derived from our standard thermometer, denoted by $-196{\cdot}7°$. This would show, therefore, that the temperature coefficient as usually defined is 0·000884 between $-35°$ and $0°$.*

These observations are specially interesting as giving additional proof that in the case of a metal of known purity the variation of resistivity, as the metal is continuously cooled, is such as to indicate that it would in all probability vanish at the absolute zero of temperature. In the case of mercury, we are able to obtain a metal in a state of almost perfect chemical purity, and which, when continuously cooled, passes into the solid condition under circumstances which are entirely favourable to the prevention of stresses in the interior of the metal, due to cooling. These measurements, therefore, afford a further confirmation of the law which we have enunciated as a deduction from experimental observations, that the electrical resistivity of a pure metal vanishes at the absolute zero of temperature.

"On the Magnetic Permeability and Hysteresis of Iron at Low Temperatures."

By J. A. Fleming, M.A., D.Sc., F.R.S., Professor of Electrical Engineering in University College, London, and James Dewar, LL.D., F.R.S., Fullerian Professor of Chemistry in the Royal Institution, &c. Received May 27,—Read June 11, 1896.

Although considerable attention has been paid to the changes produced in the magnetic properties of iron, particularly its magnetic permeability and hysteresis, at ordinary and at higher temperatures, but little information has been obtained up to the present on the behaviour of iron and steel as regards magnetic properties when cooled to very low temperatures. By the employment of large quantities of liquid air we have been able to conduct a long series of experiments on this subject, the results of which we propose here briefly to summarise, leaving for a future communication fuller details and discussion of the results. The experimental work has consisted in making measurements, chiefly by ballistic galvanometer methods, of the permeability and hysteresis loss in certain samples of iron and steel, taken in the form of rings or cylinders. The first experiments were concerned with the variation of the magnetic permeability of soft iron under varying magnetic forces, the iron being kept at a constant low temperature, obtained by placing it in liquid air in a state of very quiet ebullition in a vacuum vessel.

* This is in close agreement with the values obtained by Guillaume, Mascart, and Strecker for temperatures between 0° C. and +30° C.

Experiments on Annealed Swedish Iron.

A cylinder of iron was formed by winding up a sheet of Sankey's best transformer iron (Swedish).* The width of the strip was 4·895 cm., the thickness 0·0356 cm.; three complete layers of the sheet iron were used in forming the core. The area of cross-section of the side of the cylinder so formed was 0·5229 sq. cm. The mean diameter of the cylinder was 3·612 cm. This cylinder of iron was placed in a clay crucible packed with magnesia, the lid luted on with fire-clay, and the crucible then raised to a bright red heat in a forge, after which it was allowed to cool very slowly. The iron cylinder was thus carefully annealed out of contact with air or any material containing carbon. This soft annealed iron ring was then wound over with silk ribbon, and two windings of silk-covered copper wire placed upon it; the first or primary circuit consisted of 131 turns of No. 26 double silk-covered wire; the secondary circuit consisted of 112 turns of No. 36 silk-covered copper wire. The magnetising force to which the ring is subjected when a current is sent through the primary coil is measured by the value of $4\pi/10 \times$ the ampère-turns per unit of length of the mean perimeter of the ring, and this, in the case of the present ring, reduces to the number 14·507 times the ampère current. The magnetising force in absolute units is therefore very closely given by the number obtained by multiplying the current flowing through the primary coil in ampères by 14·5. The resistance of the primary coil at about 15° C. was 0·92 ohm, and the resistance of the secondary at the same temperature 8·98 ohms. The secondary circuit of this ring coil or transformer was then connected through appropriate resistances with a ballistic galvanometer, having a resistance of 18 ohms. The primary circuit was connected through suitable resistances and a current reverser with a circuit of constant potential. By these arrangements it was possible to reverse a definite current passing through the primary coils, and by observing the throw produced by the ballistic galvanometer, to calculate the induction in the iron core. The galvanometer was calibrated by reversing a known current passing through a long solenoid, in the centre of which was placed a secondary coil of known turns and dimensions, which was always kept in series with the secondary coil of the transformer. In this manner a series of observations was taken with gradually increasing magnetising forces. Before commencing each series of observations, the ring was carefully demagnetised by passing through the primary coil an alternating current, which was gradually reduced in strength to zero, the ring coil being thus brought into a magnetically neutral condition. An increasing

* This sheet iron was kindly given to us by Mr. R. Jenkins, to whom our thanks are due.

series of primary currents was successively passed through the primary coil and reversed, the throw of the ballistic galvanometer being noted in each case. In the first set of observations the ring was kept at the ordinary temperature of the air, 15° C., and in the second set it was immersed in liquid air, and the following table shows the results, both for the high and for the low temperature observations.

