APRIL, 1927 *PHYSICAL REVIEW* *VOLUME 29*

MAGNETIC PERMEABILITY OF IRON AND MAGNETITE IN HIGH FREQUENCY ALTERNATING FIELDS

BY G. R. WAIT

ABSTRACT

Relative values of the permeability of cast-iron filings, iron wires, and iron powder in high frequency magnetic fields.—Wwedensky and Theodortschik have found the magnetic permeability of iron, steel, and nickel in alternating fields to be abnormally large in certain frequency bands (at about 100 meters for iron) and nearly normal in other regions. The general appearance of the phenomenon suggested the existence, in the material, of resonators corresponding to these frequencies. The phenomenon has been observed also by Kralovec. Two experimental methods have been followed in the present investigation, one the resonance method and the other the heterodyne method. Both utilized, in principle, the measurement of the change in inductance of a coil due to the introduction of the sample of material into it. The wave-length ranges covered were from 80 to 1700 meters by the heterodyne method and from 50 to 160 by the resonance method. The heterodyne method was used in an improved form which eliminated drifts. The results are in disagreement with those of Wwedensky and Theordortschik and with those of Kralovec. No anomalous change in permeability was found at any frequency. The following errors, which may have misled previous investigators, were found in the course of the present work: (a) anomalous behavior of capacities in series when these are connected in tube circuits, an effect the nature of which is unknown but which is related in some way to the length of the connecting wires; (b) a general variation in the apparent permeability as measured by one coil, presumably due to effects of distributed capacity; (c) apparent anomalies when a number of coils are used without comparing the results at the same wave-length; (d) an apparent anomaly in the permeability, at a critical frequency, arising from the presence of a metal shield inside the coil; (e) an effect of drift in the heterodyne method.

The absolute value of the permeability of powdered magnetite.—The permeability of magnetite in powdered form has been measured by two fairly independent methods. The values decrease from about 1.532 at 132.2 meters to 1.401 at 85.8 meters. After due allowance is made for density of packing, these values compare favorably with the results obtained by a static method by Welo and Baudisch.

THE magnetic permeability of iron in oscillating magnetic fields of wave-lengths greater than 1000 meters, has been found to be approximately constant[1] and similar to that in stationary fields. For shorter wave-lengths, Wwedensky and Theodortschik,[2] using soft iron wires, determined the permeability between wave-lengths 54 and 705 meters and, using steel and nickel wires, between 50 and 500 meters. Their curve for iron wires, where μ, the permeability, is plotted against λ, the wave-length in meters, is shown in Fig. 1. This shows a sharp maximum of the permeability at about 100 meters, between two sharp minima. This apparently anomalous behavior of the

---

[1] R. Brown, J. Frank. Inst. **183**, 41 (1917).

[2] B. Wwedensky and K. Theodortschik, Ann. d. Physik. **68**, 463 (1922), and Phys. Zeits. **24**, 216 (1923).

permeability, at about 100 meters, was explained by the above workers as being due to the resonance of elementary magnets of which the iron is supposed to be composed, their frequency of oscillation being approximately 3×10^6 per second. J. Kralovec, making measurements on cast-iron filings, found anomalies between 80 and 90 meters and again between 100 and 110 meters. Observations on magnetite failed to show similar critical changes in permeability. The fundamental importance of obtaining definite proof as to the existence of such oscillators has led to the present investigation.

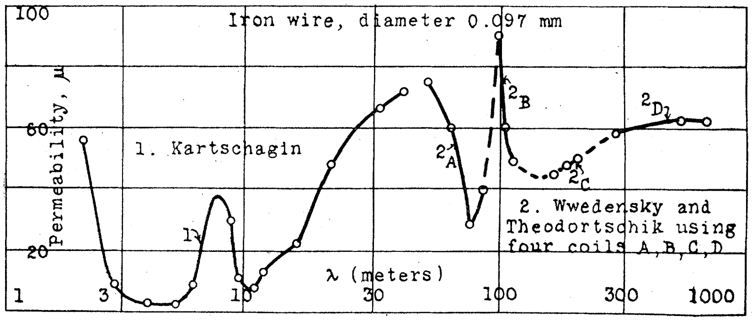

Fig. 1. Results by Kartschagin and by Wwedensky and Theodortshcik.

