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XXXII. *On the Magnetic Properties and Electrical Resistance of Iron as dependent upon Temperature.* By DAVID K. MORRIS, *Ph.D.*, formerly 1851 Exhibition Scholar, University College, London*.

[Plates II. & III.]

THE changes brought about by heating in the various physical properties of iron have been, since the first investigations into the nature of the phenomenon of recalcence by Gore and by Barrett, the subject of much experimental work, which, during the last ten years, has been largely upon the relation of the magnetic properties of iron to temperature.

As long ago as 1879, however, Baur of Zürich † described experiments on an iron bar inserted while hot into a long magnetizing helix, which served to determine its permeability at any instant, the temperature being estimated from a knowledge of the law of cooling. This method, although rough, enabled him to show that in weak magnetic fields the permeability of iron rises, and that in strong ones it falls, with rise of temperature; and that as the critical point is reached the magnetic qualities of iron in fields of all strengths very rapidly disappear.

These results have been confirmed and extended by the

* Communicated by the Physical Society: read May 14, 1897. Inaugural Dissertation for the Degree of Ph.D. at the University of Zürich.

† C. Baur, "Neue Untersuchungen über den Magnetismus," *Wied. Ann.* 1880, p. 394.

researches of Ledeboer in 1888*, and by those of Dr. Hopkinson, communicated to the Royal Society in 1889†. In the latter, a ring-magnet was used, furnished with primary and secondary coils insulated with asbestos, and capable of withstanding a red heat, which temperature was obtained by means of a gas-furnace. Measurements could thus be made of the permeability of the iron core by the ballistic method, and the temperature was deduced from the resistance of the copper secondary winding.

M. Curie, in a more recent investigation‡, used a method by which the permeability could be obtained in intense magnetic fields. He experimented on a sample of iron in the interior of an electrically-heated porcelain furnace, and deduced its magnetization from the forces acting on it when placed in a non-uniform magnetic field. A thermo-electric couple served to measure the temperature.

The variations of magnetic hysteresis with temperature have been studied by W. Kunz of Darmstadt§.

The relation of the electrical resistance of iron to temperature has also received the attention of several experimenters; curves expressing this relation, and extending to beyond the critical temperature, having been given by Kohlrausch in 1887||, by Hopkinson in 1889¶, and by Le Chatelier in 1891**.

General Description of the Method of Experiments.

By the method used in the present work, measurements of the electrical resistance and of the magnetization of the iron could be made simultaneously.

It consisted in the employment, as in Dr. Hopkinson's experiments, of a ring-magnet, whose insulation was calculated to withstand a white heat. The core of this ring-magnet was formed of a length of *insulated* iron wire or strip, whose ends projected out of the ring, so that the resistance of the iron in the core could be measured; and *in this core* was imbedded an insulated platinum wire, from the resistance of which the temperature of the iron could be deduced.

* Ledeboer, *Journal de Physique* (2) vol. vii. p. 199.

† Hopkinson, "Magnetic and other Physical Properties of Iron at a High Temperature," *Phil. Trans. Roy. Soc.* 1889, A. p. 443.

‡ P. Curie, "Propriétés magnétiques des corps à diverses températures," *Ann. de Chim. et de Phys.* July 1895, p. 289.

§ W. Kunz, *Elektrotechnische Zeitschrift*, 1894, p. 194.

|| W. Kohlrausch, *Wied. Ann.* vol. xxxiii. p. 42.

¶ Hopkinson, *Proc. Roy. Soc.* vol. xlv. p. 457.

** Le Chatelier, *Comptes Rendus*, vol. cx. p. 283.

The heating was carried out electrically. For this purpose the ring (which was made quite small, about an inch in diameter) was covered with a non-inductively wound layer of insulated platinum wire. By passing a suitable current through this wire the temperature could be raised to any required extent. The heat was thus generated exactly where wanted; and by wrapping the ring thickly with asbestos the loss of heat by radiation was made small, and the temperature in the interior fairly uniform.

In the experiments of M. Curie, 1500 watts were absorbed in obtaining a temperature of 1350° : by the above method, 73 watts (a current of 4.6 amperes with 16 volts across the terminals) was found sufficient to maintain the ring at 1150° ; and 45 watts sufficient at 800° , *i. e.*, above the critical temperature of the iron. Dealing thus with comparatively small currents, the accurate regulation of the temperature was rendered simple; whilst absolute constancy for long periods of the heating current, and therefore of the temperature, was, with a set of accumulators in good order, not difficult to attain.

To avoid oxidation of the iron, the ring-magnet was placed in a glass vessel, and the electrical connexions brought through a well-fitting cork rendered air-tight by a thick layer of sealing-wax poured over it while hot. The oxygen contained in this closed space could, previous to the experiments, be absorbed by an auxiliary coil of bare iron wire, heated to bright redness by an electric current. In the later experiments the jar was, as a preliminary, exhausted by a small air-pump to about a third of an atmosphere; during the heating, the pressure might rise above that of the atmosphere, in which case the excess of heated air was allowed to escape from a glass tube dipping into mercury; and this at other times served as a gauge to show whether the glass vessel was really air-tight.

Details of the various Ring-Magnets.

During the course of the experiments, four ring-magnets were made.

The first came quickly to grief through accidental overheating and partial oxidation of the iron. The oxide seems to have combined with the silicates of the insulating materials, forming a kind of slag, for the ring, on taking to pieces was simply a collection of platinum wires buried in a brown glassy substance with a little iron left in the core.

The experiments with the second ring (whose core was

formed of a length of ordinary soft iron wire) were more successful; but the results, though interesting, have not been thought worth including in this paper. The experience gained in the construction and use of the first two ring-magnets was turned to account in the two later ones.

Platinum wires were exclusively employed for the windings of the ring-magnets, as no substance either magnetic or fusible below 1200° was admissible. These wires, after use in one ring, were used again, with fresh insulation, in the next.

Iron cores.—The cores of the third and fourth ring-magnets (referred to in this paper as specimens A and B respectively), were formed from strips, one chosen from each of two groups of iron samples kindly procured for the author by Mr. R. Jenkins from Messrs. Jos. Sankey and Sons, of Bilston. The sample strips were 1 cm. in width; they were described as follows:—

Specimen A.—“Charcoal Iron, No. 4 Quality; thickness .02 in.”

„ B.—“Best Transformer Quality ~~XXX~~; thickness .014 in.”*

These specimens proved, after careful annealing, to be exceptionally good both as regards high permeability and low hysteresis.

Platinum Thermometer Wire. Method of deducing Temperatures.—The specimen of pure annealed platinum wire used in the measurement of temperature was from the firm of W. C. Heraeus, of Hanau, near Frankfurt-a.-M. The same piece of wire was used in both the later ring-magnets. Its diameter was .0453 cm., its specific resistance at 0° was 10,110 C.G.S. units, and its temperature-coefficient, which was remarkably high, was $\alpha_{0^{\circ}-100^{\circ}} = .00386$.

The resistance-temperature curve was taken by mounting the platinum wire (carefully re-annealed by heating to bright redness in a mass of asbestos) on a small cylindrical mica frame, and measuring its resistance at intervals of about 30° up to 200° C. in a bath of linseed oil. The temperature was measured by a standard thermometer which was carefully checked at 0° and 100° . The oil was vigorously stirred, and observations of resistance were only made when the temperature was very nearly constant.

The experiments of Callendar and Griffiths have established

* This iron, according to the above firm, gives on analysis 99.925 per cent. of iron by difference, the impurities (.075 per cent.) being distributed between carbon, phosphorus, and silicon, with a trace of manganese. It is as pure Swedish iron as can be produced commercially.

the fact that, for pure annealed platinum wire, if $\frac{1}{100}$ th part of the increase of resistance which it experiences in passing from 0° to 100° be called the increment for one "platinum degree," so that the resistance of a platinum wire is a linear function of its "platinum temperature," pt° ; then, if t° is the actual temperature on the air-thermometer scale, the difference $t^\circ - pt^\circ$ can be expressed over wide ranges of temperature by the form $a + bt + ct^2$, which in this case must be reducible to the form $t^\circ - pt^\circ = \delta\{ (t/100)^2 - t/100 \}$.

It was thought that, in the present investigation, an error in the determination of the absolute values of the higher temperatures of even several degrees was of comparatively small moment where the recalescence point for different specimens of iron is known to differ by 50° or more. The resistance-temperature curve for the platinum thermometer wire was not determined directly above 200° , but was extrapolated by the help of Callendar's formula. The value of δ for this wire was $2\cdot10$.

The *absolute* values of the temperatures given must therefore be accepted with caution. They may be wrong by as much as 5° in the neighbourhood of 800° , the error rising with the square of the temperature. For the present purpose, however, it is the *relative* accuracy which is of importance, and this is of a much higher order.

To obtain reliable measurements of temperature, it was necessary that the thermometer-wire should satisfy the following conditions:—(1) Its temperature must not differ sensibly from that of the iron which it is intended to measure; (2) its constants must not alter in any way during the heating of the ring; (3) its resistance must be measured with sufficient precision.

(1) The first condition was the most difficult to satisfy: and it was only by actually burying the thermometric wire in the core itself, and by having the temperature very nearly constant before taking any observations, that the temperature of the thermometer-wire and that of the iron core were brought to a satisfactory coincidence.

(2) With regard to the second condition: the resistance-temperature curve of the thermometer-wire, besides being taken previous to experiments, was also taken after those with each of the specimens A and B; in neither case could any alteration either in the resistance-coefficient or in the value of δ be detected. (Alterations of these constants which had taken place with former thermometer-wires were thought to be due to the fact that the insulation in contact with them had not been previously decarbonized (see p. 220).)

One alteration, however, did take place, particularly during the last annealing of specimen B, when a temperature of 1150° was reached and maintained for some time: the resistance of the thermometer-wire rose (on this occasion as much as 1 per cent.); though, as stated above, the form of its resistance curve remained throughout unchanged.

Messrs. Heycock & Neville * have repeatedly noticed such changes, though slight in amount, in their resistance pyrometers; and conclude that they were due to strains set up by the permanent expansion of the mica frames on which their wires were supported. It is possible that such increase of resistance may also be due, as Prof. Weber has suggested, to evaporation of the platinum at these high temperatures; none of the author's platinum wires retained, after *prolonged* heating, their bright metallic surface †.

In reducing the results, it has been assumed that this alteration of resistance, which was generally very small, took place entirely during the time that the ring was at its highest temperature.

(3) In order to satisfy the third condition, it was not only necessary that precise measurements of resistance should be possible ($\frac{1}{20}$ per cent. represents more than $\frac{1}{2}^{\circ}$ at 1000°), but also that the resistance of the thermometer-wire and that of its compensating leads should be measured very nearly simultaneously.

To obtain the nett resistance from a *single observation*, the following arrangement (fig. 1) was employed, which is similar to, though not identical with, that used in Callendar's platinum thermometers.

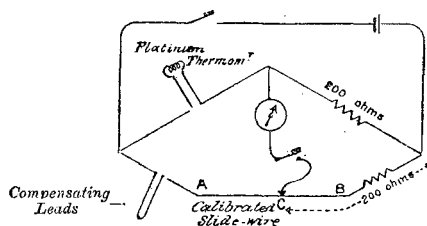
The platinum thermometer-wire and leads formed one arm of the Wheatstone's bridge, and the compensating leads (made exactly equal to those of the thermometer), plus a portion AC of the slide-wire, formed a second arm equal to

* Heycock and Neville, "On the Determination of High Temperatures by means of Platinum Resistance Pyrometers," *Trans. Chem. Soc.* 1895, p. 160.

† Since the above was written, Mr. E. H. Griffiths, F.R.S., has kindly drawn my attention to the fact that his own platinum thermometer wires on mica frames, when heated for considerable periods at temperatures of 1200° – 1400° , do not thus lose their former bright surface. It is therefore rather improbable that in my case the dull surface should point to any serious evaporation of the platinum. I have in this connexion one or two observations which I had not given as I was in doubt as to their reliability:—The mean *sectional area* of the platinum thermometer wire, as measured by the specific gravity method, diminished from $\cdot 001182$ cm^2 to $\cdot 001162$ cm^2 during use in Rings A and B; the *length* increased from 31.33 to 31.56 cm. during the heating in Ring B, and during this same heating the *weight* of the wire did not alter.—D. K. M.

the first. The other two arms contained equal resistances; the 200-ohm coil of a resistance-box in the one; and in the

Fig. 1.—Form of Bridge for Temperature Measurements.



other the smaller coils of the box (together making 200 ohms) with just so many tenths of an ohm short-circuited as were in the remainder CB of the slide-wire. It is clear then that, if C is the position of balance, the resistance AC is equal to the nett resistance of the thermometer-wire.

The resistance of the slide-wire, whose calibration curve was very uniform, was about 1.4 ohms. This was approximately that of the thermometer-wire at 1200° , so that the balancing point for all lower temperatures was within the range of the metre-long slide-wire. The resistance per unit length of the latter was conveniently obtained by inserting a standard ohm in the place of the thermometer-wire.

The above method was also applied to the measurement of the resistance of the iron in the core.

Insulation.—The chief difficulty of the method of these experiments lies in so insulating the wires themselves and the various layers of the ring-magnet from one another, that the insulation shall still remain good at the highest temperatures reached.

The only material which is practically applicable to the insulation of the wires is *asbestos paper*; this paper, which though fairly thin is by no means uniform, was used in the form of long narrow strips wound spirally over the wires to be insulated. After considerable practice, it was found possible to cover wires even as small as .3 mm. in diameter in this way with a reliable, and fairly thin and uniform covering; for such wires, a strip about 4 mm. wide was found to be most suitable.

Asbestos paper must of necessity contain starch or something similar to hold it together; and experiments proved that, when heated in a non-oxidizing atmosphere, the resulting carbon deposit reduced the insulating power of the asbestos to a very low value. This difficulty was overcome by

carefully burning out all the hydrocarbons in one layer of insulation, leaving, so to speak, nothing but the asbestos 'ash,' a white and very brittle covering; and then cautiously over-covering this with a layer of ordinary asbestos paper.