After taking a complete magnetisation curve at the ordinary temperature, the ring was immersed in liquid air, bringing its temperature down to about −185° C., and a complete series of observations taken again in the same manner, previously having first carefully

Table I.—Magnetisation Curve of Annealed Soft Iron (Sankey's Transformer Iron).

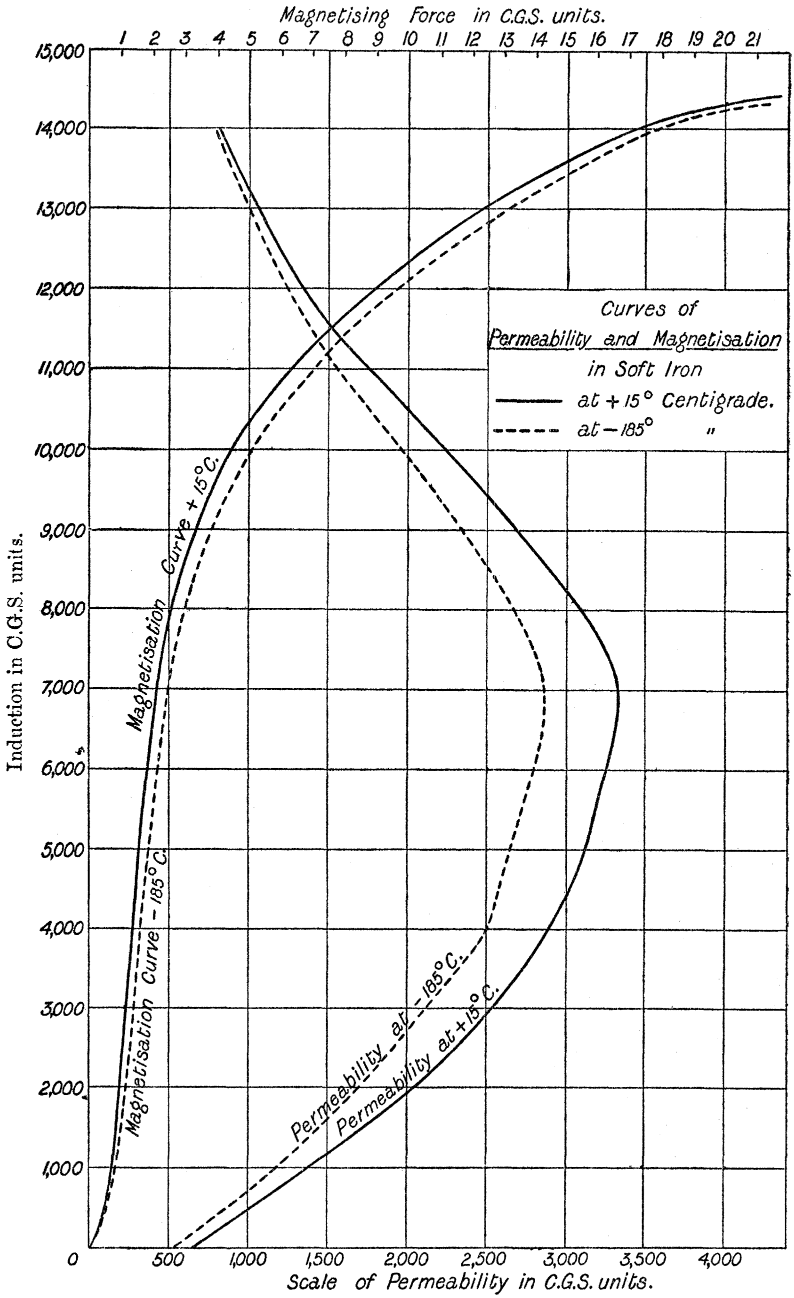
At 15° C.			At −186° C. (in liquid air).		
Magnetising force. H.	Induction. B.	Permeability. μ.	Magnetising force. H.	Induction. B.	Permeability. μ.
0·725	1000	1379	0·841	1000	1189
0·971	2000	2060	1·174	2000	1704
1·174	3000	2555	1·407	3000	2132
1·378	4000	2903	1·595	4000	2508
1·595	5000	3135	1·886	5000	2651
1·840	6000	3261	2·145	6000	2797
2·10	7000	3333	2·440	7000	2869
2·58	8000	3101	2·99	8000	2675
3·35	9000	2687	3·83	9000	2350
4·47	10000	2237	5·08	10000	1968
6·27	11000	1754	7·05	11000	1560
8·99	12000	1335	9·72	12000	1234
12·35	13000	1053	13·11	13000	992
17·22	14000	813	17·90	14000	782
22·1	14400	652	21·35	14300	670