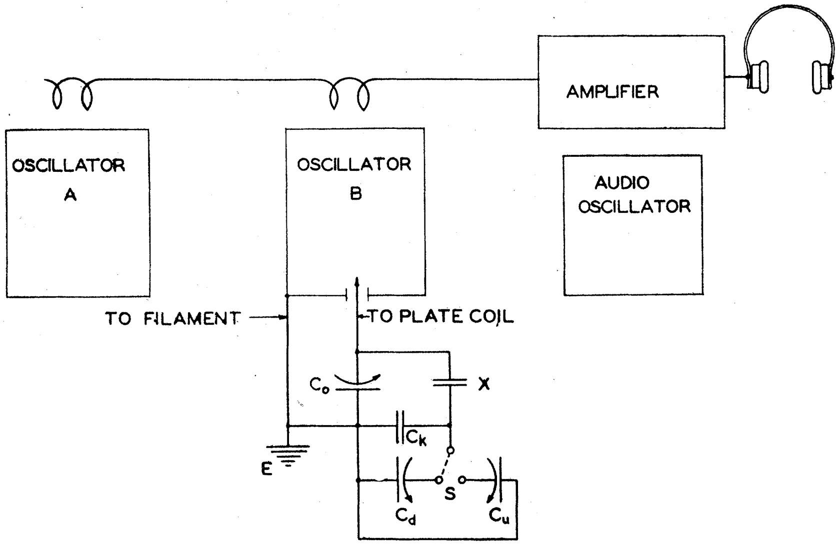

Fig. 2. Diagrammatic sketch of apparatus.

Apparatus and Experimental Methods

Two of the four methods used by Wwedensky and Theodortschik were used in a modified form in the present investigation. In method I, two electron-tube oscillators, *A* and *B*, of Fig. 2 were tuned so as to give a small number of beats which were detected by means of an audio-frequency amplifier. The two oscillators were coupled loosely; the coupling coils were connected to the "input" of a three-tube amplifying unit and the phones to the "output." The sample, upon being introduced into the coils of set B, changed the tuning of the two sets by changing the inductance of the coil. The sets were returned to the original pitch by compensating for the changed inductance by a corresponding change in the capacity C of the system of condensers shown. This change was affected by altering the setting of C_o, a variable air condenser in series with the coil. The capacity of the air condenser X, was kept constant at about 219 mmf. C_k is a mica condenser of about 5500 mmf. C_u and C_d are variable air condensers, each with a range of about 30 mmf to 900 mmf. S is a mercury switch which automatically substitutes C_d for C_u when the sample is introduced quickly into the coil by a lever system. A rigid iron structure provides for exact centering of the sample in the coil and prevents movement of the sample in any direction after introduction. Sets A and B are shielded electrically by brass boxes. The amplifying unit and also all "A" and "B" storage batteries are in wooden boxes covered with sheet iron. All exterior electrical connections are properly shielded. In some of the work a tin-foil shield was introduced into coil "B" to shield the sample. A set of six pairs of oscillating coils of properly selected inductances, wound on bakelite tubing, gave considerable overlapping of wave-lengths. The total range of wave-lengths extended from about 80 meters to 1,700 meters. Table 1 gives particulars regarding each coil.

TABLE I

Particulars of coils used.

Coil No.	1	2	3′	3	4	5
Length (cm)	5.0	5.0	5.0	5.0	5.0	7.5
Diameter (cm)	8.8	8.8	8.8	8.8	8.8	8.8
No. of turns	7	10	14	26	51	76
Obs. inductance (micro-henries)	5.1	9.5	16.4	58	208	373

To measure the wave-lengths used, an auxiliary oscillator was set at resonance with sets A and B so as to leave unaltered the tuning that had been obtained between them. Then by means of a calibrated wave-meter the frequencies of the auxiliary oscillator were determined.

The selection and arrangement of capacities shown in Fig. 2 as X, C_k, and C_u (or C_d) acted as an extremely fine adjustment of capacity of condenser C_o. The curve connecting ΔC_d and ΔC is almost a straight line, and a change of nearly 900 mmf is required in ΔC_d to produce a change of 1 mmf in ΔC.

In practice, the sample was removed from the coil, sets A and B were tuned to a convenient pitch, and the audio-frequency amplifier was tuned to a pitch giving a very small number of beats. Upon introducing the sample into the oscillating coil of set B, retuning was effected by condenser C_d. Some drift was frequently present when it was necessary to remove and reintroduce the sample several times and to make appropriate readjustments of C_d for each determination of ΔC_d. The drift was kept to a minimum by frequent charging of the storage batteries and replacing from time to time of the oscillating tubes (*UV* 199).