In the first experiments, the leakage between the heating-coil (with 10 volts across its terminals) and the secondary winding was sufficient, when the ring was at 1000° , to drive the astatic needle of the sensitive galvanometer included in the secondary circuit almost round to its stops; and though the needle could be easily brought back artificially to its zero position again, the leakage was uncertain enough in amount to render ballistic observations at this temperature quite out of the question. The introduction of the above-described improvement in the asbestos insulation reduced this leakage to about $\frac{1}{100}$ th part of its former amount; but it still represented a not very constant zero error of several centimetres.

With the object of still further reducing the leakage, mica was tried as insulation between the layers. This plan ultimately succeeded very well; but the difficulty of applying a reliable layer of mica insulation to a surface of "double curvature," such as that of a small ring, without the assistance of any adherent whatever, appeared at first insurmountable. Latterly, however, it was found that if the mica insulation for the "doubly-curved" parts was applied in the form of small suitably-shaped pieces, previously heated in a Bunsen flame * and then bent or continuously broken by pressing over a rounded edge, then, by putting each piece of mica into place as the coil of insulated wire above it was wound, a reliable layer of mica insulation could be obtained without much trouble.

Mica was also used in the later ring-magnets both for the insulation of the iron strip and for that of the thermometer-wire, in a way about to be described; it was not only put between the turns of the iron strip, but was also placed next to it, beneath the asbestos covering; since any carbon deposited from the latter would, if in contact with the glowing iron, combine with it and alter its character.

It is easily shown that no appreciable error in the measured resistance of the iron or thermometer-wire would arise from a conductivity of the insulation sufficient to give rise to even a large deflexion of the ballistic galvanometer needle.

Construction of Ring-Magnets.—The rings containing

* This diminishes the tendency of the mica to split, and seems to do so by burning off the raw cut edges.

specimens A and B were almost identical in construction, differing mainly in the superiority of the insulation of the later ring. They were made in the following way (see figs. 2-4):—

A sample iron strip was chosen, and a narrow band 2 mm. wide was cut by a cold chisel out of the middle, leaving a specimen consisting of two parallel strips each 4 mm. in width joined at one end. The mean section of this double strip was determined by the specific gravity method. It was then insulated with mica and covered with asbestos as shown in fig. 2.

Fig. 2.—Preliminary Stages. Half full size.

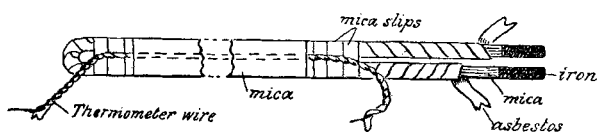
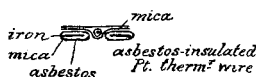


Fig. 3.—Section. Full size.



The insulated thermometer-wire was next laid in the space between the two iron strips, separated from them by slips of mica laid crosswise, and covered over by a plain mica strip (fig. 3). The whole was then rolled up on a temporary wooden form into a ring of four or five turns (fig. 4).

Thus, though asbestos was used in the core as insulation, it was the mica alone that was relied upon.

The ends of the iron specimen were then bent so as to leave the ring at right angles, and form a "stem" about 10 cms. in length. A portion of the same iron specimen resembling this stem both in form and insulation, but only leading just up to the ring and back (see fig. 6), was bound on beside the stem that compensation for its resistance might afterwards be made. The ends of the platinum thermometer-wire, together with a similar compensating resistance formed of a piece of the same platinum wire, were also led up the stem, which was in all parts most carefully insulated with mica.

The next step was to overwind the ring with three layers of platinum wire to serve respectively as magnetizing coil or primary, as heating coil, and as secondary. These wires, each of which, like the thermometer-wire, was doubly-insulated with asbestos in the way previously described, were respectively 110, 150, and 100 cm. in length, and .6, .45, and

·3 mm. in diameter. Mica insulation separated the several windings from each other and from the core.

Fig. 4.—Section of completed Ring. Scale $\frac{1}{2}$ full size.

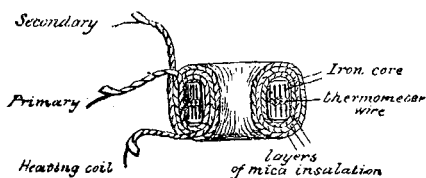
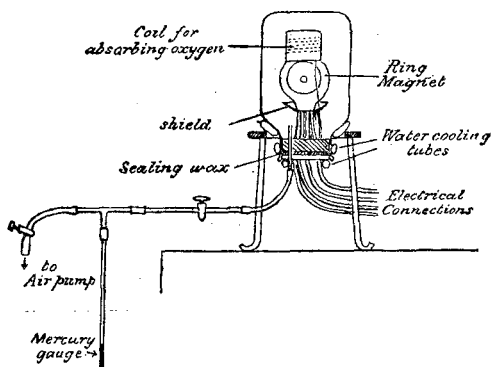


Fig. 5.—Showing Ring in Glass Vessel.



The heating wire, wound back on itself to avoid magnetizing effect, was passed once or twice round the lower part of the stem to prevent that local abstraction of heat to which the stem would otherwise have given rise.

The secondary winding was wound last of all; it being possible in this way to secure better insulation, particularly from the primary, from which even a small leakage into the secondary was much more serious than any leakage from the heating coil; for in the former case every ballistic throw due to a change in the primary current would be associated with a change of zero, while in the latter case no such change would occur.

The ring was afterwards successively covered with a layer of mica, a layer of asbestos, a covering of iron-wire gauze, and, finally, with a jacket consisting of three coverings of soft asbestos millboard. The iron gauze, which became red hot when the ring was being used at high temperatures, was placed there to intercept oxygen on its way in.

The *oxygen-absorbing coil* was, however, quite distinct from this. It consisted of two bare iron wires, connected in parallel, wound side by side on a cylindrical asbestos frame, and surrounded by a loosely-fitting asbestos mantle. Before the experiments they were heated by an electric current to a temperature at which they would readily absorb oxygen.

The coverings of the ring-magnet formed a mass of asbestos about 6 cm. in diameter; a small hole through them enabled one to see what sort of temperature had been reached in the middle of the ring.

The coil for absorbing oxygen was then made fast to the ring-magnet, and the leading wires brought through a cork (previously boiled in linseed oil), which was then inserted into the glass jar and covered with melted sealing-wax (fig. 5). Finally, the terminal wires were soldered to those leading away to the rest of the apparatus.

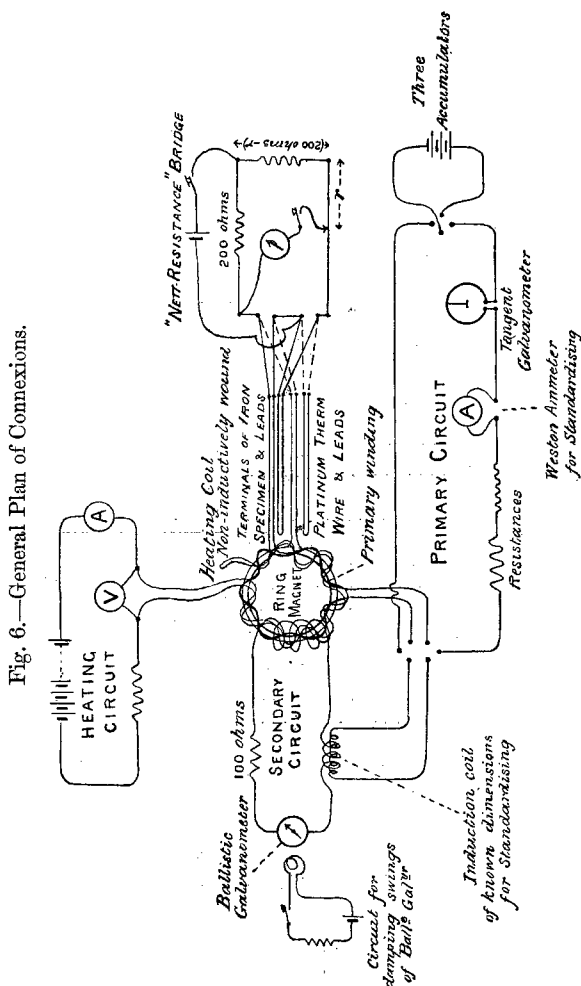
The following particulars relate to the last two ring-magnets constructed :—

| Core of ring specimen | A. | B. |
|---|-------------------|------------------------------|
| Description of iron | Charcoal Iron. | Swedish Transformer Iron. |
| Number of turns of core | 4 | 5 turns |
| Density of iron (after experiments) | 7.775 | 7.461 |
| Total sectional area of iron | .131 | .143 cm. ² |
| Mean diameter of ring | 2.35 | 2.23 cm. |
| Number of turns of primary | 28 | 29 turns. |
| „ per cm. of magnetic circuit | 3.792 | 4.143 turns per cm. |
| Field due to 1 amp. in primary | 4.765 | 5.206 C.G.S. units. |
| Mean sectional area enclosed by primary . . | .72 | .83 cm. ² |
| Number of turns of secondary | 15 | 17 turns. |
| Resistance of iron at 18° | .0486 | .0477 ohm. |

Electrical Arrangements.—Reduction of Results to Absolute Measure.—The various electrical circuits communicating with the ring-magnet are indicated in fig. 6, which needs little explanation, except perhaps with regard to the arrangement for standardizing the ballistic galvanometer.

For this purpose an auxiliary ring-magnet of known dimensions and having a non-magnetic core was used. Its secondary, in series with that of the iron ring-magnet, formed, in circuit with the galvanometer and a coil of 100 ohms, the secondary circuit, as it remained throughout the experiments. On reversing a known current in the primary of the auxiliary coil, the resulting throw of the ballistic galvanometer was a measure of its sensitiveness to induction alterations in that particular secondary circuit, whether taking place in the core of the auxiliary coil, or in that of the iron ring-magnet. Such

standardizing throws were observed before the readings at each temperature, and in this way direct compensation was made for alterations in the resistance of the secondary circuit.



The standardizing throw and the numerical data of the iron ring-magnet being known, it was possible to obtain from each ballistic observation the change of magnetic induction in the iron core to which it was due; correction being of course made for the induction which did not pass through the core.

The magnetizing current was measured with a tangent galvanometer, whose indications were compared with those of a standard Weston ammeter. The magnetizing force was assumed to be uniform in intensity throughout that part of the section of the ring occupied by the iron; which assumption is, in the present case, but approximately true, though the oblong cross-section favours the uniformity.

Description of the Experiments.

The iron cores in their initial condition may be regarded as unannealed; for the original annealing was destroyed during their preparation.

To study the effects of annealing, measurements were taken during the first heating of specimen A. With this exception, however, all the experiments recorded in this paper were made during the cooling from some definite temperature at which the iron had been thoroughly annealed, that all effects other than those due directly to change of temperatures might be eliminated. The duration of each of the long sets of experiments was about 20 hours.

The ring containing *specimen A* was first heated slowly up to 1050° , stopping at various stages on the way up for observations, and then allowed to cool, when another series of observations was made. It was afterwards heated to 920° to find whether the annealing was complete.

The ring was then taken to pieces, that the cross-section of its iron and the constants of the thermometer-wire might be re-determined.

The arrangements for absorbing the oxygen were with this ring not very perfect. The coil for this purpose had but one iron wire instead of two in parallel; and, becoming locally oxidized, the wire fused before it had absorbed all the oxygen. The cross-section of the iron core on removal from the ring and on detaching the oxide was found to have diminished by as much as 8 per cent. Since, however, no change of section occurred (as deduced from the constancy of the resistance and permeability) during the concluding heating to 920° , it may safely be assumed that the oxidation took place previous to the cooling from 1050° ; and that the section during subsequent experiments was the same as that measured at their close.

The ring-magnet, of which *specimen B* was the core, was, after preliminary magnetic measurements, heated at once to 840° , a little above the critical point; at this temperature it was kept for about two hours and then allowed to cool. The

following day the ring was again heated to this temperature, it being intended to take a series of observations during cooling. The series had, however, to be postponed, owing to an unfortunate occurrence—the sealing-wax over the cork had slightly softened during the prolonged heating, and the excess of outside pressure began to drive the cork slowly into the jar, rendering it no longer air-tight. The heating current was immediately shut off; but, when cold, the iron core was found to have been partially oxidized by the inrush of air, reducing its section about 4 per cent. To prevent a repetition of this occurrence, an indiarubber tube containing flowing water was arranged to keep the neck of the jar cool.

During the second absorption of the oxygen, the iron-wire coil, which had already been used once for this purpose, burnt out. But it was thought that the absorption might be complete, and the experiments were proceeded with. After heating the ring, therefore, a third time to 840° , a series of measurements was made while the temperature was falling.

The ring was then still further annealed by heating to 1150° ; and, during cooling, a set of observations like the previous was taken. On their completion, this ring was also taken to pieces that the cross-section of the core might be re-determined and the constants of the thermometer-wire checked. The last absorption of the oxygen does not seem to have been at all complete, for during the last heating the section diminished by 6 per cent.

Thus, in these experiments, though the method of absorbing the oxygen was shown to be efficient, yet troubles due to oxidation were by no means absent. Irrespective of the diminution of the sectional area of the iron, the presence of oxide in the core might affect the results in a variety of ways:—(1) by the shunting effect due to its conductivity, or (2) by impairing the quality of the insulation, both tending to diminish the apparent resistance of the iron; and (3) by having an appreciable permeability, affecting the magnetic measurements.

(1) The shunting effect is quite negligible. (2) Though the inner surface of the mica was altered by contact with the oxide, the insulation was not seriously injured. (3) With regard to the third possibility:—In small fields, such as those used in the present experiments, the magnetic qualities of soft iron are at ordinary temperatures so very much more intense than even those of the magnetic oxide of iron, that no perceptible alteration of the ballistic galvanometer throws could arise from any oxide present. At temperatures above the critical point, the experiments of M. Curie, already cited,

have shown that though the susceptibility of that oxide rapidly decreases with rise of temperature, yet it may be comparable with that of iron, which is also very feebly magnetic in the neighbourhood of 1000°C . The author's methods were, however, not adapted to the determination of the magnetic qualities of feebly magnetic bodies, and any determinations by them of the permeability of the iron core when $\mu < 10$ have in any case little or no worth; so that errors of such values need hardly be considered.

