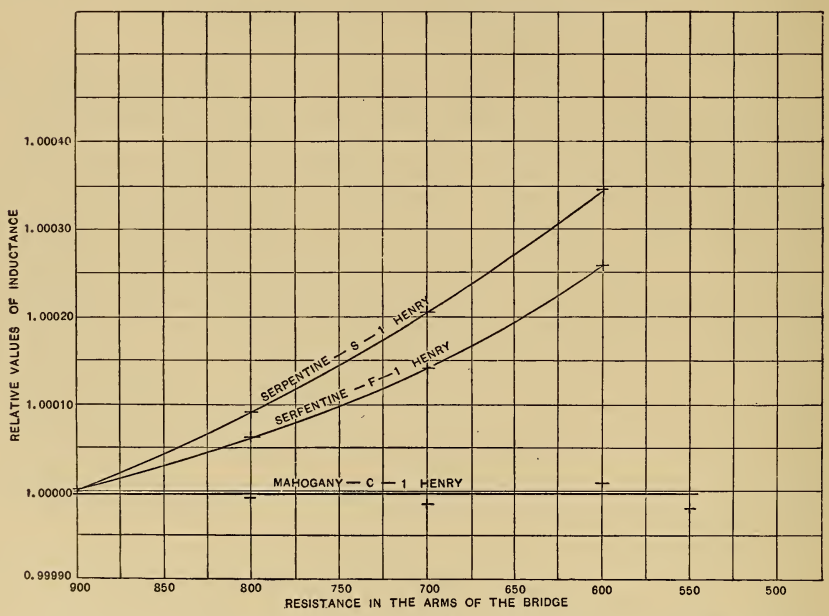

FIG. 1.—Showing the variation of the inductance of the two standards wound on serpentine as the resistances of the (equal) arms of the bridge are varied. Third standard, wound on mahogany spool, remained constant.

ances of the arms of the (square) bridge the successive values 550, 600, 700, 800, and 900 ohms. It was found that the measured inductance of the coil C (wound on mahogany) remained constant within the errors of measurement, the observations varying from the horizontal straight line (fig. 1) by not over 2 parts in 100,000 on the average. On the other hand the two coils wound on serpentine (F, Franke & Co., S, Siemens & Halske) increased steadily as the resistance was decreased, and the current therefore increased. Fig. 1 shows the changes in the relative values of the inductances of these coils.

We next measured the same coils, keeping the resistances of the arms of the bridge constant, and changing the voltage impressed on the bridge. In order to show that these changes were not due, even in part, to the heating of the bridge wires, we have frequently repeated measurements on lower voltages after making measurements at higher voltages. All the resistances were submerged in oil, and the resistances making up the four arms of the bridge were wound with relatively heavy wire having ample carrying capacity. The results of these measurements are given in fig. 2, showing, as before, a constant value for the coil C wound on a mahogany spool, but a steadily increasing value for F and S (on serpentine) as the voltage (and conse-

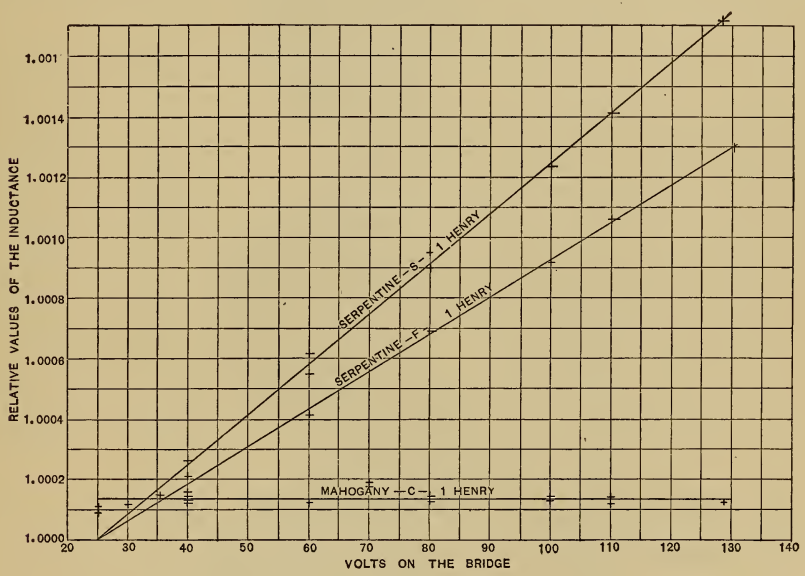

FIG. 2.—Showing variation of serpentine standards as voltage on bridge is varied, resistance remaining constant. Mahogany standard remains unchanged.