In method II, a resonating circuit was set at resonance with an oscillator. Upon introducing a sample into the coil of the resonating set, resonance could again be obtained by compensating for the changed inductance by a corresponding change in the capacity of the circuit. Detection was made by a thermocouple and galvanometer, a low and a high sensitivity galvanometer being used for magnetic fields of high and low intensity respectively.

Belz[3] showed that for a substance with cross-sectional area A' and length l', volume $V'=A'l'$, with sufficiently small susceptibility k, introduced into an oscillating coil of cross-sectional area A and length l, volume $V=Al$, if the inductance, L, of the coil is altered by an amount ΔL, then, neglecting effects arising from eddy-currents, demagnetization, end effects of the sample, and an alteration in the magnitude of the field due to the presence of the interior shield,

$$(V/V')(\Delta C/C)=(V/V')(\Delta L/L)=4\pi k$$

where C is the capacity of the system and ΔC the change in capacity necessary to compensate for the change in inductance. Wwedensky and Theodortschik applied this formulae to their results to get a quantity termed "apparent permeability." In their case, since their sample was longer than their coil, the ratio V/V' reduced to the corresponding ratio of areas. In the present paper, to make proper comparison with their results easier, the quantity $\Delta C_d/(C_o+K_n)$ has been plotted against λ, the wave-length in meters, where the expression (C_0+K_n) represents the total capacity and ΔC_d that necessary to compensate for the change in inductance of the coil due to the introduction of the sample. This procedure is sufficient to show any apparent changes in the relative values of permeability.

RESULTS BY THE BEAT METHOD

Iron filings as a sample. In preliminary work an apparently anomalous behavior for iron filings was obtained for particular settings of condenser C_o, in general similar for the various oscillating coils used. Tests showed that this could not be attributed to a faulty calibration of C_o, nor to the resonance of portions of the circuit having long lead-in wires with the main part of the circuit. The magnitude of the anomaly did not appear to depend upon the amount of iron used as a sample, and consequently could not be a permeability effect. Tests with experimental shields showed the cause of the anomaly was connected with eddy-currents set up in the shield altering the inductance of the oscillating set over the band of frequencies where the anomaly appeared.

In the definitive experiments the region of wave-lengths from about 99 to 1700 meters was covered, using iron filings as a sample. The same sample was not used throughout this range, as was the case later with the iron powder in insulating wax, consequently the results have not been given in

---

[3] M. H. Belz. Proc. Cambridge Phil. Soc. **21**, 52 (1922); Phil. Mag. **44**, 479 (1922).

graphs. However, in all the tests with these samples, after remedying the difficulty produced by the interior shield, no change in permeability at apparently critical frequency occurred.

Iron powder as a sample. For iron powder embedded in insulating wax, and formed into a sphere, relative premeability curves are shown in Fig. 3 for wave-lengths 84 to 1300 meters. Aside from small irregularities, the curves are smooth. In the region of 85 to 95 meters, there are irregularities amounting to about three percent of the value of ordinate. This is greater than can be ascribed to experimental error. This variation always occurred to some extent in the preliminary work, and was always of the same form regardless of the sample used. Various tests applied definitely proved that this was not due to eddy-currents set up in the sample nor to a change in its permeability.

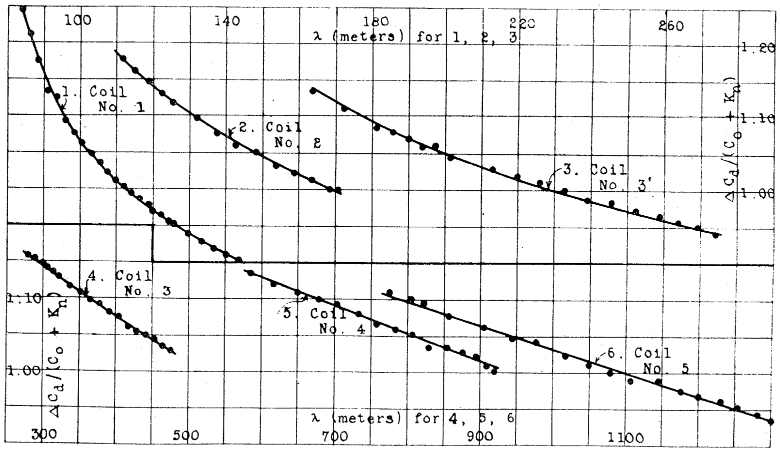

Fig. 3. Results for iron powder embedded in insulating wax, made into spherical form, for wave-lengths 84 to 1300 meters.