demagnetised the ring as described by an alternating current. The ring was then taken out of the liquid air, allowed to warm up again to the ordinary temperature, and another complete set of observations taken at the ordinary temperature. In this manner a series of eighteen complete sets of observations were taken, about half of them being at 15° C. and half of them at −185° C. In cooling the ring in liquid air, it was found to be important to cool it slowly by holding it some time in the dense gaseous air lying over the liquid air. If suddenly plunged into liquid air the iron becomes hardened. It was found that after the first five sets of observations, which were some-

what variable, the annealed iron ring was brought into a completely stable condition, in which the curve of magnetic induction plotted in terms of magnetising force taken at the low temperature was different from that taken at 15° C. by a perfectly constant amount, the observations at the low temperature always lying on one curve, and those at the higher temperature always lying closely on the other curve. In the diagram in fig. 1 the two magnetisation curves are shown, the firm line curve being the magnetisation curve at 15° C., and the dotted curve being the magnetisation curve taken at −185° C. in the liquid air. The figures in Table I are the mean values obtained from the curves plotted from the thirteen sets of closely consistent observations. These curves show that the permeability of soft annealed iron is reduced when it is cooled to about 200° below zero, for the whole range of magnetic forces between zero and 25 C.G.S. units. The permeability curves for the two states are likewise similarly shown on the same chart. The maximum permeability for this iron corresponds with a magnetising force of about 2 C.G.S. units; the maximum permeability at the ordinary temperatures for this iron is 3400, being reduced to 2700 when the iron is cooled to the temperature of liquid air. The percentage reduction in permeability becomes less as the magnetising force is increased beyond or reduced below this critical magnetising force. These experiments were repeated, as above stated, many times very carefully with this ring of annealed soft Swedish iron, and also with a second ring of the same kind, and have invariably shown the same results, viz., that the permeability of soft annealed iron is decreased by being cooled to this low temperature within the range of magnetising forces from 0 to 25. It will be seen that the highest induction reached in the case of this iron is 14,500 C.G.S. units, corresponding to a magnetising force of 25. This iron is of very high magnetic quality, and is of the same character as that which is much used for the construction of alternating current transformers in commercial use.

A series of experiments was then made with the same transformer, keeping the magnetising forces constant, but allowing the iron to rise gradually in temperature up from the temperature of liquid air to 15° C. In these experiments the transformer was embedded in a mass of paraffin wax with a platinum wire resistance thermometer also embedded in the same mass in close contact with the ring coil. The paraffin wax encasing the ring coil and thermometer having been cooled down to the temperature of liquid air by immersing it in a large bath of the liquid air, it was then lifted out and placed in a vacuum-jacketed test-tube, so as to heat up with extreme slowness, and a series of observations taken by reversing a constant magnetising force at intervals, and observing at the same instant the temperature of the ring coil as given by the platinum thermometer.

FIG. 1.


Magnetising Force in C.G.S. units.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Induction in C.G.S. units.
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500 1,000 1,500 2,000 2,500 3,000 3,500 4,000
Scale of Permeability in C.G.S. units.
Curves of
Permeability and Magnetisation
in Soft Iron
at + 15° Centigrade.
at − 185° "
Magnetisation Curve + 15° C.
Magnetisation Curve − 185° C.
Permeability at − 185° C.
Permeability at + 15° C.

The results of these observations are given in Table II, and these observations are set out in the curve marked soft annealed iron in fig. 2.

Table II.—Variation of the Magnetic Permeability of Soft Annealed Swedish Iron with Temperature.

Magnetising force = 1·77 C.G.S.