quently the current) was increased. In this case the current is carried through a much wider range than before, the maximum being about five times the minimum. The total variation of the inductance of the F coil (while the current is increased in the ratio of 1 to 5) is about 12 parts in 10,000, while the S coil varies 16 parts in 10,000 under the same circumstances. The C coil (on mahogany) varied from the constant value corresponding to the horizontal line in fig. 2 by about 2 parts in 100,000 on the average. The values of the inductances given in figs. 1 and 2 are referred to their lowest value as unity, except the C coil in fig. 2, which is referred to a value 1.0001 as its lowest value for convenience in plotting. Inasmuch as variations of two parts in

100,000 can be detected in the measurements, it would be necessary to keep the current constant within 2 or 3 per cent of its value in using the serpentine inductance, in order that the measured value of the inductance should always be the same. This is, of course, a very awkward condition to impose.

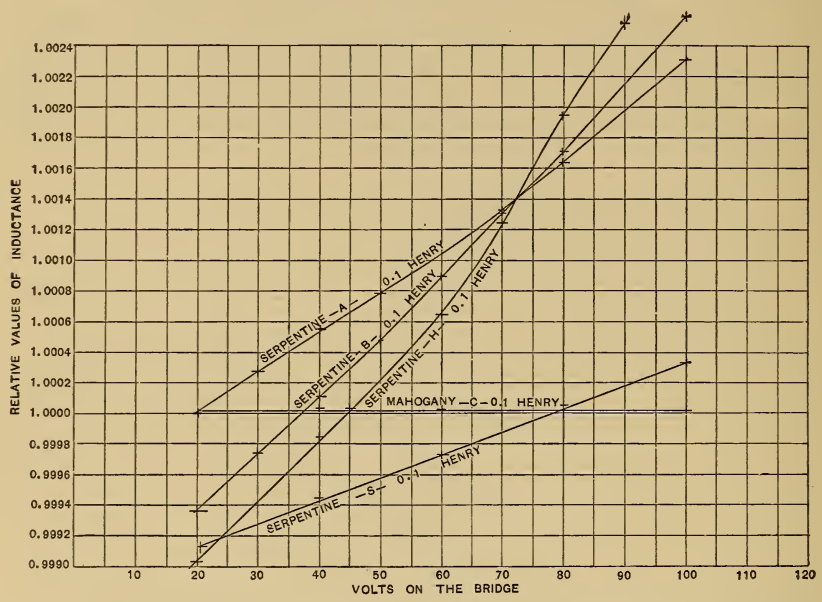

FIG. 3.—Showing variation of inductance of four serpentine 0.1 henry standards. Mahogany standard remains unchanged.

Fig. 3 gives the results of measurements made on five coils of 0.1 henry, each, as follows:

Schedule of inductance coils, each of 0.1 henry.

A = Inductance coil from Franke & Co., on serpentine.
B = Inductance coil from Franke & Co., on serpentine.
C = Inductance coil from Carpentier, on mahogany.
H = Inductance coil from Hartmann & Braun, on serpentine.
S = Inductance coil from Siemens & Halske, on serpentine.

The results agree with the measurements made on tne three coils of 1.0 henry each, in that the mahogany spool has a constant value as the current was increased in the ratio one to five, whereas the other four on serpentine all increased. The four coils, A, B, H, and S, in