In Fig. 4 are presented curves for iron powder and iron wires showing the usual depression at 91.3 meters. When, however, the inductance in series with condenser C_d is increased, the depression gives way to a small maximum. When the inductance is added both to condensers C_u and C_d, the irregularity at this point disappears. This together with considerable additional evidence (a fuller discussion of which is prohibited on account of the lack of space) indicate that this irregularity is due to resonance between certain parts of the circuit.

A regular run with iron powder as a sample, made after shortening the connections between condensers X and C_x gives a curve (curve 6, Fig. 4) that is free from any resonance phenomenon, and is approximately horizontal. Data for curve 5 of Fig. 4 were obtained after replacing the connections as before. It will be seen that the resonance phenomenon has reappeared. It may be well to point out that the value of condenser C_k was different for these two curves from that for all previous curves; this has altered the absolute values involved in these curves. All the above evidence points to the fact that the phenomenon shown between 85 and 95 meters is due to the resonance of one part of the circuit with another, and has nothing to do with the resonance of the elementary magnets of the sample. A sample set of observations and computations is shown in Table 2.

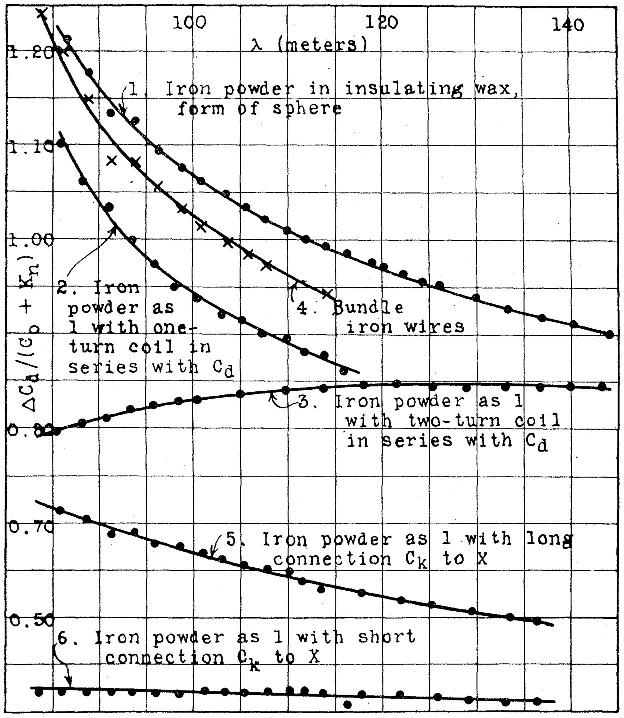

Fig. 4. Tests on iron powder and wires showing apparent irregularities due to particular circuit connections.

TABLE II

Sample set of observations and computed values of approximate permeability μ, for a bundle of 24 iron wires 24 cm long, 0.0127 cm in diameter each, using oscillating coil No. 1.

$C = X^2C_d/(C_u + C_k + X)\,(C_d + C_k + X)$; $C_k = 5501$ mmf; $X = 219$ mmf; $\mu = A\Delta C/A'C + 1$

A, cross-sectional area of oscillating coil, $= 60.85$ cm^2

A', cross-sectionl area of sample, $= 0.0121$ cm^2

C_o Div	C_o mmf	C_d Div	C_d mmf	ΔC_d mmf	C_u mmf	ΔC mmf	μ	λ meters
5	44.5	93.3	510.1	508.7	1018.8	0.580	8.47	83.7
10	65.5	91.8	501.9	516.6	1018.5	0.590	8.21	85.8
15	91.2	89.8	491.0	527.1	1018.1	0.603	7.92	88.5
20	117.2	89.7	490.5	527.2	1017.7	0.603	7.53	91.2
25	142.8	84.8	464.4	552.9	1017.3	0.636	7.52	93.7
30	168.5	82.0	449.6	567.4	1017.0	0.654	7.36	96.2
35	194.5	79.1	434.1	582.4	1016.5	0.673	7.24	98.5
40	220.0	76.2	418.4	597.8	1016.2	0.692	7.13	100.7
45	246.0	73.0	401.2	614.6	1015.8	0.714	7.04	103.3
50	272.0	70.0	385.0	630.4	1015.4	0.734	6.99	105.5
55	298.0	67.0	369.4	645.6	1015.0	0.747	6.81	107.5
70	376.0	57.0	312.2	696.6	1008.8	0.821	6.68	114.0