The only serious effect of the oxidation was to alter the sectional area of the iron. By directly measuring this section both before and after the experiments with each ring-magnet, uncertainties in the absolute values, both of the permeability and resistance measurements, were practically eliminated in all the series of observations, except that taken after annealing specimen B at 840° ; and even in this case the alteration of resistance which took place gave the means of determining with but little uncertainty that sectional area which was not directly measured. Whilst cooling from 1150° a pause of half-an-hour was made at 1071° . During this time the resistance of the iron did not increase, and it is therefore concluded that from this time onwards no further change of section due to oxidation took place.

Method of taking Observations at each Temperature.—The experiments with specimen B were as follows (with specimen A they were similar but not so full):—

When the temperature had become quite stationary, and the “standardizing throw” had been observed, the iron core was *de-magnetized* by repeatedly reversing the magnetizing current whilst diminishing its strength.

Observations were then taken, by the method of reversals, of the magnetic induction in the core for each of eight values of the field; beginning with $\mathbf{H} = \cdot 078$ and $\cdot 153$ to get the *permeability under very small forces*, and ending with $\mathbf{H} = 9\cdot 20$. Next, the iron core was carried through a cyclic process of magnetization between *definite limits of magnetic field* ($\mathbf{H} = +6\cdot 83$), observations being taken by the “step-by-step” method—sixteen steps round the cycle. This process had, however, been previously gone through several times till the iron had reached a cyclic state. Finally, the iron was carried through a further cyclical magnetization, this time between *definite limits of induction* (e. g. $\mathbf{B} = \pm 4550$ lines/cm²).

The last experiment was by far the most difficult; for the magnetizing currents had to be so adjusted that the *sum* of the ballistic throws during one half of the cycle might add up to a certain previously calculated amount depending on the

magnitude of the standardizing throw. The difficulty was much reduced by diminishing the number of observations, though the number taken (just eight all round the cycle) barely suffices to determine the hysteresis loop.

The group of experiments at one temperature was concluded by a measurement of the resistance of the iron.

Throughout the whole of such sets of experiments, and particularly when working immediately below the critical point, where the magnetic properties vary so rapidly, the most scrupulous attention was paid to the temperature that it should not, if possible, be allowed to alter more than a fraction of a degree; and this attention was the more necessary when working with the larger magnetizing currents, for their heating effect in the primary circuit was quite perceptible.

The time-period of the ballistic galvanometer needle being about eleven seconds, magnetic "creeping" effects lasting much more than a second would not be recorded.

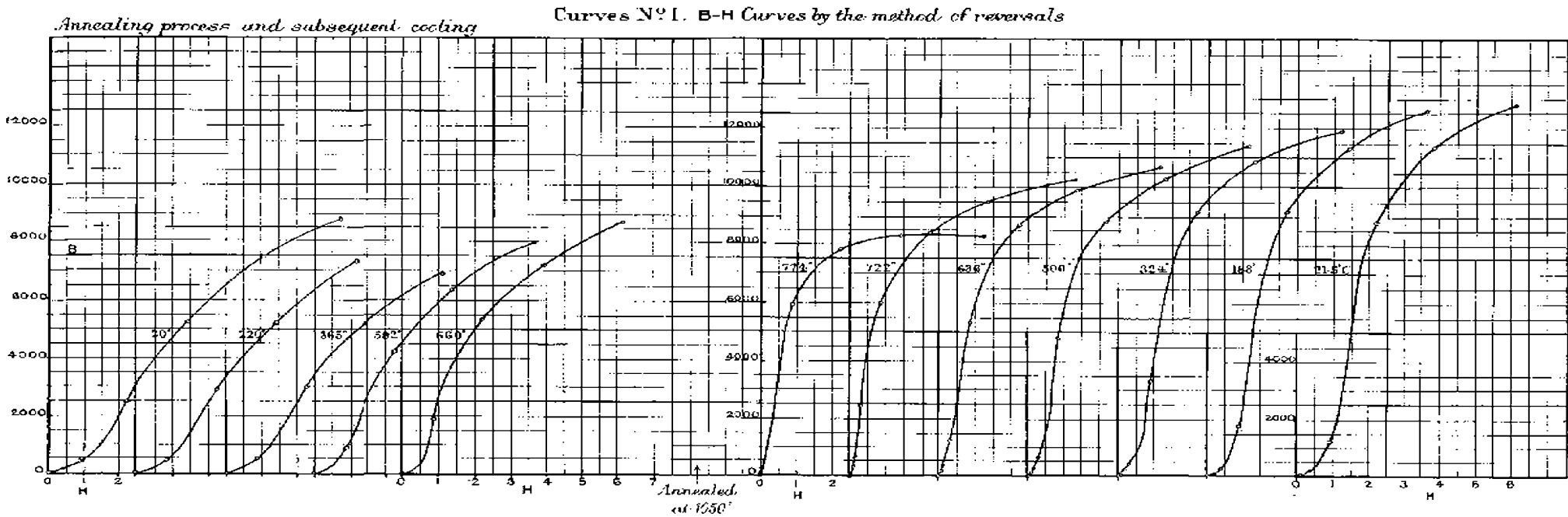
In reducing the observations for each curve of cyclic magnetization, the mean of the corresponding throws taken during the ascending and descending halves of the process has in every case been taken; though this eliminates any systematic unsymmetry which the curve might have possessed.

Discussion of Results.

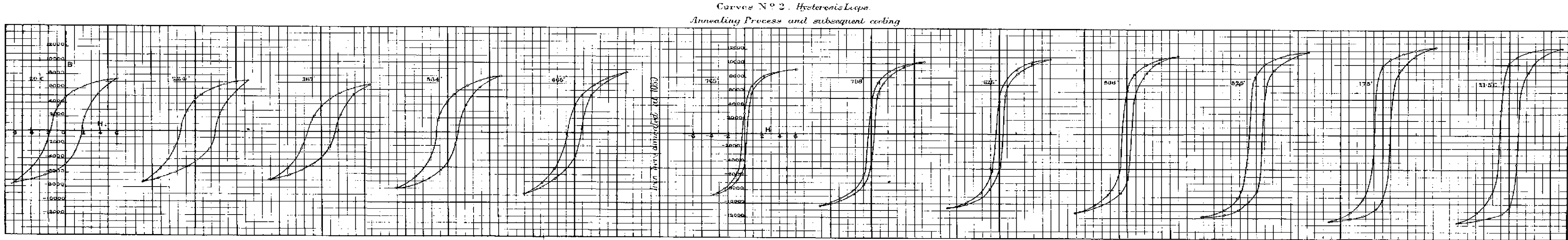
The results of the experiments are given in the accompanying Tables and Curves (Plates II. & III. and Woodcuts, pp. 247-254); the series being in each case arranged in the order in which they were taken.

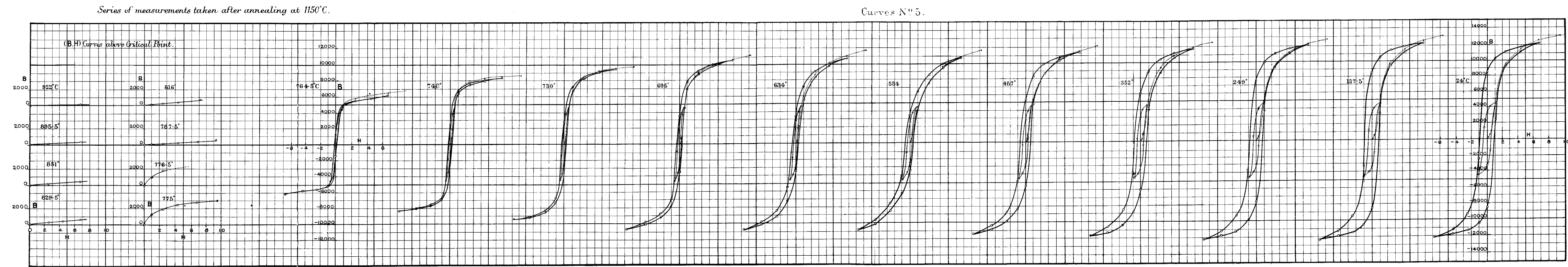
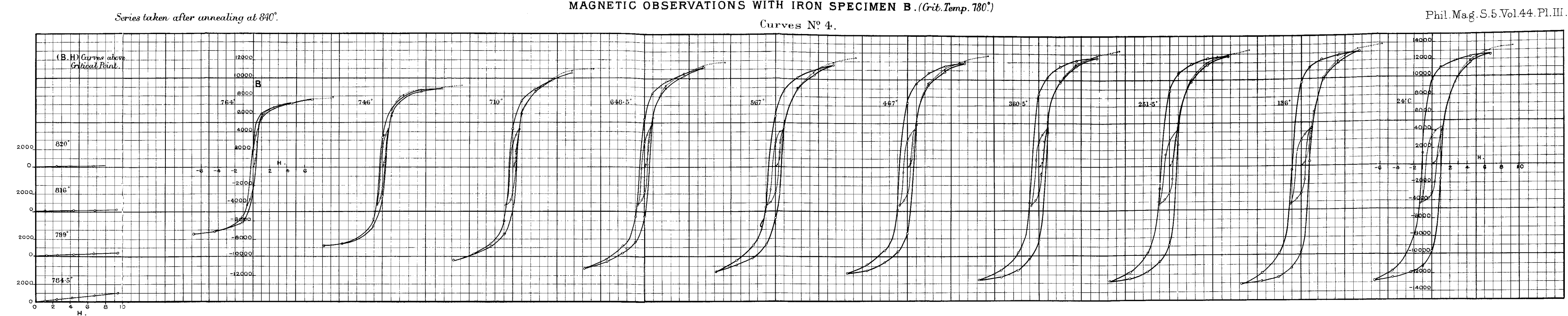
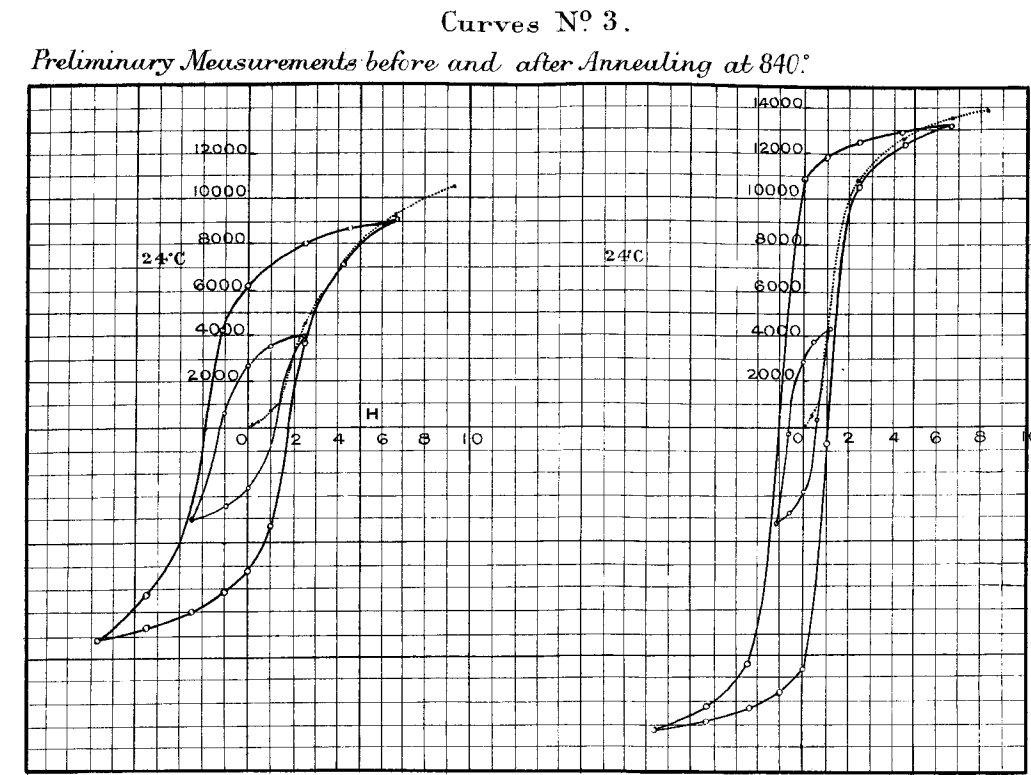
I. *Curves of Magnetization by the Method of Reversals.*—The effect of annealing (at 1050°) on specimen A is strikingly shown in the curves marked 1, and in the corresponding permeability curves 9 and 10. Its effect on the *maximum* permeability and corresponding field is shown in Table IX. The ultimate result of the annealing was to increase the maximum permeability at ordinary temperatures three-fold ($\mu=1555$ to 4050) whilst reducing the corresponding field to little more than half its former value (3.72 to 2.02).

The first annealing of specimen B affected the permeability in a similar manner (compare curves No. 3). The experiments on this specimen, however, were carried out with a view to showing especially the *difference between annealing at a red heat and at a low white heat*. The curves of magnetization at different temperatures obtained after annealing respectively at 840° and 1150° are numbered 7 and 8; whilst the corresponding permeability-temperature curves for different



MAGNETIC OBSERVATIONS WITH IRON SPECIMEN A.
Crit. Temp. 795°.





Explanation

The larger Hysteresis Loops are all taken exactly within the Limits $H = \pm 6.83$ CGS Units.

The smaller loops are within the limits of Induction $B = \pm 4260$ lines for the 1st series and $B = \pm 4550$ lines for the 2nd series

The dotted curves are the B-H curves taken by the Method of Reversals.

strengths of magnetic field are shown in the curves 11, 12, and 13.