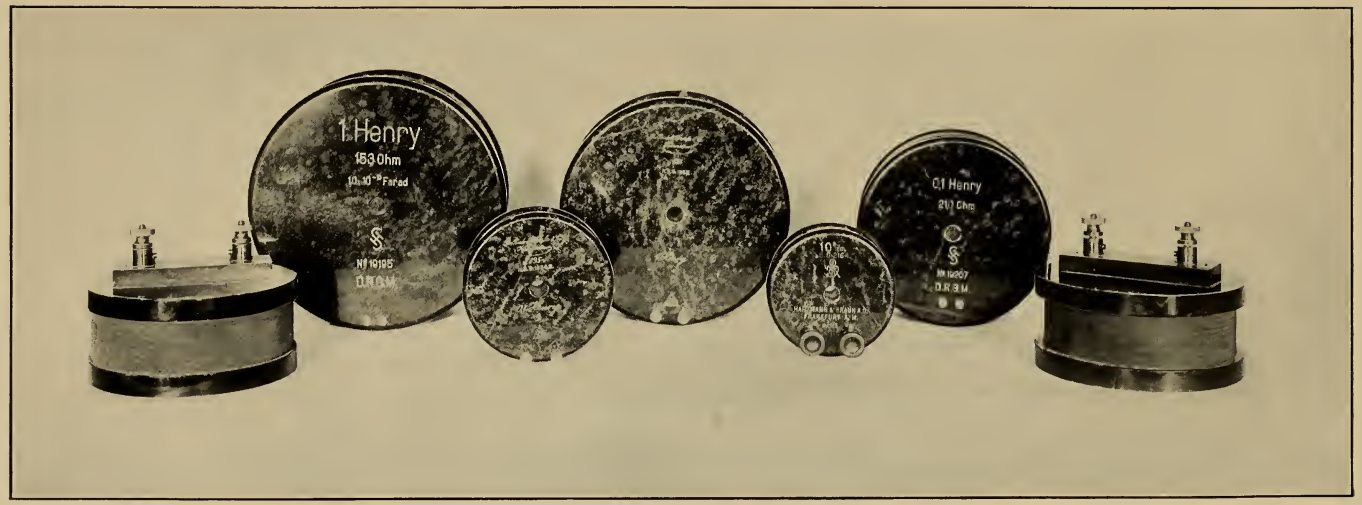

FIG. 6.—FIVE SERPENTINE AND TWO MAHOGANY INDUCTANCE STANDARDS.

The two larger serpentine spools are those of Figs. 1 and 2. The three smaller serpentine spools and the mahogany spool at the right are those of Fig. 3.

fig. 3, are all referred to the lowest value of A as unity; hence the differences shown in the figure are the actual differences of the coils. The fifth coil C (on mahogany) has so large a value (nearly 2.5 per cent greater than the others) that it would fall more than a meter above the others if plotted on the same scale. Hence it has been reduced to the lowest value of A as its initial value for comparison. The five determinations of the inductance of this coil at 20, 40, 60, 80, and 100 volts on the bridge lie very near the horizontal line, the mean variations being not over 2 parts in 100,000.

On the other hand, the four coils wound on serpentine increase largely as the current is increased, the current being of course proportional to the voltage on the bridge. The amount of increase varies from 12 parts in 10,000 for the S coil to 23 for A, 31 for B, and 40 for H. Since the inductance of a coil is proportional to the average permeability of its magnetic circuit, and the principal magnetic reluctance is in the region occupied by the spool, it is evident that the curves of fig. 3 represent approximately the permeabilities of the four serpentine spools. One is straight throughout, two are slightly curved, and the fourth, H is decidedly curved, showing a rapidly increasing permeability as the current is increased. They are all made from serpentine having the same appearance, but S is a relatively large spool in which the strength of field within the spool is relatively smaller, whereas H is the smallest of the four spools and therefore has the largest number of turns of wire and the strongest field, the inductances of the four spools being equal. The range of inductance in the serpentine spool S therefore corresponds to the lower end only of H, A, and B, which are straight lines. We may therefore conclude that if the spools were all as large as S, the lines would all be sensibly straight, and conversely if all were as small as H they would be curved in much the same way.

It is a coincidence that three curves intersect at one point. Thus there is one value of the current for which these three coils have the same inductance. At lower current, H has the smallest value, and at larger currents it has the largest value. The coil B is intermediate in value both at large and small values of the current.

This explains discrepancies in the relative values of these coils which we have often noticed. That is, comparisons by bridge methods, which may be made with great precision, have not given the same ratios at different times, and we were at a loss to account for the fluctuating ratios. It may be that other observers have been troubled in the same way, for serpentine inductance standards are considerably used.

3. INDUCTANCE OF A COIL INCREASED BY PROXIMITY OF SERPENTINE.

In order to demonstrate further the fact that the serpentine spools are appreciably magnetic, we made a series of measurements on the same inductance coils, with one coil placed directly on another, or between two others, so that the reluctance of its magnetic circuit might be reduced by the magnetic serpentine. The following are some of the results obtained:

(*a*) Serpentine henry placed on (or under) mahogany henry increases the value of the latter by 2.3 millihenrys.

(*b*) On the other hand, mahogany henry placed on (or under) a serpentine henry makes no appreciable change in the inductance of the latter.