Magnetite in a powdered condition in insulating wax. Results for powdered magnetite in insulating wax formed into a sphere, are shown by curve 1 in Fig. 5. It will be seen that the slope of the curve is large, the difference between the maximum and minimum values of ordinate amounting to about 27 percent of the smallest value. Now, using the same data to compute the permeability (designated as method A), by means of the equation $\mu=(V/V')(\Delta C/C)+1$, curve 7 of Fig. 5 is obtained. The slope of the latter curve is very small compared with that of the former. The difference between the maximum and minimum values of ordinate in this case is less than 5 percent of the smallest value. Similarly, if the premeability (obtained as for curve 7, Fig. 5) had been used as the ordinate in curves of Fig. 3 their slopes would have been somewhat smaller. The difference in ordinates at overlapping wave-lengths for any two curves would under these circumstances have been less; however, each curve would still require an appreciable correction-factor in order to produce superposition throughout the overlap. It is probable that the failure of Wwedensky and Theodortschik to consider this possibility has led to an error in their results. This is particularly evident

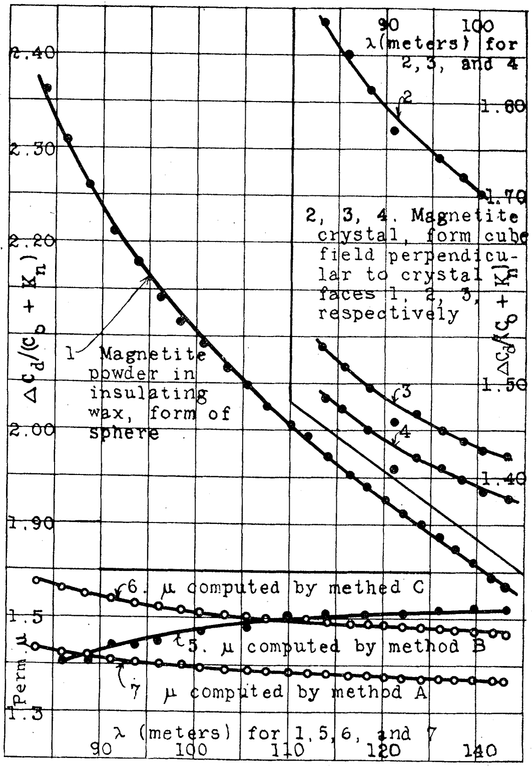

Fig. 5. Results for magnetite powder and magnetite crystal.

in the region (see Fig. 1 for wave-lengths between 90 and 100 meters) where the greatest change in permeability appears to have occurred, and which was explained by them on the basis of resonance of elementary magnets.

A crystal of magnetite was sawed perpendicular to its crystal axes so as to form a cube. 0.8 cm on a side. The results using this as a sample are shown in curves 2, 3, and 4 of Fig. 5. It will be seen that the value of the former quantity depends upon the direction of magnetization with respect to the axes of the crystal. The value of the ordinates for curve 2 are about 22 percent greater than those for curve 3, whereas those for curve 4 are about 3 percent less than those for curve 3. Calculating the permeabilities by means of the equation $\mu=(V/V')\ (\Delta C/C)+1$ (which is permissible for relative values only) one finds that the permeability perpendicular to face 2 is less than that perpendicular to face 1 by 1.8 percent and greater than that perpendicular to face 3 by 0.26 percent. As a check, the relative permeabilities along the three different axes of the cube were determined by a static method at the Bureau of Standards by Mr. R. L. Sanford and his staff to whom thanks are due for this as well as for other courtesies extended. The permeability perpendicular to face 1 was found at field strengths 20 and 50 gauss, respectively, to be 2.2 and 3.4 percent greater than that perpendicular to face 2. No difference in permeability perpendicular to faces 2 and 3 could be detected by this method. The results by the two methods are thus in very good agreement, particularly so since the field strengths in the interior of the oscillating coil (calculated from a knowledge of the current flowing through the coil and the number of turns per centimeter) was always smaller than 20 gauss.