A reference to these will show that the difference between annealing at these two temperatures is very marked; the iron having by the last annealing been rendered much more susceptible to weak magnetic fields. Annealed at 840° , the maximum permeability at ordinary temperatures was about 4000 in a field of 1.84 C.G.S. units; annealed at 1150° this rose to the remarkably high value of 4680 in the much smaller field of 1.48. The effect of this difference in annealing is, at temperatures immediately below the critical point, even more striking, as is shown by a comparison of the μ - t curves (Nos. 11 & 12) for values of H below unity.

An interesting point with regard to specimen B is the *diminution of permeability* which it experiences in the neighbourhood of 550° C. This diminution can be traced on the μ - t curves for all but the highest values of H , though it is especially noticeable when the magnetizing force is about 1 C.G.S. unit. The effect is more pronounced after the annealing at 1150° than after that at 840° . This peculiarity is hardly, if at all, possessed by specimen A, though it must be borne in mind that the temperature-interval between observations is here much greater, and the effect may thus be disguised. In some earlier experiments made on a ring-magnet having soft commercial iron wire for its core, the minimum of permeability, which occurred at about 500° , was still more marked than in specimen B; the depression being noticeable in the μ - t curves for fields as large as 5 C.G.S. units. It may be mentioned that, in a list of those temperatures at which the physical properties of iron undergo marked alteration, Tomlinson* gives 550° as that at which the internal friction of soft iron begins to rapidly increase, and at which the "specific heat of electricity" for that material changes sign.

The *permeability under small magnetizing forces* ($H < .5$ C.G.S. unit) rises at first slowly ($.2$ to $.3$ per cent. per degree) when the temperature is raised; then, in the neighbourhood of 300° , quite rapidly. It remains nearly constant between 400° and 550° , after which it rises with increasing rapidity to an enormously high value ($\mu = 12660$ for $H = .078$ is the highest observed) only to sink still more rapidly at the critical temperature to a value quite insignificant.

As the magnetic field gets smaller (curves 11 and 12) the

* H. Tomlinson, Phil. Mag. vol. xxvi. July 1888, p. 21.

maximum of permeability increases, and the temperature at which it occurs approaches the critical temperature, so that in very small fields the fall of the permeability is exceedingly sudden.

An examination of the **B-H** curves at various temperatures (Nos. 6, 7, and 8) shows that as the temperature rises, the initial slope of the curve increases and approaches more and more nearly to the maximum slope. And the critical temperature occurs just when they would coincide, *i. e.* when the **B-H** curve would start from the origin with its maximum slope, and the maximum permeability would occur in an infinitely small magnetic field.

The *critical temperature* is as near as can be given 795° for specimen A, and 780° for specimen B. For the soft iron wire specimen it was about 770° .

Above this temperature the induction is proportional to the magnetizing force (curves 4 and 5) indicating the *same permeability for all forces*, a result in accordance with the experiments of M. Curie. The curve of variation of the permeability with temperature (No. 13, II.) is given with some diffidence as the observations were liable to considerable error (see first part of Tables IV. and V.), and as the results are too remarkable to pass without further corroboration. It indicates a maximum of about $\mu = 100$ at 820° , and another of $\mu = 17$ at about 1050° ; whilst between 920° and 980° the permeability is but 2.3.

II. *Curves of Cyclic Magnetization.*—The variations in the form of these curves due to changes of temperature can be studied in the series of curves Nos. 2, 4, and 5, in which the results recorded in Tables II., VI.–VIII. are plotted.

The process of annealing of specimen A is graphically depicted in the first of these series.

In series No. 5 it will be noticed how, as the temperature rises and approaches 550° , the inclination of the curves to the vertical axis increases, and how with further rise of temperature the curves become more erect and angular. Those taken at $764^{\circ}5$ in this series are interesting as showing the magnetic condition of the iron almost immediately below the critical temperature. The coercive force required to remove the remanent magnetism was little more than $\frac{1}{10}$ of a C.G.S. unit. For the steep-sloping part of the curve the value of $\frac{dB}{dH}$ is about 15000; when **H** is much above 1 unit, its value is about 150. The transition from the steep part of the curve to the gently-sloping part is very sudden.

These values of $\frac{d\mathbf{B}}{d\mathbf{H}}$ are of the same order of magnitude in all the sets of curves of both series taken within 50° of the critical temperature, and they seem to represent an approximately constant property of the iron in this region.

The area enclosed by each hysteresis loop has been summed up and divided by 4π , giving the quantity $\frac{1}{4\pi} \int \mathbf{H} d\mathbf{B}$, the work done in ergs per c.cm. of the iron by the magnetic forces during the performance of one cycle. The results are given beside the corresponding temperatures in the Tables numbered X. (a and b), and are plotted in curves 14-16, which show the way in which the hysteresis diminishes to zero as the iron is heated up to the critical temperature.

No evidence of hysteresis above this temperature could be experimentally obtained, a result which one might be led to expect from the fact that the permeability at these temperatures is the same in all magnetic fields.

A comparison of the two curves No. 15 shows the marked diminution of hysteresis at all temperatures which resulted from annealing at 1150° instead of at 840° . The curves expressing the hysteresis for cycles within definite limits of induction (Curves 16 I. & II.) are not comparable, as the limits during the later series were, owing to oxidation, greater than during the former. In order to render them comparable a third curve has been dotted in, for which the ordinates of I. were multiplied by a constant 1.11 (the assumed ratio of the hysteresis when $\mathbf{B} = \pm 4260$ to that when $\mathbf{B} = \pm 4550$, which, according to results of many observers, cannot at ordinary temperatures be far wrong). Comparing then curve I. with curve III. an idea is obtained of the extent to which the hysteresis can be diminished by annealing at the high temperature 1150° , instead of at the lower one 840° . The comparison is given on Table X. c.

Table X. d. shows concisely the various stages of annealing of specimen B. The hysteresis at ordinary temperatures for $\mathbf{B} = \pm 4550$ was originally 1480 ergs per cub. centim. per cycle. Prolonged annealing at 840° reduced this to about 800 ergs; whilst annealing at 1150° brought the hysteresis down to 612 ergs.

In a paper read before the Institution of Civil Engineers about a year ago*, Prof. Ewing described some tests which

* Ewing, "Magnetic Testing of Iron and Steel," Journ. Inst. C. E. May 1896.

he made on a sample of transformer plate of similar thickness and obtained from the same firm as the author's were. The maximum permeability was about 4500, while the hysteresis varied from 740 down to 580 ergs for $\mathbf{B} = \pm 4000$; and attention is drawn to these values as representing the best iron both as regards high permeability and low hysteresis which he had tested. It is therefore of interest to note that specimen B had after annealing at 1150° a maximum permeability of over 4600 at ordinary temperatures, and a hysteresis as calculated for $\mathbf{B} = +4000$ of just under 500 ergs, corresponding to a hysteresis loss of but .295 watts per lb. at a frequency of 100 \sim . The following values are taken from the magnetization curve at 24°C. :—

| B. | H. | μ . |
|-------|------|---------|
| 2000 | .74 | 2700 |
| 4000 | 1.01 | 3960 |
| 6000 | 1.33 | 4520 |
| 8000 | 1.82 | 4400 |
| 10000 | 2.84 | 3520 |
| 12000 | 5.63 | 2130 |

Between 0° and 200° the *diminution of hysteresis with rise of temperature is .08 per cent. per degree*, when the limits of induction are kept constant.

W. Kunz* concludes from his experiments that for soft iron the hysteresis is expressible as a linear function of the temperature. This is not in accordance with the author's results. The curves expressing this relation (Nos. 16) for specimen B are far from straight, and show a decided dip at about 500° corresponding to the minima which occur near that temperature on the permeability-curves.

III. *Resistance-Temperature Curves.*—The variations of specific resistance with temperature are shown graphically on curves 17 and 18.

By taking a sufficient number of observations (see Tables XI. and XII.) the author has been able to show that the resistance-temperature curve undergoes *no abrupt change of direction* at or near the critical temperature. (Previous observers have given curves all of which were *broken* at this temperature; an examination of the figures given by Hop-

* W. Kunz, 'Elektrotechnische Zeitschrift,' 1894, p. 196.

kinson and Le Chatelier in the papers already cited shows that in each case they would be more strictly satisfied by a *continuous curve* like those here given.)

The annealing of specimen A has reduced its specific resistance considerably.

With specimen B, the further annealing at 1150° has but slightly altered it from the condition as regards specific resistance in which it was after the annealing at 840° .

The temperature-coefficients and specific resistance at 0° and 1000° are given at the foot of Tables XI. and XII.

As regards the resistance-changes both of specimens A and B, and of the soft commercial iron previously tested :—The resistance rises with rising temperature at a rate which increases fairly uniformly till a specific resistance of about 100,000 C.G.S. units is reached. Here the maximum slope of the curve occurs at a point *but few degrees below the critical temperature*. The rate of increase of resistance then falls off rapidly, so that at 1000° the temperature-coefficient is about $\cdot 0024$ and the specific resistance 118,000.

With specimen B, which, judging from the low value of its specific resistance at 0° (10,050 C.G.S. units) and from the high value ($\cdot 0057$ at 0°) of its temperature-coefficient, should be a sample of very pure iron, the *maximum coefficient* after annealing at 1150° was $\cdot 0204$ at about 765° . The number of observations on this resistance-temperature curve (18 II.) make it perhaps permissible to note its irregularities a little more closely. A flat part of the curve will be noticed between 830° and 900° , and the temperature-coefficient, which remains tolerably constant over this range, has at 865° the value $\cdot 0068$. (Dr. Hopkinson gave $\cdot 0067$ as the coefficient of iron above the critical temperature.) The points of maximum curvature 800° and 920° seem to be in agreement with the minima of the permeability curve (No. 13) obtained at the same time.

The above experiments were carried out in the laboratories of the Physical Institute of the Polytechnicum, Zürich ; and the author takes this opportunity of expressing his gratitude to the director, Prof. H. F. Weber, for encouragement received throughout the progress of the work.

Zürich, March 1897.

TABLE I.—SPECIMEN A.

Induction and Permeability in various Magnetic Fields
taken at different temperatures.

(a) Before annealing. (Curves 1 and 9.)

| H in C.G.S. units. | 20° | | 220°. | | 365°. | | 532°. | | 660°. | |
|------------------------------|----------|-------|----------|-------|----------|-------|----------|-------|----------|-------|
| | B | μ | B | μ | B | μ | B | μ | B | μ |
| ·917 | 401 | 438 | 463 | 505 | 506 | 552 | 933 | 1017 | 1864 | 2033 |
| 2·24 | 2495 | 1114 | 2868 | 1281 | 2990 | 1335 | 4180 | 1867 | 5285 | 2360 |
| 3·94 | 5325 | 1352 | 5345 | 1357 | 5145 | 1306 | 6380 | 1620 | 7215 | 1830 |
| 6·10 | 7465 | 1225 | 7270 | 1192 | 6850 | 1107 | 8000 | 1312 | 8685 | 1440 |
| 8·26 | 8805 | 1066 | | | | | | | | |

(b) After annealing at 1050° C. (Curves 1, 6, and 10.)

| H in C.G.S. units. | 774°. | | 722°. | | 636°. | | 506°. | |
|------------------------------|----------|-------|----------|-------|----------|-------|----------|-------|
| | B | μ | B | μ | B | μ | B | μ |
| ·070 | | | 292 | 4170 | 109 | 1560 | 64 | 915 |
| ·140 | | | 583 | 4170 | 272 | 1950 | 166 | 1190 |
| ·343 | | | 2475 | 7220 | 1188 | 3465 | 617 | 1800 |
| ·917 | 5980 | 6520 | 6008 | 6550 | 5395 | 5880 | 4790 | 5220 |
| 2·24 | 7795 | 3480 | 8360 | 3730 | 8630 | 3850 | 8820 | 3940 |
| 3·94 | 8290 | 2105 | 9475 | 2405 | 9870 | 2480 | 10320 | 2620 |
| 6·10 | 8330 | 1366 | 10180 | 1670 | 10705 | 1750 | 11310 | 1855 |

| H in C.G.S. units. | 324°. | | 188°. | | 21°·5. | |
|------------------------------|----------|-------|----------|-------|----------|-------|
| | B | μ | B | μ | B | μ |
| ·070 | 48 | 685 | 29 | 414 | 21? | 300? |
| ·140 | 104 | 743 | 68 | 485 | 50 | 357 |
| ·343 | 366 | 1067 | 248 | 723 | 181 | 527 |
| ·917 | 3355 | 3660 | 1890 | 2060 | 1208 | 1318 |
| 2·24 | 9105 | 4060 | 9175 | 4095 | 8845 | 3950 |
| 3·94 | 10925 | 2775 | 11420 | 2900 | 11435 | 2904 |
| 6·10 | 11960 | 1960 | 12550 | 2060 | 12770 | 2093 |

(c) After re-heating to 920°. (Curves not given.)

| H in C.G.S. units. | 770°. | | 759°. | | 680°. | | 630°. | | 22°. | |
|------------------------------|----------|-------|----------|-------|----------|-------|----------|-------|----------|-------|
| | B | μ | B | μ | B | μ | B | μ | B | μ |
| ·070 | | | 158 | 2260 | 112 | 1600 | 69 | 985 | 24 | 343 |
| ·140 | | | 391 | 2800 | 261 | 1870 | 164 | 1170 | 53 | 379 |
| ·343 | | | 1908 | 5560 | 1298 | 3785 | 810 | 2360 | 168 | 490 |
| ·917 | 5810 | 6340 | 5850 | 6380 | 5745 | 6260 | 5020 | 5470 | 1430 | 1560 |
| 2·24 | 8045 | 3590 | 8120 | 3625 | 8560? | 3820? | 8390 | 3745 | 8485 | 3790 |
| 3·94 | 8940 | 2270 | 9465 | 2405 | 9945 | 2525 | 9825 | 2495 | 11380 | 2890 |
| 6·10 | 9110 | 1494 | 10180 | 1670 | 10840 | 1778 | 10790 | 1770 | 12790 | 2095 |

TABLE II.—SPECIMEN A.