(*c*) Serpentine henry placed on a serpentine henry increases the inductance of the latter. For example, S increases F 2.4 millihenrys, and F increases S 2.2 millihenrys. F, between two serpentines, is increased 4.1 mh, and S, between two, is increased 3.5 mh.

(*d*) Serpentine 0.1 henry on serpentine 0.1 henry is increased about 0.25 mh, and on serpentine 1.0 henry about 1.7 mh, on an average. On 0.01 henry it is increased about 0.2 mh, and on 0.001 henry about the same.

The above results show that the smaller inductance coils also are magnetic and can affect the magnetic circuit of other coils if near them.

4. EFFECT OF MAGNETIC SERPENTINE IMITATED BY IRON FILINGS OR WIRE.

In order to illustrate further the effect of magnetic material in the spools of inductance coils, we have made a number of measurements on the coils with iron wire or iron filings in or near them.

(*a*) With a single piece of soft iron wire, 4 cm long, 1.0 mm in diameter, inserted in the axis of the mahogany spool, the inductance was increased over 2 per cent, as shown in (*a*) fig. 4, the form of the curve showing that the permeability of the circuit increased to a maximum and then decreased as the current in the coil increased.

(*b*) With six pieces of iron wire, each 5 cm long, arranged radially on the bottom of the mahogany spool (inverted), the inductance increased over 1 per cent, as shown in (*b*) fig. 4. In this case the permeability did not reach its maximum, the wires not being in a strong magnetic field, as in case (*a*). As the voltage was increased from 60 to 100, the inductance changed nearly 3 parts in 1,000, which is much greater than the change in the case of the serpentine coils.

(*c*) A piece of this wire 2 mm long (weighing 21 mg) inside the coil produced a sensible change in the inductance of the coil; that is, 5 parts in 100,000. A few particles of iron (weighing 9 mg) increased the inductance by 2 parts in 100,000. This is only one part iron to over a hundred thousand of the spool, if the latter were serpentine.

(*d*) Iron filings, sprinkled over the wooden spool, also increased the inductance, fig. 5; 2 grams of the filings increasing the inductance initially by 1 part in 800, the amount increasing further with the current, as is the case with the serpentine.

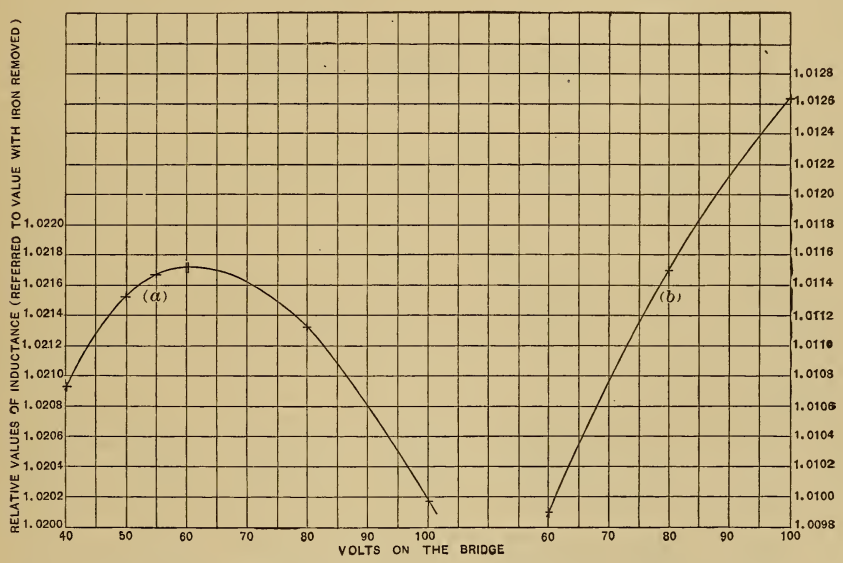

FIG. 4.—Showing change of inductance of standards; (*a*) when a piece of iron wire is inserted in axis of coil; (*b*) when six pieces of iron wire are placed radially outside the spool.

(*e*) Iron filings placed in the center of the F serpentine spool (8.2 grams filled a hole along the axis of the spool) increased the inductance initially by 70 parts in 10,000, and this increased further by 17 parts in 10,000 as the voltage was carried up from 40 to 120 volts. This is nearly double the rate of increase of the inductance that occurs without the filings. These experiments show that the behavior of the serpentine spools is fully explained by supposing them to contain a very small amount of iron.