Curves 2, 3, and 4 of Fig. 5, show the usual depression of about 1.5 per cent at about 91 meters, which becomes less than 0.15 percent using the equation $\mu=(V/V')\ (\Delta C/C)+1$. This then is a very small variation but, small as it is, its presence has been successfully explained on the basis of the resonance of one part of the circuit with another. This again brings out the extreme sensitiveness of the method used in these measurements, and indicates how small any variation in permeability must be if it has escaped detection.

Absolute value of permeability of magnetite in a powdered condition. A magnetite crystal was powdered and the powder then worked into soft insulating wax. Observations were made with this as a sample, first in the form of a sphere and then as a flat sheet perpendicular to the magnetic field. In case of a sphere, for static conditions, the demagnetizing field is equal to $4\pi I_1/3$, consequently, $H_1=H'-4\pi I_1/3$, where I_1 is the intensity of magnetization, H' is the magnetizing field with the sample absent, and H_1 the actual field inside the sample. Substituting I_1/k for the value of H_1, and μ for $(1+4\pi k)$ in the above equation and solving for I_1, then $I_1=3kH'/(2+\mu)$, where k is the susceptibility of the material in question. In the case of a sheet perpendicular to the field, $H_2=H'-4\pi I_2$, and one obtains in a similar way, $I_2=kH'/\mu$. If the ratio $I_1/I_2=r$, then $\mu=2r/(3-r)$. Now r may be taken as being equal to the ratio of ΔC_a for sphere and sheet, which can be obtained for various wave-lengths. This then, gives a method (designated B) of determining the absolute value of permeability in which the demagnetizating effect of the sample has been eliminated. In Fig. 5, curve 5 shows the value of the permeability obtained by this method for wave-lengths 85.8 to 132.2 meters. It will be seen that the values decrease from about 1.532 for the greatest wave-length to about 1.401 for the shortest wave-length.

The following circumstances all tend to make the observed value of the permeability lower than its true value (some of the effects are the most pronounced at shorter wave-lengths and possibly may account for the observed decrease with wave-length):

1. Because the eddy-current effect is larger in the sphere than in the slab, the ratio of ΔC for the sphere and slab is reduced. The reductions are relatively greater for the shorter wave-lengths since the eddy-current effect increases with frequency.

2. The mean field strength for the slab is greater than for the sphere since the periphery of the slab is nearer the coil than is the surface of the sphere.

3. The decrease in the field strength of the coil with decreasing wave-length will cause the observed values of the permeability to fall off at the shorter wave-lengths.

4. Because of the finite thickness of the slab, the values of ΔC obtained for this case are too large for all values of the wave-length.

Welo and Baudisch[4] recently determined, by a static method, the permeability of chemically prepared powdered magnetite. Since the permeability of a powder depends upon its density of packing,[5] a direct comparison between the results of their work and the present can be made only after each has been reduced to conditions of similar packing. Each of the results may be reduced to a permeability of the material in solid form by means of formulas developed in the paper[5] by Dr. Breit. The final results, however, will depend upon the assumptions made regarding conditions and state of the powder. For instance, Dr. Breit has treated the following cases: (*a*) a space lattice of spheres; (*b*) a space lattice of spherical holes; (*c*) laminary structure of powder the direction of the laminae being distributed statistically.

For an approximate determination of permeability under condition (*a*) the equation $(\mu-1)/(\mu+2)=q[(\mu_o-1)/(\mu_o+2)]$ may be used, where μ is the permeability of powdered form, μ_o is the true permeability in solid form and q is the ratio of volume occupied by the solid material to the volume occupied by solid material and holes. From the results of Welo and Baudisch, μ is taken as equal to 2.1 (which is only approximate, since it was not measused for such low field strengths as was used in the present case). The value of q is taken as equal to 0.254 (which also is only approximate since the density of packing, where it varied from 1.32 grams per cm^3, was reduced to

---

[4] L. A. Welo and O. Baudisch, Phil. Mag., **50**, 399 (1925).