*Data for Cyclic B-H Curves at various Temperatures.*Limits of Cycle: $H = \pm 6 \cdot 10$.

(a) Before annealing. (Curves 2.)

| H | 20°. | 224°. | 367°. | 534°. | 665°. |
|--|----------|----------|----------|----------|----------|
| | B | B | B | B | B |
| 6·10 | 7370 | 7145 | 6830 | 7980 | 8610 |
| 3·94 | 6985 | 6645 | 6300 | 7365 | 7715 |
| 2·24 | 6380 | 5945 | 5530 | 6500 | 6570 |
| ·917 | 5620 | 5090 | 4660 | 5410 | 5240 |
| 0 | 4800 | 4232 | 3805 | 4265 | 3750 |
| — ·917 | 3513 | 2793 | 2285 | 1750 | — 526 |
| — 2·24 | — 1642 | — 2365 | — 2600 | — 3935 | — 5148 |
| — 3·94 | — 5410 | — 5345 | — 5170 | — 6380 | — 7140 |
| — 6·10 | — 7370 | — 7145 | — 6830 | — 7980 | — 8610 |
| Hysteresis in ergs per cm. ³ } | 3900 | 3210 | 2800 | 2670 | 1850 |

(b) After annealing at 1050° C. (Curves 2 and 14.)

| H | 765°. | 708°. | 625°. | 506°. | 325°. | 175°. | 21°·5. |
|--|----------|----------|----------|----------|----------|----------|----------|
| | B | B | B | B | B | B | B |
| 6·10 | 9100 | 10220 | 10640 | 11185 | 11850 | 12320 | 12480 |
| 3·94 | 8790 | 9630 | 10085 | 10615 | 11400 | 12000 | 12190 |
| 2·24 | 8075 | 8720 | 9220 | 9880 | 10815 | 11520 | 11760 |
| ·917 | 6720 | 7205 | 7730 | 8565 | 9925 | 10835 | 11180 |
| 0 | 2985 | 3930 | 4780 | 6190 | 8170 | 9565 | 10210 |
| — ·917 | — 5830 | — 5845 | — 5290 | — 4290 | — 2005 | 1389 | 4170 |
| — 2·24 | — 7880 | — 8275 | — 8400 | — 8620 | — 9090 | — 9145 | — 8990 |
| — 3·94 | — 8780 | — 9440 | — 9750 | — 10190 | — 10810 | — 11210 | — 11340 |
| — 6·10 | — 9100 | — 10220 | — 10640 | — 11185 | — 11840 | — 12320 | — 12480 |
| Hysteresis in ergs per cm. ³ } | 500 | 920 | 1345 | 2060 | 3090 | 4110 | 4570 |

(c) After re-heating to 920°. (Curves not given.)

| H | 738°. | 679°. | 630°. | 22°. |
|--|----------|----------|----------|----------|
| | B | B | B | B |
| 6·10 | 10370 | 10840 | 10660 | 12520 |
| 3·94 | 9565 | 10115 | 10020 | 12210 |
| 2·24 | 8515 | 9120 | 9085 | 11790 |
| ·917 | 6880 | 7510 | 7505 | 11185 |
| 0 | 3535 | 4397 | 4500 | 9995 |
| — ·917 | — 5610 | — 5240 | — 4435 | 2766 |
| — 2·24 | — 8100 | — 8365 | — 8080 | — 8420 |
| — 3·94 | — 9450 | — 9820 | — 9670 | — 11210 |
| — 6·10 | — 10370 | — 10840 | — 10660 | — 12520 |
| Hysteresis in ergs per cm. ³ } | 780 | 1280 | 1510 | 4720 |

TABLE III.—SPECIMEN B.

Preliminary Measurements at 24° C. (Curves No. 3.)
Induction and Permeability in various Magnetic Fields.

| H | Initial condition. | | After 2 hours at 840°. | | After 5 hours at 840°. | |
|----------|--------------------|-------|------------------------|-------|------------------------|-------|
| | B | μ | B | μ | B | μ |
| ·078 | 14 | 178 | 32 | 410 | 35 | 450 |
| ·153 | 37 | 242 | 79 | 516 | 84 | 549 |
| ·378 | 102 | 270 | 280 | 741 | 307 | 813 |
| 1·017 | 560 | 550 | 2656 | 2608 | 2995 | 2942 |
| 2·49 | 4352 | 1746 | 10295 | 4135 | 10525 | 4230 |
| 4·40 | 7265 | 1652 | 12395 | 2816 | 12405 | 2820 |
| 6·83 | 9220 | 1349 | 13420 | 1963 | 13340 | 1953 |
| 9·20 | 10420 | 1133 | 14005 | 1523 | 13920 | 1515 |

Cyclic **B-H** Curves between Limits **H** = $\pm 6\cdot83$.

| H | Initial condition. | After 2 hours at 840°. | After 5 hours at 840°. |
|--------------------------------------|--------------------|------------------------|------------------------|
| | B | B | B |
| 6·83 | 9120 | 13100 | 13120 |
| 4·40 | 8670 | 12800 | 12820 |
| 2·49 | 8005 | 12425 | 12430 |
| 1·017 | 7135 | 11905 | 11885 |
| 0 | 6165 | 10890 | 10740 |
| -1·017 | 4265 | 1420 | 778 |
| -2·49 | -3882 | -10105 | -10380 |
| -4·40 | -7270 | -12140 | -12210 |
| -6·83 | -9120 | -13100 | -13120 |
| Hysteresis in } ergs per c. cm. } | | 4740 | 5020 |
| | | | 4625 |

Cyclic **B-H** Curves at 20° C.

Limits of Cycle : **B** = ± 4020 .

Limits **B** = ± 4140 .

| Initial condition. | | After 2 hours at 840°. | | After 5 hours at 840°. | |
|---|----------|---|----------|---|----------|
| H | B | H | B | H | B |
| 2·47 | 4025 | ? 1·15 | 4015 | 1·170 | 4140 |
| 1·007 | 3520 | ·646 | 3760 | ·660 | 3810 |
| 0 | 2763 | 0 | 2887 | 0 | 2900 |
| -1·007 | 870 | -·646 | - 63 | -·660 | - 242 |
| -2·47 | -4025 | -1·15 | -4015 | -1·170 | -4140 |
| Hysteresis } = $1218 \frac{\text{ergs}}{\text{cm.}^3}$ per cycle } | | Hysteresis = $664 \frac{\text{ergs}}{\text{cm.}^3}$ | | Hysteresis = $669 \frac{\text{ergs}}{\text{cm.}^3}$ | |

TABLE IV.—SPECIMEN B.

Induction and Permeability in various Magnetic Fields taken successively during cooling from 840° C.

Above critical Temperature. (Curves 4, 7, and 13.)

| H | 820°. | | 816°. | | 799°. | |
|-------------------|-------|----|-------|-----|-------|----|
| | B | μ | B | μ | B | μ |
| 1·017 | | | 19 | 19 | 40 | 39 |
| 2·49 | 29 | 12 | 35 | 14 | 97 | 39 |
| 4·40 | | | 78 | 18 | 163 | 37 |
| 6·83 | 84 | 12 | 101 | 15 | 262 | 38 |
| 9·20 | | | 124 | 13 | 363 | 39 |
| Mean Permeability | } | | 12 | ... | 16 | 38 |

| H | 797°. | | 788°. | | 784°·5. | | 782°·5. | |
|-------------------|-------|----|-------|-----|---------|-----|---------|-------|
| | B | μ | B | μ | B | μ | B | μ |
| 1·017 | | | | | 124 | 122 | | |
| 2·49 | | | | | 273 | 110 | | |
| 4·40 | | | | | 518 | 118 | | |
| 6·83 | 349 | 51 | 409 | 60 | 787 | 115 | 825 ? | 121 ? |
| 9·20 | | | | | 1035 | 113 | | |
| Mean Permeability | } | | ... | ... | ... | 116 | ... | ... |

Below critical Temperature. (Curves 4, 7, and 11.)

| H | 770°. | | 764°. | | 746°. | |
|-------|-------|------|-------|------|-------|------|
| | B | μ | B | μ | B | μ |
| ·078 | | | 298 | 3820 | 198 | 2540 |
| ·153 | | | 663 | 4330 | 490 | 3200 |
| ·378 | | | 2780 | 7360 | 2248 | 5950 |
| 1·017 | | | 5675 | 5575 | 5830 | 5730 |
| 2·49 | | | 6720 | 2700 | 8020 | 3220 |
| 4·40 | 5960 | 1355 | 7070 | 1606 | 8565 | 1956 |
| 6·83 | 6500 | 952 | 7410 | 1084 | 8905 | 1304 |
| 9·20 | | | 7870 | 856 | 9165 | 996 |

| H | 710°. | | 648°·5. | | 567°. | | 467°. | |
|-------|-------|------|---------|------|-------|------|-------|------|
| | B | μ | B | μ | B | μ | B | μ |
| ·078 | 131 | 1680 | 90 | 1150 | 61 | 780 | 57 | 730 |
| ·153 | 322 | 2100 | 230 | 1500 | 141 | 920 | 143 | 935 |
| ·378 | 1722 | 4560 | 1041 | 2755 | 645 | 1710 | 511 | 1354 |
| 1·017 | 5955 | 5850 | 5685 | 5585 | 5110 | 5020 | 5195 | 5100 |
| 2·49 | 8630 | 3470 | 9030 | 3625 | 8995 | 3610 | 9475 | 3800 |
| 4·40 | 9840 | 2260 | 10440 | 2375 | 10695 | 2430 | 11030 | 2510 |
| 6·83 | 10580 | 1550 | 11350 | 1662 | 11770 | 1725 | 12090 | 1770 |
| 9·20 | 10955 | 1191 | 11870 | 1290 | 12315 | 1340 | 12660 | 1377 |

Table IV.—(continued).

| H | 360°·5. | | 251°·5. | | 136°. | | 24°. | |
|-------|---------|------|---------|------|-------|------|-------|------|
| | B | μ | B | μ | B | μ | B | μ |
| ·078 | 50 | 640 | 31 | 400 | 30 | 380 | 20 | 250 |
| ·153 | 126 | 820 | 70 | 450 | 68 | 440 | 40 | 260 |
| ·378 | 571 | 1510 | 294 | 778 | 318 | 840 | 178 | 470 |
| 1·017 | 5125 | 5040 | 4360 | 4280 | 3253 | 3200 | 1934 | 1900 |
| 2·49 | 9800 | 3935 | 9940 | 3990 | 10005 | 4020 | 9420 | 3780 |
| 4·40 | 11580 | 2630 | 11980 | 2720 | 12140 | 2760 | 11835 | 2690 |
| 6·83 | 12705 | 1862 | 12890 | 1888 | 13260 | 1942 | 12980 | 1902 |
| 9·20 | 13320 | 1449 | 13525 | 1471 | 13860 | 1507 | 13600 | 1480 |

TABLE V.—SPECIMEN B.

Induction and Permeability in various Magnetic Fields
taken successively during cooling from 1150° C.
Above critical Temperature. (Curves 5, 8, 12, and 13.)

| H | 1145°. | | 1047°. | | 980°. | | 975°. | | 960°. | |
|-----------------------|--------|---|--------|----|-------|---|-------|-----|-------|-----|
| | B | μ | B | μ | B | μ | B | μ | B | μ |
| 1·017 | | | | | | | | | | |
| 2·49 | | | 42 | 17 | 15 | 6 | | | | |
| 4·40 | | | | | | | | | | |
| 6·83 | 52? | 8 | | | | | 17 | 2·5 | 17 | 2·5 |
| 9·20 | | | | | | | | | | |
| Mean Permeability ... | ... | 8 | ... | 17 | ... | 6 | ... | 2·5 | ... | 2·5 |

| H | 922°. | | 895°·5. | | 851°. | | 829°·5 | | 816°. | | 787°·5. | |
|-------------------|-------|-----|---------|----|-------|------|--------|-----|-------|-----|---------|-----|
| | B | μ | B | μ | B | μ | B | μ | B | μ | B | μ |
| 1·017 | | | | | | | | | 108 | 106 | 51 | 50 |
| 2·49 | | | 129 | 52 | 173 | 69 | 260 | 104 | 260 | 104 | 120 | 48 |
| 4·40 | | | | | | | 434 | 99 | 434 | 99 | 215 | 49 |
| 6·83 | 16 | 2·3 | 388 | 57 | 475 | 70 | 650 | 96 | 781 | 114 | 336 | 49 |
| 9·20 | | | | | | | | | | | 518? | 56? |
| Mean Permeability | } | 2·3 | ... | 54 | ... | 69·5 | ... | 100 | ... | 106 | ... | 51 |

Below critical Temperature. (Curves 5, 8, and 12.)

| H | 776°·5. | | 775°. | | 764°·5. | | 748°. | |
|-------|---------|-----|-------|------|---------|-------|-------|-------|
| | B | μ | B | μ | B | μ | B | μ |
| ·078 | | | | | 631 | 8090 | 485 | 6210 |
| ·153 | | | | | 1935 | 12660 | 1585 | 10360 |
| ·378 | | | | | 4210 | 11140 | 4465 | 11820 |
| 1·017 | 925 | 908 | 1353 | 1330 | 5020 | 4930 | 6720 | 6600 |
| 2·49 | 1788 | 718 | 1964 | 789 | 5780 | 2320 | 7980 | 3200 |
| 4·40 | | | 2442 | 556 | 6305 | 1434 | 8290 | 1885 |
| 6·83 | | | 2798 | 410 | 6440 | 943 | 8555 | 1252 |
| 9·20 | | | 3006 | 327 | 6550 | 712 | 8645 | 940 |

Table V. (continued).

| H | 730°. | | 695°. | | 634°. | | 554°. | |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| | B | μ | B | μ | B | μ | B | μ |
| ·078 | 372 | 4770 | 243 | 3120 | 126 | 1620 | 73 | 935 |
| ·153 | 1161 | 7600 | 713 | 4660 | 332 | 2170 | 172 | 1120 |
| ·378 | 4165 | 11020 | 3565 | 9430 | 2128 | 5630 | 996 | 2640 |
| 1·017 | 6850 | 6730 | 6845 | 6720 | 5780 | 5680 | 4275 | 4200 |
| 2·49 | 8415 | 3380 | 8985 | 3610 | 8800 | 3530 | 7565 | 3040 |
| 4·40 | 9160 | 2085 | 9985 | 2270 | 10160 | 2280 | 9630 | 2190 |
| 6·83 | 9495 | 1390 | 10670 | 1562 | 11050 | 1620 | 10940 | 1603 |
| 9·20 | 9730 | 1024 | 11110 | 1209 | 11670 | 1269 | 11690 | 1271 |

| H | 457°. | | 352°. | | 249°. | | 137°·5. | | 24°. | |
|-------|-------|-------|-------|-------|-------|-------|---------|-------|-------|-------|
| | B | μ | B | μ | B | μ | B | μ | B | μ |
| ·078 | 78 | 1000 | 77 | 980 | 48 | 615 | 43 | 550 | 35 | 450 |
| ·153 | 172 | 1125 | 167 | 1090 | 113 | 740 | 99 | 650 | 85 | 555 |
| ·378 | 989 | 2620 | 879 | 2325 | 457? | 1210? | 471 | 1246 | 356 | 942 |
| 1·017 | 5200 | 5110 | 5115 | 5020 | 4730 | 4650 | 4410 | 4330 | 4010 | 3940 |
| 2·49 | 8710 | 3495 | 9230 | 3705 | 9385 | 3770 | 9740 | 3910 | 9480 | 3810 |
| 4·40 | 10460 | 2380 | 10930 | 2485 | 11145 | 2535 | 11560 | 2625 | 11400 | 2590 |
| 6·83 | 11475 | 1680 | 11930 | 1748 | 12170 | 1783 | 12495 | 1830 | 12440 | 1823 |
| 9·20 | 12150 | 1321 | 12460 | 1355 | 12760 | 1388 | 13090 | 1423 | 13040 | 1418 |

TABLE VI.—SPECIMEN B.