5. MAGNETOMETER AND CHEMICAL TESTS.

The serpentine inductances were also tested with a magnetometer, and found to be magnetic. By placing one of the serpentine spools

Table I.—Results of Measurements on three Inductance Coils of 1 Henry each; Coils Measured Singly and in Series, June 9, 1905.

[Current through coils=0.05 ampere for first set, 0.045 ampere for second set.]

No.	Coils.	r position 1.	r position 2.	r mean corrected.	$2r+P$	P, R, S, and C	Voltage on bridge.	L_0 henrys.	$L=L_0+\alpha$ henrys.	L_s sum of single values.	$\Delta=L_s-L$ henrys.
1	S	528.996	529.146	529.117	1658.122	$P=R=599.888$	69.75	1.00043	1.00041	.....	.....
2	F	528.202	528.332	528.313	1656.514	$S=600.505$	69.7	0.99946	0.99945	.....	.....
3	S+F	1357.268	1357.550	1357.450	3314.788	$C=1.00474$	93.0	1.99998	1.99996	1.99986	−0.00010
4	F	528.195	528.341	528.314	1656.516	.....	69.7	0.99946	0.99945	.....	.....
5	C	540.358	540.490	540.470	1680.828	.....	70.0	1.01413	1.01412	.....	.....
6	F+C	1368.606	1368.910	1368.799	3337.486	.....	93.4	2.01367	2.01365	2.01357	−0.00008
7	S	529.035	529.148	529.137	1658.162	.....	69.75	1.00046	1.00043	.....	.....
8	C	540.370	540.493	540.478	1680.844	.....	70.0	1.01414	1.01413	.....	.....
9	S+C	1369.435	1369.708	1369.413	3339.114	.....	93.4	2.01466	2.01463	2.01456	−0.00007
10	S	528.997	529.146	529.117	1658.122	.....	69.75	1.00044	1.00042	.....	.....
11	F	528.198	528.328	528.309	1656.506	.....	69.7	0.99946	0.99944	.....	.....
12	S+F	1357.252	1357.543	1357.439	3314.766	.....	93.4	1.99997	1.99993	1.99986	−0.00007

13	C	540.357	540.501	540.475	1680.838	.....	70.0	1.01414	1.01412	.....	.....
14	S	528.999	529.130	529.111	1658.110	.....	69.75	1.00042	1.00040	.....	.....
15	F	528.187	528.328	528.304	1656.496	.....	69.7	0.99945	0.99944	.....	.....
16	F+C	1368.590	1368.910	1368.791	3337.470	.....	93.4	2.01368	2.01366	2.01356	−0.00010
17	S+C	1369.422	1369.715	1369.609	3339.106	.....	93.4	2.01465	2.01461	2.01452	−0.00009
18	F	221.140	221.146	221.168	1242.246	$P=R=799.910$	78.8	0.99934	0.99932	.....	.....
19	C	230.327	230.341	230.359	1260.628	.....	79.0	1.01412	1.01410	.....	.....
20	F+C	851.442	851.490	851.523	2502.956	$S=800.662$	96.6	2.01352	2.01350	2.01342	−0.00008
21	S	221.712	221.729	221.745	1243.400	$C=1.00474$	78.8	1.00026	1.00024	.....	.....
22	F	221.125	221.144	221.159	1242.228	.....	78.8	0.99932	0.99930	.....	.....
23	S+F	842.838	842.894	842.928	2485.766	.....	96.3	1.99969	1.99966	1.99954	−0.00012
24	C	230.315	230.336	230.351	1260.612	.....	79.0	1.01411	1.01410	.....	.....
25	S+C	852.042	852.062	852.114	2504.138	.....	96.6	2.01447	2.01444	2.01432	−0.00012
26	S	221.696	221.726	221.736	1243.382	.....	78.8	1.00025	1.00022	.....	.....
27	F	221.111	221.131	221.146	1242.202	.....	78.8	0.99930	0.99928	.....	.....
28	S+F+C	1473.257	1473.308	1473.336	3746.582	.....	119.4	3.01398	3.01394	3.01360	−0.00034

in a magnetizing solenoid its permanent magnetism could be reversed so that, when it was removed to the magnetometer, the deflection of the latter was reversed. The normal permanent magnetism of the spools was probably due to the earth's magnetic field.