Temperature measured in platinum degrees by standard thermometer P_1.

Temperature.	Permeability.
0°	2835
− 20	2815
− 40	2770
− 60	2727
− 80	2675
−100	2622
−120	2560
−140	2497
−160	2438
−180	2381
−200	2332

The results show that as the temperature rises up from −185° C., or −200° on the platinum scale temperature, up to the ordinary temperature, the permeability of the soft iron for the particular magnetising force selected increases perfectly uniformly, the curve of increasing permeability with temperature being nearly a straight line.

In the next place, we have examined the hysteresis of the same soft iron ring at different temperatures and for different maximum inductions. These observations were carried out by taking a complete series of hysteresis curves with the ballistic galvanometer, gradually increasing the inductions from zero to 12,000. After the complete hysteresis curves were obtained, their areas were carefully integrated with an Amsler planimeter, and the values reduced so as to express the hysteresis loss in watts per lb. per 100 cycles per second, and these values plotted in terms of the maximum value of the magnetic induction per square centimetre of the iron core corresponding to each particular hysteresis loss. Nothing would be gained by giving the full details of all the observations by which these hysteresis curves were obtained. They were exceedingly numerous, and the tedious nature of the ballistic observations made it a matter of prolonged observation to secure the whole series necessary, but the final results are shown in Table III. The curve in fig. 3 represents the increase of hysteresis loss with induction, and the observations which

Fig. 2.