Data for Cyclic **B-H** Curves taken successively at diminishing temperatures after annealing at 840° C.

Limits of Cycle : **H** = $\pm 6\cdot83$. (Curves 4 and 15.)

| H | 764°. | 746°. | 710°. | 648°·5. | 567°. |
|--------------------------------------|-------|-------|--------|---------|--------|
| | B | B | B | B | B |
| 6·83 | 7370 | 8870 | 10350 | 11130 | 11495 |
| 4·40 | 7060 | 8545 | 9730 | 10500 | 10935 |
| 2·49 | | | 8870 | 9665 | 10090 |
| 1·017 | 6005 | 6425 | 7380 | 8295 | 8620 |
| 0 | | 3246 | 4330 | 5515 | 5770 |
| -1·017 | -5560 | -5820 | -6000 | -5555 | -4535 |
| -2·49 | | | -8555 | -8900 | -8860 |
| -4·40 | -7060 | -8480 | -9700 | -10250 | -10480 |
| -6·83 | -7370 | -8870 | -10350 | -11130 | -11495 |
| Hysteresis in } ergs per c. cm. } | 426 | 573 | 1010 | 1650 | 2180 |

Table VI. (continued).

| H | 467°. | 360°·5. | 251°·5. | 136°. | 24°. |
|------------------------------------|----------|----------|----------|----------|----------|
| | B | B | B | B | B |
| 6·83 | 11910 | 12540 | 12770 | 13040 | 12685 |
| 4·40 | 11400 | 12110 | 12390 | 12720 | 12360 |
| 2·49 | 10695 | 11495 | 11805 | 12230 | 11895 |
| 1·017 | 9520 | 10355 | 10810 | 11380 | 11110 |
| 0 | 7240 | 8245 | 8925 | 9770 | 9680 |
| -1·017 | - 4940 | - 4010 | - 2608 | - 429 | 1395 |
| -2·49 | - 9340 | - 9715 | - 9820 | - 9910 | - 9395 |
| -4·40 | -10830 | -11495 | -11735 | -11980 | -11610 |
| -6·83 | -11910 | -12540 | -12770 | -13040 | -12685 |
| Hysteresis in ergs per c. cm. } | 2550 | 3195 | 3700 | 4360 | 4700 |

TABLE VII.—SPECIMEN B.

Data for Cyclic B-H Curves taken successively at diminishing temperatures after annealing at 1150° C.

Limits of Cycle: **H** = $\pm 6\cdot83$. (Curves 5 and 15.)

| H | 764°·5. | 748°. | 730°. | 695°. | 634°. |
|---|----------|----------|----------|----------|----------|
| | B | B | B | B | B |
| 6·83 | 6145 | 8240 | 9420 | 10615 | 10760 |
| 4·40 | 5815 | 8030 | 9100 | 10035 | 10060 |
| 2·49 | 5490 | 7670 | 8495 | 9205 | 9080 |
| 1·017 | 5075 | 6800 | 7185 | 7820 | 7180 |
| 0 | 1389 | 2455 | 2856 | 3480 | 3215 |
| -1·017 | -5060 | -6540 | -6835 | - 6920 | - 5490 |
| -2·49 | -5485 | -7575 | -8320 | - 8870 | - 8430 |
| -4·40 | -5795 | -7975 | -9040 | - 9850 | - 9860 |
| -6·83 | -6145 | -8240 | -9420 | -10615 | -10760 |
| Hysteresis in ergs per c. cm. per cycle } | 120 | 328 | 426 | 797 | 1010 |

| H | 554°. | 457°. | 352°. | 249°. | 137°·5. | 24°. |
|---|----------|----------|----------|----------|----------|----------|
| | B | B | B | B | B | B |
| 6·83 | 10825 | 11360 | 11735 | 12110 | 12280 | 12150 |
| 4·40 | 10025 | 10810 | 11230 | 11730 | 11950 | 11810 |
| 2·49 | 8650 | 9950 | 10435 | 11125 | 11420 | 11300 |
| 1·017 | 6377 | 8340 | 8875 | 9980 | 10510 | 10400 |
| 0 | 3322 | 5395 | 6050 | 7520 | 8525 | 8560 |
| -1·017 | - 4140 | - 4930 | - 3960 | - 3881 | - 3196 | - 2327 |
| -2·49 | - 7600 | - 8710 | - 8650 | - 9295 | - 9570 | - 9290 |
| -4·40 | - 9575 | -10365 | -10620 | -11100 | -11330 | -11150 |
| -6·83 | -10825 | -11360 | -11735 | -12110 | -12280 | -12150 |
| Hysteresis in ergs per c. cm. per cycle } | 1345 | 2025 | 2565 | 3130 | 3500 | 3660 |

TABLE VIII.—SPECIMEN B.

Data for Cyclic B-H Curves between constant limits of Induction taken successively at diminishing temperatures.

(a) After annealing at 840° C.

Limits of Cycle : $B = \pm 4260$. (Curves 4 and 16.)

| 764°. | | 746°. | | 710°. | | 648°·5. | | 567°. | |
|--|-------|--|-------|--|-------|--|-------|--|-------|
| H | B | H | B | H | B | H | B | H | B |
| ·60 | 4250 | ·60 | 4255 | ·73 | 4265 | ·81 | 4260 | ·93 | 4250 |
| ·31 | 3520 | ·32 | 3547 | ·34 | 3668 | ·36 | 3725 | ·56 | 3970 |
| 0 | 2092 | 0 | 2261 | 0 | 2611 | 0 | 2860 | 0 | 2870 |
| —·31 | —1762 | —·32 | —1359 | —·34 | —440 | —·36 | —189 | —·56 | —2263 |
| —·60 | —4250 | —·60 | —4255 | —·73 | —4265 | —·81 | —4260 | —·93 | —4250 |
| Hysteresis } = 187 $\frac{\text{ergs}}{\text{cm.}^3}$ per cycle | | 216 $\frac{\text{ergs}}{\text{cm.}^3}$ | | 318 $\frac{\text{ergs}}{\text{cm.}^3}$ | | 357 $\frac{\text{ergs}}{\text{cm.}^3}$ | | 398 $\frac{\text{ergs}}{\text{cm.}^3}$ | |

| 467°. | | 360°·5. | | 251°·5. | | 136°. | | 18°. | |
|--|-------|--|-------|--|-------|--|-------|--|-------|
| H | B | H | B | H | B | H | B | H | B |
| ·88 | 4265 | ·93 | 4265 | 1·05 | 4265 | 1·20 | 4265 | 1·318 | 4265 |
| ·38 | 3760 | ·40 | 3743 | ·42 | 3732 | ·43 | 3700 | ·426 | 3725 |
| 0 | 3010 | 0 | 2930 | 0 | 3000 | 0 | 3033 | 0 | 3115 |
| —·38 | —733 | —·40 | 924 | —·42 | 1378 | —·43 | 1630 | —·426 | 1910 |
| —·88 | —4265 | —·93 | —4265 | —1·05 | —4265 | —1·20 | —4265 | —1·318 | —4265 |
| Hysteresis } = 396 $\frac{\text{ergs}}{\text{cm.}^3}$ per cycle | | 495 $\frac{\text{ergs}}{\text{cm.}^3}$ | | 590 $\frac{\text{ergs}}{\text{cm.}^3}$ | | 656 $\frac{\text{ergs}}{\text{cm.}^3}$ | | 744 $\frac{\text{ergs}}{\text{cm.}^3}$ | |

(b) After annealing at 1150° C.

Limits of Cycle : $B = \pm 4550$. (Curves 5 and 16.)

| 764°·5. | | 748°. | | 730°. | | 695°. | |
|---|-------|--|-------|--|-------|--|-------|
| H | B | H | B | H | B | H | B |
| ·640 | 4543 | ·403 | 4540 | ·443 | 4547 | ·516 | 4540 |
| ·210 | 3690 | ·174 | 3662 | ·184 | 3722 | ·197 | 3712 |
| 0 | 1660 | 0 | 2002 | 0 | 2272 | 0 | 2564 |
| —·210 | —2665 | —·174 | —1921 | —·184 | —1468 | —·197 | —897 |
| —·640 | —4543 | —·403 | —4540 | —·443 | —4547 | —·516 | —4540 |
| Hysteresis } = 81 $\frac{\text{ergs}}{\text{cm.}^3}$ per cycle | | 109 $\frac{\text{ergs}}{\text{cm.}^3}$ | | 128 $\frac{\text{ergs}}{\text{cm.}^3}$ | | 178 $\frac{\text{ergs}}{\text{cm.}^3}$ | |

Table VIII. (continued).

| 634°. | | 554°. | | 457°. | | 352°. | |
|--|-------|--|-------|--|-------|--|-------|
| H | B | H | B | H | B | H | B |
| ·730 | 4540 | ·935 | 4550 | ·898 | 4553 | ·881 | 4542 |
| ·336 | 3928 | ·373 | 3770 | ·371 | 3840 | ·361 | 4002 |
| 0 | 2720 | 0 | 2520 | 0 | 2827 | 0 | 3060 |
| —·336 | —1886 | —·373 | —1074 | —·371 | —488 | —·361 | 239 |
| —·730 | —4540 | —·935 | —4550 | —·898 | —4553 | —·881 | —4542 |
| Hysteresis } = 264 $\frac{\text{ergs}}{\text{cm.}^3}$ per cycle | | 335 $\frac{\text{ergs}}{\text{cm.}^3}$ | | 379 $\frac{\text{ergs}}{\text{cm.}^3}$ | | 475 $\frac{\text{ergs}}{\text{cm.}^3}$ | |

| 249°. | | 137°·5. | | 18°. | |
|--|-------|--|-------|--|-------|
| H | B | H | B | H | B |
| 1·001 | 4550 | 1·032 | 4545 | 1·114 | 4545 |
| ·382 | 3952 | ·388 | 3980 | ·398 | 3972 |
| 0 | 3043 | 0 | 3188 | 0 | 3184 |
| —·382 | 712 | —·388 | 1163 | —·398 | 1386 |
| —1·001 | —4550 | —1·032 | —4545 | —1·114 | —4545 |
| Hysteresis } = 508 $\frac{\text{ergs}}{\text{cm.}^3}$ per cycle | | 555 $\frac{\text{ergs}}{\text{cm.}^3}$ | | 613 } $\frac{\text{ergs per c. cm.}}{\text{per cycle.}}$ | |

TABLE IX.

Relation of Maximum Permeability and of the Field in which it occurs to Temperature.

(The values are estimated from the curves, and are only approximate.)

SPECIMEN A.

(Curves 9 and 10.)

Before annealing.

After annealing at 1050°.

| Tempera- ture. | Maximum Permea- bility. | Correspond- ing Magnetic Field. |
|-------------------|-------------------------------|---------------------------------------|
| °C. | μ | H |
| 20 | 1355 | 3·70 |
| 220 | 1370 | 3·25 |
| 365 | 1360 | 2·80 |
| 532 | 1880 | 2·20 |
| 660 | 2650 | 1·50 |

| Tempera- ture. | Maximum Permea- bility. | Correspond- ing Magnetic Field. |
|-------------------|-------------------------------|---------------------------------------|
| °C. | μ | H |
| 722 | 8350 | ·44 |
| 636 | 5950 | ·92 |
| 506 | 5450 | 1·05 |
| 324 | 4860 | 1·46 |
| 188 | 4370 | 1·70 |
| 21·5 | 4050 | 2·02 |

Table IX. (continued).

SPECIMEN B.

(Curves 11 and 12.)

After annealing at 840°.