[5] G. Breit, Amsterdam Proc. Akad. Wet. **25**, 293 (1922).

results for this density by a method only approximately correct, and since the density of the solid material is assumed to be equal to 5.2 grams per cm^3). The value of μ_o comes out negative for this case, which indicates that the conditions specified under (*a*) cannot be true here. Turning now to the results of the present investigation, the value of μ is taken equal to 1.521 and q by assuming that the density of the solid is equal to 5.2 grams per cm^3, equal to 0.229, from which we get μ_o equal to 6.5. For the case of (*b*) the equation as given, may be rewritten into a more convenient form for use, for instance,

$$\mu_0=(1/4)\left\{1+(\mu-1)(2+3p/q)+([1+(\mu-1)(2+3p/q)]^2+8\mu)^{1/2}\right\}$$

where $p=(1-q)$. By means of this equation, from the results of Welo and Baudisch we get μ_o equal to 6.6 and from the present data it comes out equal to 3.9. For the case of (*c*), the equation as given may be rewritten in the form,

$$\mu_0=-3+(3p/q)(\mu-1)+\left\{9[1-p/q)(\mu-1)]^2+24(p/q)(\mu-1)+1\right\}^{1/2}$$

Calculating μ_o from the results of Welo and Baudisch, we find it equal to 7.0 and from the present results equal to 4.0. In view of the fact that the sample used by Welo and Baudisch had the greater density of packing, it would seem that cases (*b*) and (*c*) might more appropriately be applied to their results than to the present ones, and that case (*a*) might more appropriately be applied to the latter. One can see from these comparisons that μ_o obtained by the static method and that obtained for an oscillating magnetic field are in approximate agreement, perhaps as closely as the difference in conditions and the uncertainty of assumptions should warrant one to expect.

A second method (designated *C*) of determining the absolute value of permeability, while retaining certain defects that have been eliminated by the previous method, may also be considered. This method makes use of a simple calculation for the change in the inductance of a solenoid of finite length due to the introduction into its center of a sphere of permeability μ. It neglects the effect of eddy-currents and of the inhomogeneity of the field.

By definition, the change in the inductance of a coil brought about by the introduction of the sphere is equal to the change in flux through the coil produced by the sphere, provided a unit current is flowing through the coil. The unit current causes a certain field H in the region into which the sphere is put. Under the influence of this field the sphere is magnetized so as to have a magnetic moment $r^3[(\mu-1)/(\mu+2)]H$. As long as the sphere is small, the field H is sufficiently homogeneous to cause a uniform magnetization of the sphere. Under these circumstances, it is equivalent to a doublet. The flux through the coil due to the doublet may, for convenience, be thought of as produced by a small turn of wire enclosing an area S, carrying a current J and placed in the same position as the sphere. The area S must be perpendicular to H and the product SJ must be equal to $r^3[(\mu-1)/(\mu+2)]H$ so as to make the equivalent shell of S have the same moment as the sphere. The flux through S due to a unit current in the big coil is SH and, therefore, on account of the reciprocity of mutual induction the flux through the big coil due to a current J in the single turn is $SJ \cdot H$. This is the required change in induction $\Delta L = SJH = r^3[(\mu-1)/(\mu+2)]H^2$.

If the coil is a solenoid of length $2b$, radius a, with n turns per unit length, $H = 4\pi n\, b/(b^2+a^2)^{1/2}$. Also the inductance, with the sphere removed is $L_o = 8\pi^2 a^2 n^2 b \cdot K$, where K is Nagaoka's correction factor. Hence

$$\frac{\Delta L}{L_0} = \frac{[4\pi r^3/3][3(\mu-1)/(\mu+2)]\,[b^2/(b^2+a^2)]}{2\pi a^2 bK} = -\frac{\Delta C}{C}$$

(The development of this equation is due to Dr. G. Breit.)

The above equation may now be applied to the case of the sphere of wax containing the magnetite powder, where $r = 0.906$ cm. For the oscillating coil used, $a = 4.4$ cm, $b = 2.5$ cm, $K = 0.5562$, therefore $(\mu-1)/(\mu+2) = 602.9(-\Delta C/C)$. The values of μ computed by means of this formula have been plotted in curve 6 of Fig. 5. The values of the permeability obtained by means of the equation $\mu = (V/V')\ (\Delta C/C) + 1$ have been plotted in curve 7 of Fig. 5. If due allowance be made, as explained before, for the various factors that tend to lower the value of the permeability of curve 5 at the shorter wave-lengths, there is fair agreement between the values given in curves 5 and 6. The values represented by curve 7 could hardly be expected to give a closer agreement with the other two curves since several factors are operating to effect both its slope and its absolute value.