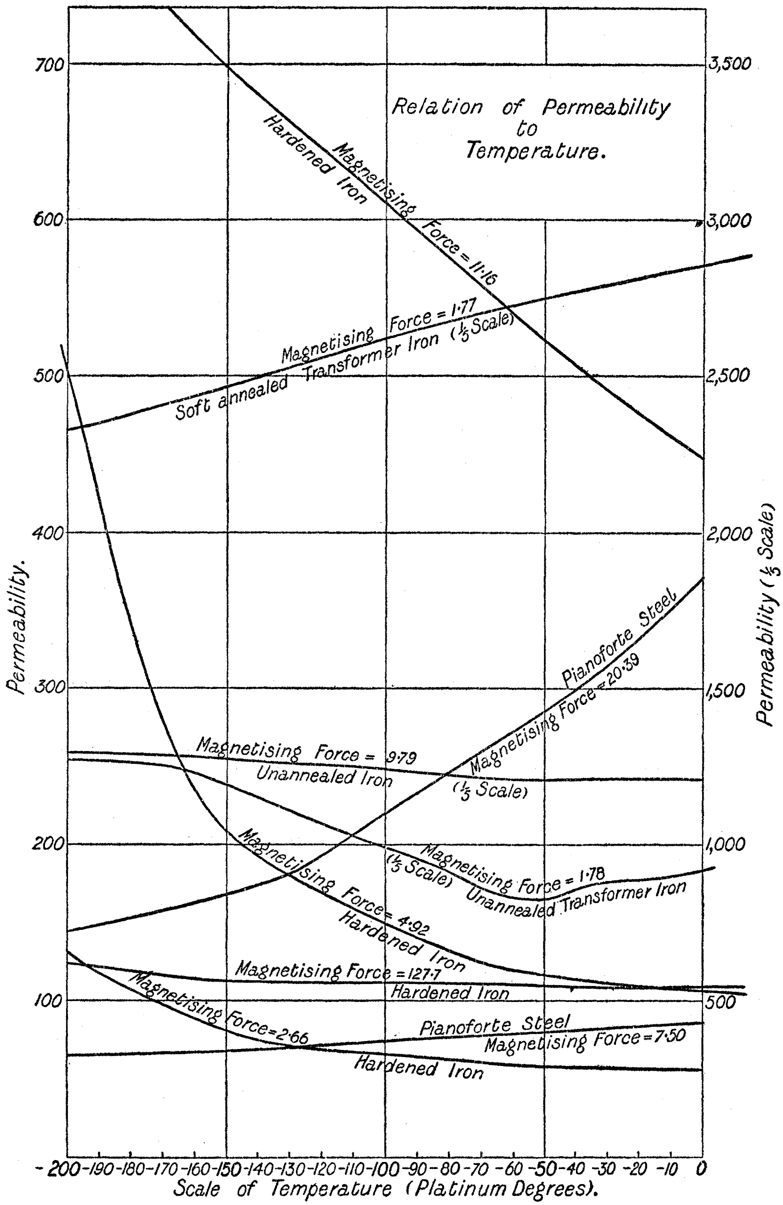

Relation of Permeability to Temperature.
Magnetising Force = 11·16
Hardened Iron
Magnetising Force = 1·77
Soft annealed Transformer Iron (1/5 Scale)
Pianoforte Steel
Magnetising Force = 20·39
(1/5 Scale)
Magnetising Force = 9·79
Unannealed Iron
Magnetising Force = 1·78
(1/5 Scale)
Unannealed Transformer Iron
Magnetising Force = 4·92
Hardened Iron
Magnetising Force = 127·7
Hardened Iron
Magnetising Force = 2·66
Pianoforte Steel
Magnetising Force = 7·50
Hardened Iron
Permeability.
Permeability (1/5 Scale)
700
600
500
400
300
200
100
3,500
3,000
2,500
2,000
1,500
1,000
500
-200 -190 -180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0
Scale of Temperature (Platinum Degrees).

FIG. 3.

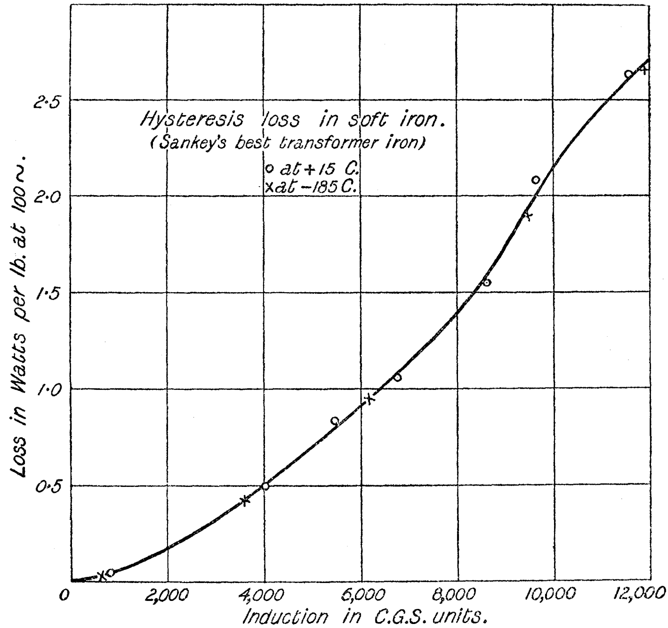


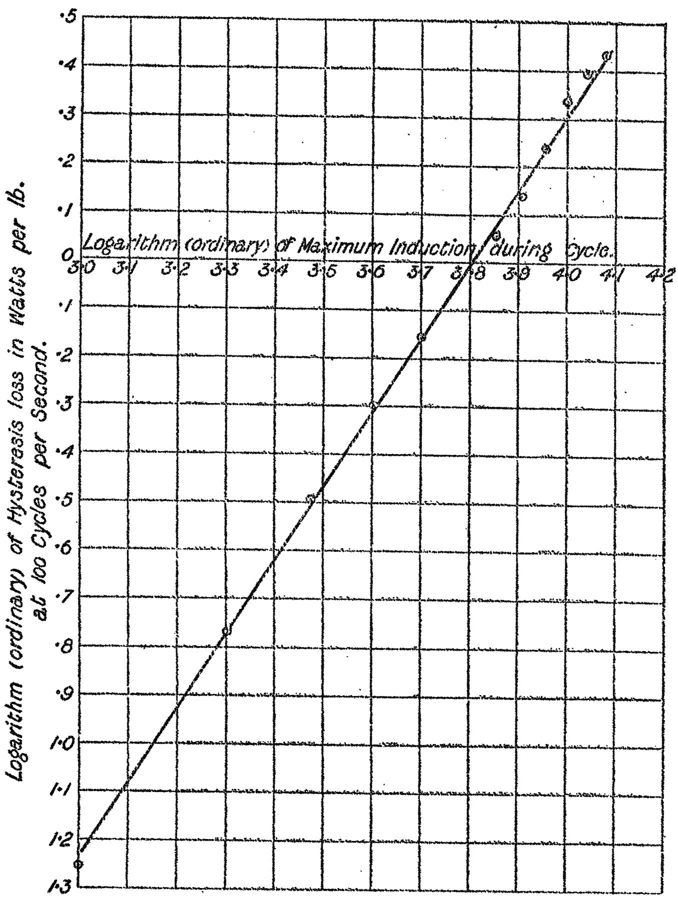
Table III.—Hysteresis Loss in Soft Annealed Swedish Iron in Watts per pound per 100 cycles per second for various maximum Inductions.