After annealing at 1150°.

| Temperature. | Maximum Permeability. | Corresponding Field. | Temperature. | Maximum Permeability. | Corresponding Field. |
|--------------|-----------------------|----------------------|--------------|-----------------------|----------------------|
| °C. | μ | H | °C. | μ | H |
| 764 | 7800 | 50 | 764.5 | 14600 | 20 |
| 746 | 7090 | 58 | 748 | 13400 | 25 |
| 710 | 6070 | 72 | 730 | 11700 | 33 |
| 648.5 | 5610 | 93 | 695 | 9430 | 43 |
| 567 | 4900 | 1.09 | 634 | 6040 | 58 |
| 467 | 5190 | 1.18 | 554 | 4240 | 99 |
| 360.5 | 5280 | 1.13 | 457 | 5120 | 94 |
| 251.5 | 4940 | 1.38 | 352 | 5050 | 96 |
| 136 | 4250 | 1.69 | 249 | 4820 | 1.19 |
| 24 | 3980 | 1.84 | 137.5 | 5020 | 1.36 |
| | | | 24 | 4680 | 1.48 |

TABLE X.

Variation of Magnetic Hysteresis with Temperature.

(See Curves 14, 15, and 16.)

(a) Cycle between constant Limits of Magnetizing Force.

SPECIMEN A.

SPECIMEN B.

Limits: $H = \pm 6.10$.
After annealing at 1050°.Limits: $H = \pm 6.83$.
Annealed at 840°.

Annealed at 1150°.

| Temperature. | Hysteresis in ergs per c.cm. per cycle. | Temperature. | Hysteresis in ergs per c.cm. per cycle. | Temperature. | Hysteresis in ergs per c.cm. per cycle. |
|--------------|---|--------------|---|--------------|---|
| °C. | | °C. | | °C. | |
| 765 | 500 | 764 | 426 | 764.5 | 120 |
| 708 | 920 | 746 | 573 | 748 | 328 |
| 625 | 1345 | 710 | 1010 | 730 | 426 |
| 506 | 2060 | 648.5 | 1650 | 695 | 797 |
| 325 | 3090 | 567 | 2180 | 634 | 1010 |
| 175 | 4110 | 467 | 2550 | 554 | 1345 |
| 21.5 | 4570 | 360.5 | 3195 | 457 | 2025 |
| | | 251.5 | 3700 | 352 | 2565 |
| | | 136 | 4360 | 249 | 3130 |
| | | 24 | 4700 | 137.5 | 3500 |
| | | | | 24 | 3660 |

Table X. (continued).

(b) Cycle between constant Limits of Magnetic Induction.

SPECIMEN B.

Annealed at 840°. Limits:
B = ±4260.

| Tempera- ture. | Hysteresis in ergs per c.cm. per cycle. |
|-------------------|---|
| °C. | |
| 764 | 187 |
| 746 | 216 |
| 710 | 318 |
| 648.5 | 367 |
| 567 | 398 |
| 467 | 396 |
| 360.5 | 495 |
| 251.5 | 590 |
| 136 | 656 |
| 18 | 744 |

Annealed at 1150°. Limits:
B = ±4550.

| Tempera- ture. | Hysteresis in ergs per c.cm. per cycle. |
|-------------------|---|
| °C. | |
| 764.5 | 81 |
| 748 | 109 |
| 730 | 128 |
| 695 | 178 |
| 634 | 264 |
| 554 | 335 |
| 457 | 379 |
| 352 | 475 |
| 249 | 508 |
| 137.5 | 555 |
| 18 | 613 |

(c) SPECIMEN B.

Comparison of Hysteresis
after annealing at 840° and
1150°.

(Reduced to a uniform Induction
Limit of B = ±4550.)

| Tempera- ture. | Annealed at 840°. | Annealed at 1150°. |
|-------------------|----------------------|-----------------------|
| °C. | | |
| 20 | 822 | 612 |
| 200 | 686 | 530 |
| 400 | 504 | 437 |
| 600 | 430 | 302 |
| 700 | 358 | 176 |
| 750 | 236 | 106 |

(d) Hysteresis of SPECIMEN B

at 20° and Induction Limits ±4550,
showing various stages of annealing.

| | Hysteresis in ergs per c.cm. per cycle. |
|---|---|
| Initial condition | 1480 |
| After 2 hrs. at 840° | 810 |
| „ 5 hrs. „ | 780 |
| „ 6 hrs. „ and very gradual cooling. | 822 |
| After heating to 1150° and very gradual cooling. | 612 |

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TABLE XI.

IRON SPECIMEN A.

Electrical Resistance at Different Temperatures.

(a) Before and during annealing. (Curve 17, I.)

| Temperature. ° C. | Specific Resistance in C.G.S. units. | Temperature. ° C. | Specific Resistance in C.G.S. units. |
|----------------------|---|----------------------|---|
| 18 | 14610 | 530.5 | 61550 |
| 127 | 22150 | 535.5 | 61550 |
| 189 | 26300 | 643 | 77400 |
| 210.5 | 27680 | 674 | 83400 |
| 213 | 27880 | 752 | 96700 |
| 354.5 | 41300 | 763 | 99700 |
| 373 | 43450 | | |

(b) After annealing at 1050°. (Curve 17, II.)

[Critical Temp.: 795°.]

| Temperature. ° C. | Specific Resistance in C.G.S. units. | Temperature. ° C. | Specific Resistance in C.G.S. units. |
|----------------------|---|--|---|
| 1050 | 115800 ? | 330.5 | 37000 |
| 1026.5 | 115800 ? | 201.5 | 25130 |
| 950.5 | 114200 | 171.5 | 23480 |
| 936 | 113100 | 18 | 13820 |
| 870 | 109400 | 16 | 13580 |
| 881 | 110000 | After reheating to 920°. (Also plotted for Curve II.) | |
| 808.5 | 101100 | | |
| 805 | 101100 | | |
| 786 | 97200 | | |
| 761 | 92600 | | |
| 724.5 | 86600 | 885.5 | 110600 |
| 706 | 84400 | 916 | 112800 |
| 653 | 75600 | 736 | 89000 |
| 620 | 71350 | 686.5 | 81300 |
| 504.5 | 55550 | 681 | 79750 |
| 506 | 55700 | 632.5 | 72400 |
| 327 | 36760 | 630 | 72900 |
| 321 | 36280 | 20 | 13940 |
| | | 16.8 | 13510 |

| | | Before annealing. | After annealing. at 1050°. |
|--------------------------|--------------------|----------------------|----------------------------------|
| Temperature-Coefficient | { at 0° | ·0044 | ·0045 |
| | { maximum value at | | |
| | { about 780° | ·0125 | ·0144 |
| | { at 1000° | | ·00236 |
| Specific Resistance..... | { at 0° | 13600 | 12500 |
| | { at 1000° | | 115600 |
| | | | { C.G.S. Units. |

TABLE XII.

IRON SPECIMEN B.

Electrical Resistance at Different Temperatures.

(a) After annealing at 840°. (Curve 18, I.)

[Critical Temp. = 782°.]

| Temp. ° C. | Sp. Resist. in C.G.S. Units. | Temp. ° C. | Sp. Resist. in C.G.S. Units. | Temp. ° C. | Sp. Resist. in C.G.S. Units. |
|---------------|------------------------------------|---------------|------------------------------------|---------------|------------------------------------|
| 826° | 108300 | 679° | 83750 | 358·5 | 39800 |
| 800 | 105100 | 649 | 78900 | 314·5 | 34920 |
| 786·5 | 103000 | 605·5 | 71950 | 252·5 | 28660 |
| 772 | 100000 | 555 | 64400 | 190·5 | 23280 |
| 764 | 8600 | 561 | 65400 | 128·5 | 18440 |
| 751 | 96200 | 517 | 59250 | 101 | 16410 |
| 739·5 | 94200 | 466·5 | 52700 | 52 | 13210 |
| 714·5 | 89300 | 413·5 | 45900 | 18 | 11110 |

(b) After annealing at 1150°. (Curve 18, II.)

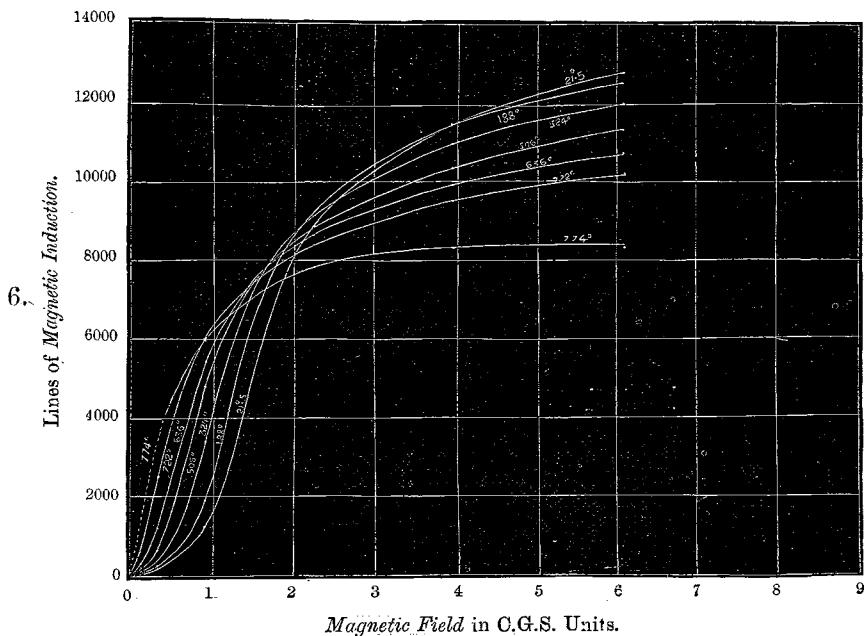
[Critical Temp. = 778°.]

| Temp. ° C. | Sp. Resist. in C.G.S. Units. | Temp. ° C. | Sp. Resist. in C.G.S. Units. | Temp. ° C. | Sp. Resist. in C.G.S. Units. |
|---------------|------------------------------------|---------------|------------------------------------|---------------|------------------------------------|
| 1150° | 120600 ? | 871° | 113400 | 630·5 | 76400 |
| 1142 | 121000 ? | 858 | 112500 | 637 | 77400 |
| 1115·5 | 120850 | 844 | 111400 | 594 | 70850 |
| 1095·5 | 120600 | 824·5 | 109600 | 553·5 | 64850 |
| 1071·5 | 120350 | 813·5 | 108400 | 554 | 64900 |
| 1058·5 | 120050 | 792·5 | 105600 | 503·5 | 57850 |
| 1036 | 119650 | 787 | 104600 | 454·5 | 51770 |
| 1014·5 | 119100 | 781 | 103400 | 406 | 45720 |
| 989·5 | 118550 | 770 | 100900 | 386 | 43400 |
| 983 | 118350 | 765·5 | 100000 | 861 | 40580 |
| 977·5 | 118200 | 764·5 | 99850 | 295·5 | 34020 |
| 972 | 118100 | 745·5 | 96150 | 252·5 | 29080 |
| 946·5 | 117200 | 744 | 95650 | 196·5 | 24020 |
| 926·5 | 116600 | 725·5 | 92050 | 140·5 | 19410 |
| 916·5 | 116200 | 697·5 | 87200 | 84 | 15390 |
| 891·5 | 114900 | 658 | 80850 | 18 | 11140 |

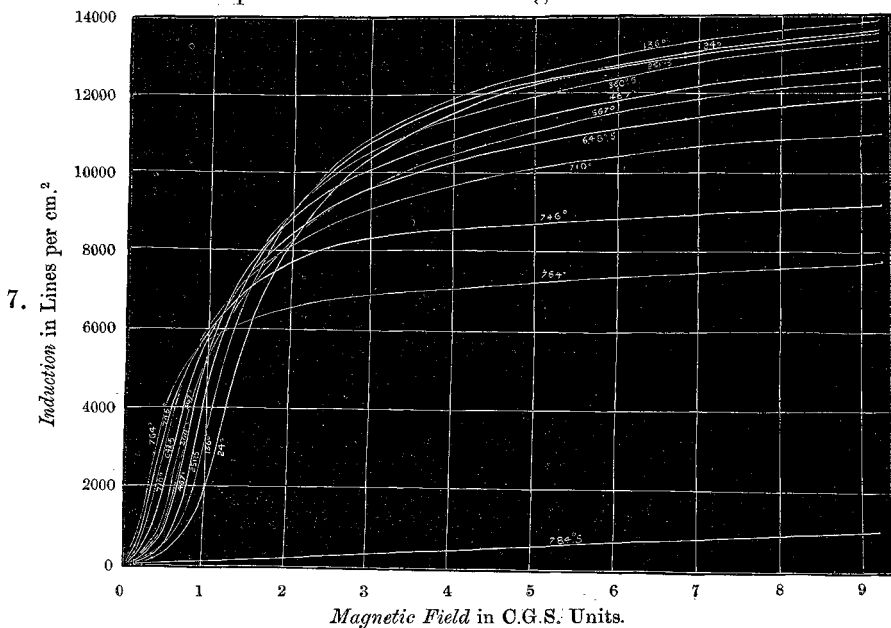
| | | After annealing at 840°. | After annealing at 1150°. | |
|--------------------------|--|--------------------------------|---------------------------------|--------------------|
| Temperature-Coefficient | { at 0°..... | ·0057 | ·0057 | |
| | { maximum value at about 765° | ·0189 | ·0204 | |
| | { at 1000° | | ·00244 | |
| Specific Resistance..... | { at 0°..... | 10950 | 10050 | } C.G.S. Units. |
| | { at 1000° | | 11800 | |

B-H Curves at various Temperatures.