Chemical analysis shows that the serpentine of one of the spools contained 0.6 per cent of iron, which is chiefly in the form of magnetite.

The serpentine inductance coils of 1 henry each were measured alone and in series, increasing the voltage on the bridge when they were in series, so that the current through the coils was nearly the same then as when they were measured alone. This prevented the

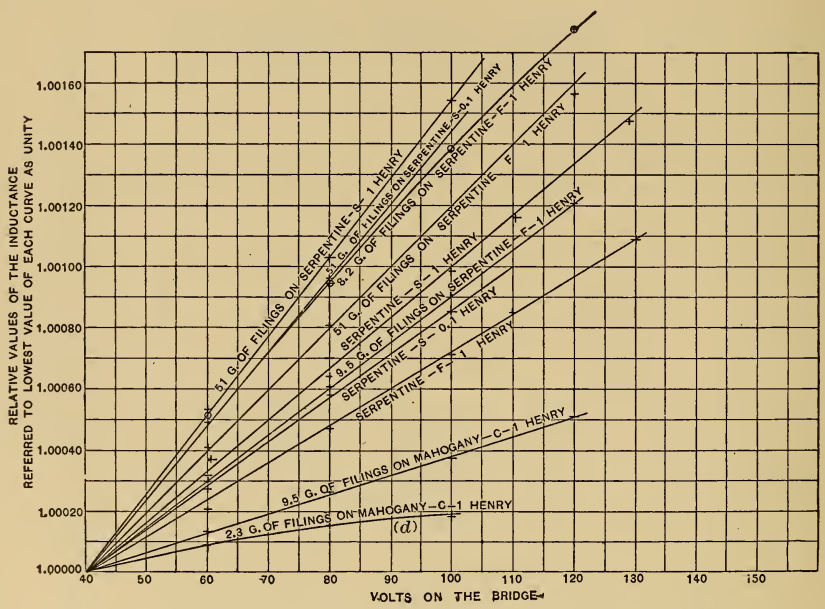

FIG. 5.—Showing effect of iron filings in imitating or increasing the effect of magnetic impurities in the serpentine.

[NOTE.—The curve "8.2 g of filings on serpentine F 1 henry" was obtained with the filings placed *inside* the coil.]

small decrease in value which had formerly resulted when the coils were measured in series, and the residual differences were this time found to be negative and nearly constant, whereas they had before been positive and variable, being smaller with the sum of the mahogany and serpentine than for two serpentines, Table I. This constant negative difference of about 8 parts in 200,000 might perhaps have been due to errors in the resistances; at any rate it is not the same as the residuals due to the variability in the inductance arising from the magnetic material in the serpentine spools.

In Table II we give a summary of the separate measurements of the three coils, taken from Table I. It will be seen that the different determinations of the coils agree very closely, showing that the accidental errors of measurement are very small. The variations would

Table II.—Summary of Measurements of the Inductance Given in Table I.

1	2	3	4	5
No.	Current in coils, amperes.	Measured inductances.		
		Coil F, henrys.	Coil S, henrys.	Coil C, henrys.
1	0.05	0.99945	1.00041	1.01412
2	0.05	0.99945	1.00043	1.01413
3	0.05	0.99944	1.00042	1.01412
4	0.05	0.99944	1.00040	
5	0.045	0.99932	1.00024	1.01410
6	0.045	0.99930	1.00022	1.01410
7	0.045	0.99928		

probably have been greater if the resistances had been varied, on account of variations in the resistances. The last three measurements with a little smaller current are, of course, smaller for coils F and S (serpentine spools) than the first four, but the coil C (mahogany spool) remains substantially the same throughout. In an article in Bulletin No. 2 (issued February 1, 1905), on the Absolute Measurement of Inductance, we called attention to some slight discrepancies which we were at a loss to understand. We now know that they were due to the magnetic impurities in the serpentine spools on which one of the coils was wound.

Hartmann and Braun exhibited at St. Louis some inductance coils wound on white marble. These would undoubtedly be entirely free from magnetism. Wooden spools are cheaper and when the wood is thoroughly seasoned seem to be quite permanent. This question we are investigating further. We have ordered some of these inductance standards wound on marble from Hartmann & Braun, and have designed some to be built for us in this country. When these standards have been thoroughly tested for stability and constancy with

different testing currents we shall determine their values by several different methods in order to ascertain what sensibility and how close agreement may be found among entirely different methods.

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