I. At +15° C.		II. At −185° C. (in liquid air).	
Maximum induction. B.	Hysteresis loss. W.	Maximum induction. B.	Hysteresis loss. W.
844	0·0397	688	0·02519
4026	0·4957	3603	0·4246
6743	1·062	6185	0·949
9687	2·070	9461	1·907
11618	2·632	11916	2·658
8593	1·545		
5516	0·823		

were taken at ordinary temperatures are denoted by the small circles. The observations for hysteresis loss which were taken at the temperature of liquid air are denoted by the crosses. It will be seen that substantially the circles and the crosses lie on the same curve. The results of these observations, therefore, show that there is practically no change in the hysteresis loss in soft iron by cooling it to the tem-

perature of liquid air. If, instead of plotting the hysteresis loss and induction, the ordinary logarithms of these quantities are taken as coordinates, the curve, as shown in fig. 4, then obtained is

FIG. 4.



very nearly a straight line as far as the limit of an induction of about 9000, and from the inclination of this line it is clear that the hysteresis loss, W, in watts per lb. per 100 cycles is found to be related to the maximum induction B in C.G.S. units per square centimetre by the law $W = \frac{1156}{10^9} B^{1·56}$, or, if the hysteresis loss is reckoned in ergs per cubic centimetre per cycle = W′, then $W' = 0·002\ B^{1·56}$. These results are quite in accordance

with certain conclusions of Messrs. Laws and Warren (see 'Proceedings of the American Academy of Sciences,' vol. 30, p. 490). These observers made a series of experiments on a material which was practically a very soft steel, and employing a differential watt meter, measured the hysteresis loss in the iron at varying and increasing temperatures up to 600° or 700°. They found that the hysteresis loss in this material did not begin to decrease sensibly until about 150° C.; after that it decreased regularly in accordance with the simple linear function of the temperature. In one experiment which they tried with the same material cooled to −78° C. in solid carbonic acid and ether, they found no difference between the hysteresis loss of this soft steel at that temperature and at the ordinary temperatures. Our results, which have been carried to the much lower temperature of liquid air, indicate that in the case of soft annealed Swedish iron the hysteresis loss is not changed by cooling from ordinary temperatures to the temperature of liquid air. As we know that the hysteresis loss of soft iron decreases when the temperature is increased, from the ordinary experience with transformers in commercial use, the matter that requires further investigation is to discover the temperature at which the hysteresis loss sensibly changes and begins to diminish.

Experiments on Unannealed Swedish Iron.

We have also carried out a series of experiments of the same character with unannealed iron and steel. A ring coil was constructed of sheet iron of the same quality as that forming the core of the soft iron transformer above described, but no special pains were taken to anneal the iron, and as it was "hardened" in a magnetic sense by being bent into shape, this difference in quality showed itself in the magnetic observations. A ring coil was constructed of the following dimensions:—The thickness of the strip was 0·031 cm., width of the strip 1·24 cm., the ring was formed by $23\frac{1}{2}$ layers of this sheet iron wound up closely into the form of a ring. The outside diameter of this ring was 4 cm., the inside diameter 2·13 cm., the cross-section of the iron in the ring was therefore 0·9032 sq. cm., and the mean perimeter of the ring 9·62 cm. This iron ring was not annealed in any way, but it was simply wound over with silk ribbon, and then had placed upon it two coils of wire. The primary coil consisted of 150 turns of No. 26 wire, having a resistance of 0·383 ohm, and the secondary coil consisted of 240 turns of No. 36 wire having a resistance of 8·092 ohms. As the diameter of cross-section of the ring was not very small compared with the mean diameter of the ring, it was necessary to calculate by a proper integration the mean value of the mean magnetising force in terms