RESULTS BY RESONANCE METHOD

Iron filings, iron powder, and iron wires as samples. Results by this method have been obtained on iron filings, coarse and fine, in and out of paraffin, iron powder, and iron wires. The bundle of wires used as a sample was packed into a glass tube having a diameter of 0.8 cm and 10.5 cm long, each wire being on the average about 0.002 cm in diameter. The other samples were packed into glass tubes having diameters between 1.2 and 1.3 cm and lengths between 10 and 11 cm. In the case of the fine and the coarse filings in paraffin, two different field strengths were used, namely, 0.05 and 0.6 gauss respectively, and for the other cases 0.6 gauss only. The strength of the field was kept constant by varying the coupling between the oscillating and the resonating circuits, thereby keeping the deflection of the detecting galvanometer constant.

In the early part of the work, considerable difficulty was experienced with apparent variations in permeability, which were not always reproducible. Later results, however, showed that this was only an apparent variation and was in reality due entirely to instrumental causes. The region where the apparently large variation in permeability appeared in the results of Wwedensky and Theodortschik[2] has been covered by this method, yet there appeared to be no critical variation in permeability with frequency within this range.

DISCUSSION OF RESULTS

Comparison of the present results with those obtained by previous investigators. The methods and results of Wwedensky and Theodortschik[2], hereafter referred to as W. and T., have been critically examined in an effort to find an explanation of discrepancies that exist between this work and theirs. It will be well to point out a few things, which in the opinion of the writer may have seriously affected the results of the previous investigations.

1. A serious drift occurred in the work of W. and T., which affected what they called their zero-reading (corresponding to the reading of C_u in the present investigation), amounting sometimes to as much as 13 percent of their total compensating capacity. This necessarily must have affected the accuracy of their results if the drift was not uniform, and if the time of reading the condenser with the sample in was not midway between the times of the two zero-readings. The methods in the present investigation greatly reduced, if they did not entirely eliminate, the possibility of drift. Two separate condensers were used, one when the sample was "out," and the other when it was "in," making it unnecessary to consume time in reading the compensating condenser until the sample was "out." A lever system permitted introduction of the sample in less than a second, and at the same time substitution of one condenser for the other. Thus adjustments with sample "in" and "out" were made within few seconds at most and any drift, was found negligibly small in actual practice.

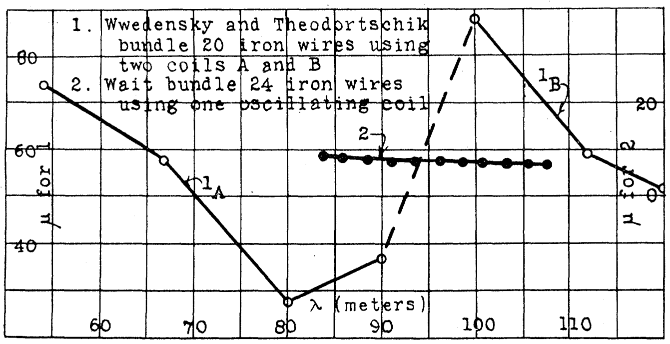

Fig. 6. Comparison of results on iron wires by Wwedensky and Theodortschik, and by Wait.

2. Fig. 6 gives the results of W. and T., the sample being a bundle of soft iron wires used in two different oscillating coils and shows the resonance band ascribed by W. and T. to the resonance of the elementary magnets of which the iron was supposed to consist. Fig. 6 gives also the results of the present investigation, the sample being a bundle of soft iron wires

of a similar diameter to those used by the other workers and like theirs having a length much greater than that of the coil, using, however, only one oscillating coil. W. and T. connected points, as shown by the dotted portion of their curve, obtained by different coils, a procedure which the writer's results show is not justified as correction-factors are required to refer data obtained with different coils to a standard coil.

The author wishes to express his indebtedness to the Director and staff of the Department of Terrestrial Magnetism, and particularly to Dr. G. Breit for valuable advice and assistance, to Mr. J. A. Fleming for continued interest, to Mr. C. Huff and assistants for help in designing and constructing apparatus, and to Mr. J. B. Goldsmith for assistance in the construction of graphs.

CARNEGIE INSTITUTION OF WASHINGTON,
DEPARTMENT TERRESTRIAL MAGNETISM,
October, 1926.