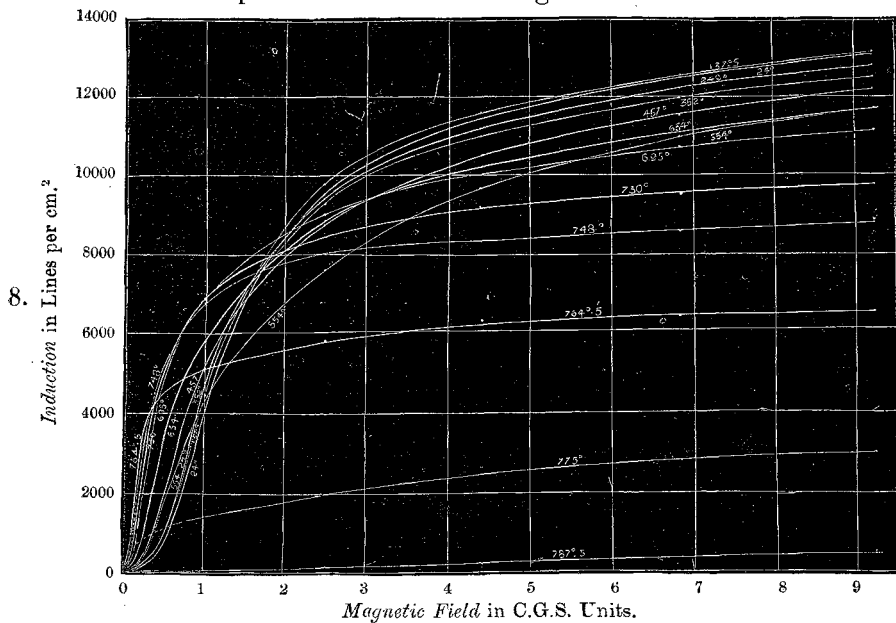
Specimen A after annealing at 1050° C.



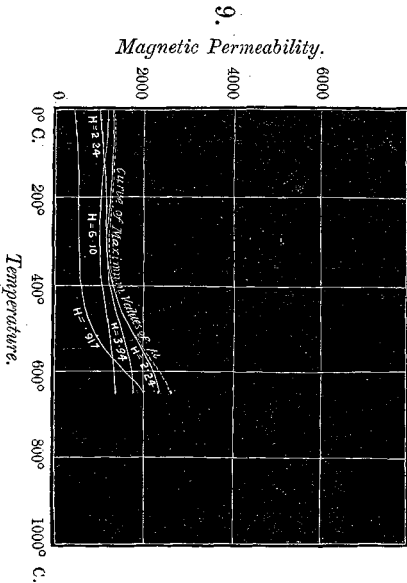
B-H Curves at various Temperatures.
Specimen B after annealing at 840° C.



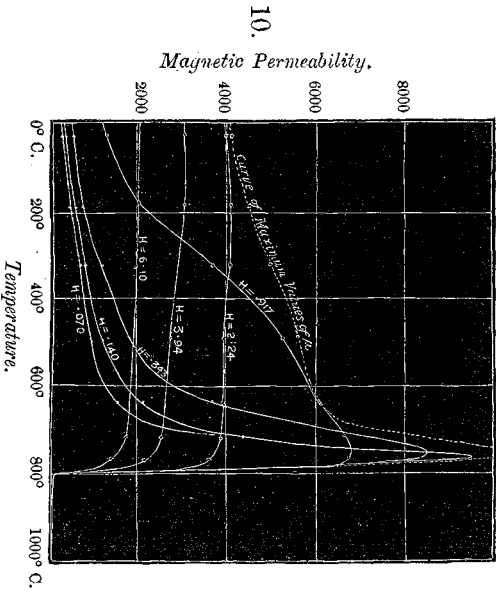
B-H Curves at various Temperatures.
Specimen B after annealing at 1150° C.



Permeability-Temperature Curves.
Specimen A before annealing.

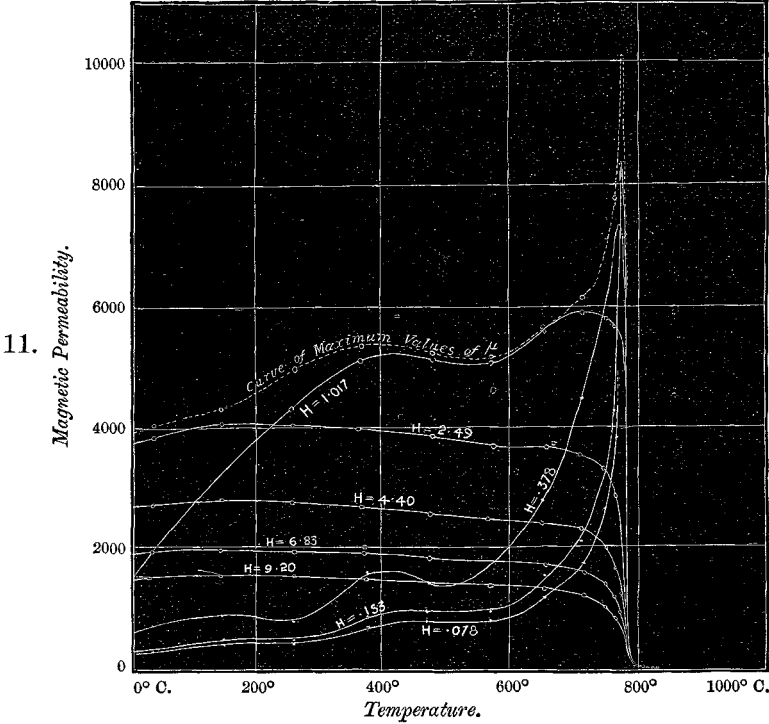


Specimen A after annealing at 1050° C.



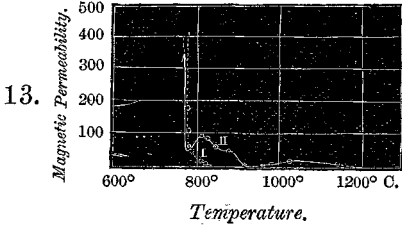
Permeability-Temperature Curves.

Specimen B after annealing at 840° C.



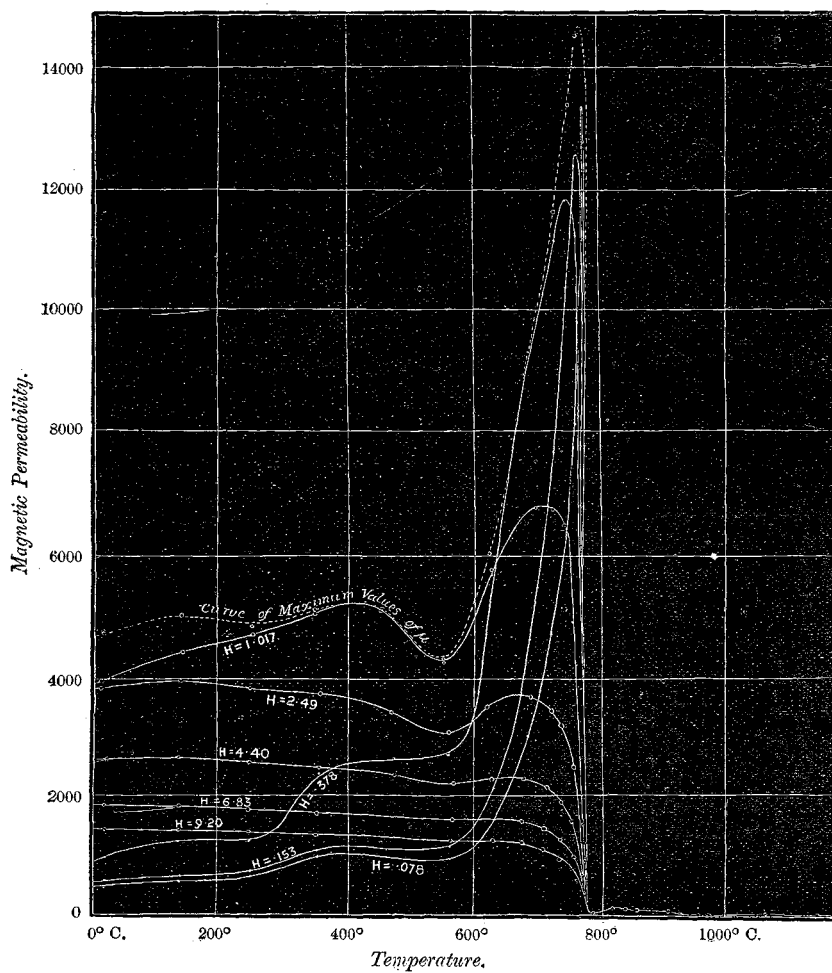
Magnetic Permeability of Iron specimen B
at Temperatures above its Critical Point.

Curve I. After annealing at 840° C. Curve II. After annealing at 1150° C.



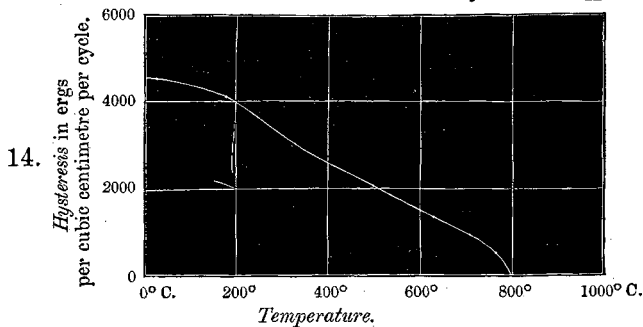
Specimen B after annealing at 1150° C.

12.



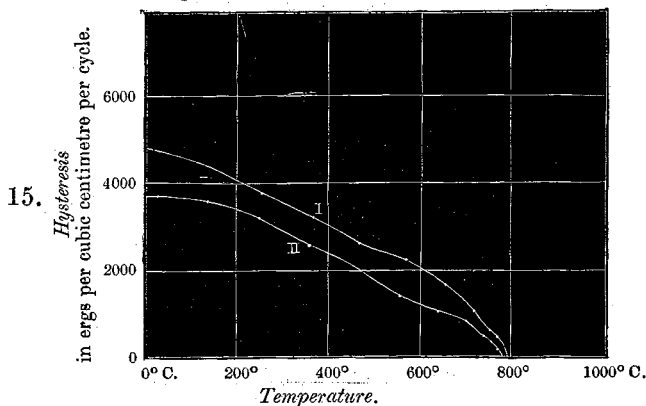
Hysteresis-Temperature Curves.

Specimen A. Annealed at 1050° C. Limits of Cycle. $H = \pm 6.10$.



Specimen B. Limits of Cycle. $H = \pm 6.83$ C.G.S. Units:

Curve I. After annealing at 840° C. Curve II. After annealing at 1150° C.



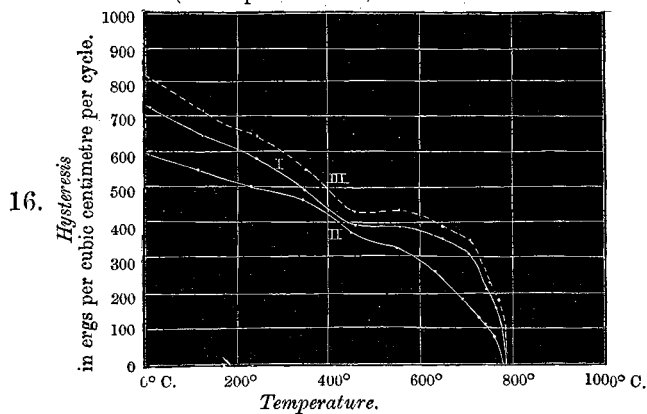
Specimen B.

Limits of Hysteresis Loop.

Curve I. After annealing at 840° C. $B = \pm 4260$.

„ II. After annealing at 1150° C. $B = \pm 4550$.

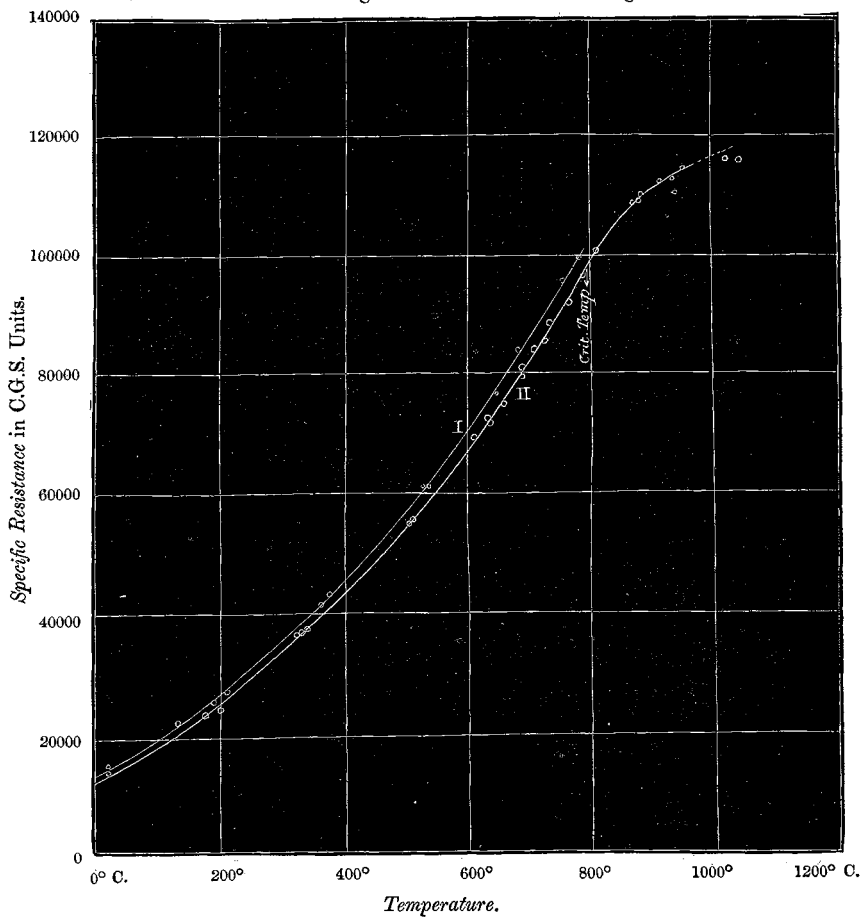
„ III. Calculated from I. for the Limits $B = \pm 4550$.
(to compare with II.)



Resistance-Temperature Curves.

17. Iron specimen A. (Crit. temp. $795^{\circ}\text{C}.$)

Curve I. Before annealing. Curve II. After annealing at $1050^{\circ}\text{C}.$



Resistance-Temperature Curves.

18. Iron specimen B. (Crit. temp. $780^{\circ}\text{C}.$)

Curve I. After annealing at $840^{\circ}\text{C}.$ Curve II. After annealing at $1150^{\circ}\text{C}.$