of the current passing through the primary coil, and it was found that the mean magnetising force to which the iron was exposed was closely expressed by the value 20·219, multiplied by the ampère current flowing through the primary coil. This coil had its secondary circuit connected up to the galvanometer, as above described, and a series of observations were taken with this coil by reversing a constant magnetising current passing through the primary coil, and observing the throw of the ballistic galvanometer connected with the secondary circuit. The ring coil, together with the platinum thermometer, was embedded, as above described, in a mass of paraffin wax, and the whole mass, after having been cooled down to the temperature of liquid air, was slowly allowed to heat up again. Observations were taken with two different magnetising forces over the range of temperature from −185° C. up to the ordinary temperature, and from the calculated induction in the ring determined for each magnetising force, the permeability was found corresponding to each particular force and temperature. The results of these observations are given in Table IV, and are delineated in fig. 2, in the form of two curves marked unannealed iron.

Table IV.—Variation of Magnetic Permeability of Unannealed Swedish Iron with Temperature.

Temperature measured in platinum degrees by standard thermometer P_1.

	Permeability.	
Temperature.	Magnetising force, 1·78.	Magnetising force, 9·79.
0°	917	1210
− 20	885	1212
− 40	857	1212
− 60	832	1208
− 80	913	1230
−100	993	1240
−120	1067	1255
−140	1153	1265
−160	1230	1280
−180	1262	1290
−200	1272	1293

The results of the observations, as indicated in fig. 2 in the curves marked Unannealed Iron, show that for this unannealed iron the permeability increases as the temperature falls, and is exactly the reverse in the case of the same quality of iron carefully annealed. The difference, also, between the two materials is very marked

at low temperatures. The soft annealed iron if cooled slowly to $-185°$ C. recovers its original permeability when heated up again to ordinary temperatures. The unannealed iron, however, after cooling to the same low temperature, retains some of its increased permeability when heated up again to 15° C. The unannealed iron cannot be taken over the temperature range again and again with the same definite permeability values at each recurrent temperature, as in the case of the soft annealed iron. The unannealed iron is more or less permanently changed in magnetic character every time it is heated or cooled.

With this transformer, a long series of observations were taken to determine the hysteresis loss corresponding to different inductions when taken at the ordinary temperatures, and the temperature of liquid air. The hysteresis cycles were taken with the ballistic galvanometer over wide ranges of maximum induction, the transformer being alternately at the ordinary temperature and in liquid air, but no constant magnetic condition could be obtained. In one set of observations, at a given maximum induction the hysteresis loss was increased when the transformer was raised in temperature, and for another series of observations at the same induction it was diminished. It is therefore impossible to make any definite statement with regard to the magnetic hysteresis loss in this unannealed iron ring coil at the two temperatures. The mere fact of immersing the unannealed iron in the liquid air changes its magnetic qualities to such a degree that it is no longer the same material, magnetically considered, after, as before its immersion. One curious fact, however, was noticed very soon with regard to unannealed iron, and that is, that if the unannealed iron ring coil has a small magnetising current passed through its primary coil, the secondary coil being connected to the galvanometer, the sudden immersion of this ring coil into liquid air invariably causes a deflection of the ballistic galvanometer, even when the primary magnetising current remains perfectly constant in value, thus showing a sudden and very large increase in the permeability of the unannealed iron. Whilst the iron is in the liquid air it retains this increased permeability. If brought suddenly out its permeability again diminishes, but not with equal rapidity. This is partly accounted for by the fact that the iron is cooled with immense rapidity when it goes into the liquid air, but it heats up again much more slowly when it is brought out. The definite fact, however, remains, which has been repeatedly observed, that the cooling of this unannealed iron to a low temperature always increases its permeability, as far as we know, no matter whatever may be the magnetising force employed. One difficulty experienced in dealing with unannealed iron is the fact that in taking it up to the high magnetising forces, and by the process required to remove residual

magnetism by the application of an alternating current, the iron is so altered in magnetic qualities that it is impossible to repeat two sets of observations under precicely similar circumstances. With regard to the unannealed iron, it may be noted that if an ordinary magnetisation curve is taken up to very high magnetisation forces, and the iron then demagnetised by the application of an alternating current gradually reduced, the first magnetisation curve can never be repeated exactly again on applying increasing magnetisation forces, but a curve is obtained which lies slightly inside the first curve, and which indicates that the permeability has been reduced. The subsequent repetition of this process will give a series of curves which occupy different positions, but which do not precisely repeat any of them. Hence it is impossible to repeat at a constant temperature with this unannealed iron exactly any magnetisation or permeability curve. In the case of the annealed iron it is quite different. A magnetisation curve can be obtained after having carefully de-magnetised the iron, if this magnetisation is pressed up to nearly its limit and the iron then de-magnetised by the application of an alternating and decaying magnetising force, a second magnetisation curve can be obtained on again applying an ascending magnetising force, but it will not coincide exactly with the first curve. The annealed iron can, however, be brought back into its original condition by dipping it a few times into liquid air. Under these conditions, we have been able to repeat as frequently as required the observations with the annealed iron taken at the different temperatures. In the case of the unannealed iron the changes produced in it by immersing it in the liquid air and by magnetising and demagnetising it, are such as to render it almost impossible to obtain results capable of precise repetition, with respect to the hysteresis loss and permeability for varying magnetising forces.

Experiments with Hardened Iron.

A third set of experiments were taken with a ring coil of the same dimensions as the ring coil made of soft annealed transformer iron first described. This third coil was constructed of the same sample of Sankey's transformer sheet iron as the above described soft annealed ring, but it was treated subsequently to its formation in the following manner :—

A short piece of iron gas-pipe was made red hot in a forge; the ring coil, having been constructed, was dropped into the red-hot pipe, and the ends of this pipe loosely plugged up with slag wool; the red-hot pipe was then covered over with cinders, and the mass allowed to cool. Under these conditions the ring coil was annealed in an atmosphere of carbonic oxide and in contact with hot carbon; the sheet

iron was, therefore, under these circumstances, case-hardened, and will be referred to as the hardened iron ring. Having been formed into a transformer in the above-described manner, a long series of observations were taken with this coil to determine its permeability at different temperatures and with different magnetising forces. The results of these observations are shown in the Table V below, and are delineated graphically in the curves in fig. 2, marked Hardened Iron. The results show in a remarkable manner that the iron so treated undergoes a very considerable increase in magnetic permeability when it is cooled to the temperature of liquid air; for certain magnetising forces the permeability at the lowest temperature reached may be increased as much as five times. In this respect, therefore, this iron presents in an exaggerated degree the same qualities found in the unannealed iron.

Table V.—Variation of Magnetic Permeability with Temperature of Hardened Iron.

Temperature measured in platinum degrees by standard thermometer P_1.

Temperature.	Permeability.			
	H = 2·66.	H = 4·92.	H = 11·16.	H = 127·7.
0°	56·0	106·5	447·5	109·0
− 20	57·0	109·5	476·0	108·5
− 40	58·0	114·0	506·5	109·0
− 60	59·0	119·8	540·0	110·5
− 80	62·5	132·5	575·0	111·0
−100	65·5	150·0	610·0	112·0
−120	69·2	169·3	645·0	112·0
−140	75·3	192·5	680·0	112·3
−160	89·5	236·0	717·0	114·0
−180	107·5	338·0	762·0	119·5
−200	132·0	502·0	823·0	124·0

Experiments with Steel.

We have also examined the behaviour of a ring coil made of steel pianoforte wire. We have found in this case the curious result that pianoforte steel behaves in the same manner as the annealed soft iron; its permeability is decreased as the temperature is lowered. The results of the measurements with this steel-core ring are shown in Table VI, and graphically in the curves in fig. 2, marked steel.

Table VI.—Variation of Permeability with Temperature.

Pianoforte Steel.

Temperature measured in Platinum degrees by standard thermometer P_1.

	Permeability.	
Temperature.	Magnetising force, 7·50.	Magnetising force, 20·39.
− 0°	86·0	361·0
− 20	84·0	332·5
− 40	81·0	299·5
− 60	79·0	271·5
− 80	77·0	246·5
−100	74·0	220·0
−120	71·5	193·0
−140	68·5	174·3
−160	67·0	163·0
−180	66·0	153·0
−200	64·5	144·0

We propose to continue the examination of the anomalous behaviour so presented by iron in different states of hardening by examining in the same way the changes of permeability in the case of several iron rings of the same dimensions formed in the one case of soft annealed iron, and in another case of the same quality of iron hardened, and in the remaining cases using steel of known composition at different states of temper. We desire to add that in the conduct of this research we have been under great obligations to Mr. J. E. Petavel for rendering us very efficient assistance in taking the exceedingly tedious ballistic galvanometer observations, and in reducing them when taken.