II. *The Thermomagnetic Analysis of Meteoric and Artificial Nickel-iron Alloys.*

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SECTION I.—DESCRIPTION OF THE MATERIALS OF WHICH THE THERMOMAGNETIC PROPERTIES WERE INVESTIGATED.

§ 1. THE experiments described in this paper arose from the desire of Sir ARTHUR W. RÜCKER to obtain, in connection with his researches on the nature of the Earth's magnetic field, further data concerning the properties of such magnetic materials of natural origin as may be present in appreciable quantity in the Earth's crust.

Iron of cosmic origin contains nearly always an appreciable quantity of nickel, and the magnetic properties of this material, especially their variation with temperature, have received very little attention. Most of the published data are qualitative only, and from them no very definite conclusion can be drawn beyond the fact that meteoric iron appears to be of very variable permeability. It was, therefore, thought desirable to make a careful quantitative study of a typical example of such material.

§ 2. The meteoric iron used in the experiments was bought from the firm of Dr. A. E. FOOTE, and the mass from which the sample was cut is described by A. E. FOOTE in the 'American Journal of Science' [4], vol. 3, p. 65, 1897. The whole meteorite weighed about 237 kilogs. and was found in the Sacramento Mountains, Eddy Co., New Mexico. A careful analysis of some fragments yielded the results :—

$$\begin{aligned} \text{Fe} &= 91{\cdot}39 \\ \text{Ni} &= 7{\cdot}86 \\ \text{Co} &= 0{\cdot}52 \\ \hline & 99{\cdot}77 \end{aligned}$$

The material is thus apparently remarkably free from elements other than those of the ferromagnetic group.

After a ring about 2 centims. deep and $5\frac{1}{2}$ centims. external diameter had been cut from the sample supplied, a solid disc-shaped core, about $3\frac{3}{4}$ centims. in diameter, remained. The ends and cylindrical surface of this were afterwards polished carefully and etched. At the conclusion of the experiments, the outer oxidised layer of the ring was removed on the lathe and the ring was then etched in order that its structure might be compared with that of the material which had not received thermal treatment.

§ 3. Different samples of the turnings produced during the formation of the ring were kindly analysed by Mr. E. A. WRAIGHT, of the Royal School of Mines, with the following mean result:—

Fe = 92·84 (92·5 to 93·0 in different samples)
Ni = 6·81
Co = 0·37.

In some of the samples there were traces of chromium, whilst others contained up to 0·025 per cent. of sulphur. Examination of the polished surface of the core above mentioned showed the presence of an isolated speck of a brass-coloured mineral which was almost certainly sulphide of iron (troilite), and it is probable that the sulphur found in some analyses was present in this form. No trace of carbon or phosphorus was found in the analyses.

§ 4. Mr. A. FOWLER, Assistant Professor of Physics in the Royal College of Science, kindly examined the meteorite spectroscopically between the D lines and λ 4170 and found that there were no lines not accounted for by Fe, Ni, Co and Cr. The cobalt lines were relatively inconspicuous. Three chromium lines were identified with certainty.

§ 5. The grosser structure of the meteorite was shown very clearly by the markings on the polished and etched cylindrical core. The distribution of the more and less nickeliferous layers was easily discernible. The actual thicknesses of the layers, and their geometrical arrangement with respect to one another, could be observed by tracing the course of individual layers across the plane and cylindrical surfaces of the core. The approximate relation between the positions of the layers observed is represented in fig. 1.

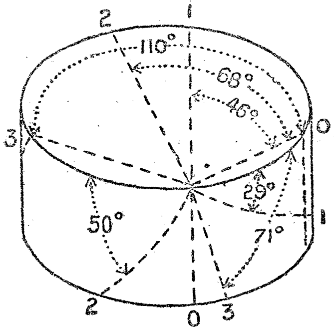


Fig. 1.

All the layers observable were parallel to one or other of the four planes represented by their traces upon the plane and cylindrical surfaces, viz., 00, 11, 22 and 33 respectively. Some of the layers appeared to be appreciably curved. The numbers marked on the plane circular face in fig. 1 were judged to be the closest approximations that could be got to the general directions of the layers.

The true angles between each of the planes 00, 11, &c., and the plane faces of the core were determined by means of a hand goniometer. The numbers on the cylindrical surface in the diagram represent these angles.

Within the limits of observation the plane 00 was at right angles to the plane faces of the core. This accidental circumstance has the effect of simplifying slightly the calculation of the angles between the various planes. For, taking the plane of the circular face of the core as the plane of xy, the plane 00 may be taken as the plane of yz. Attention being paid to signs, the intercepts of each of the other three planes on the axes of x, y and z are then in the ratio

$$\tan \theta : 1 : \sin \theta \tan \phi,$$

where θ is the angle between the trace of 00 and of one of the other planes on the circular face and ϕ is the real angle between the latter plane and the circular face. Hence, using the data given on the diagram, the direction-cosines of the planes 11, 22 and 33 can be calculated.

In this way the angles between the planes of the layers were found to be :—

$$\theta_{01} = 70^\circ,\ \theta_{12} = 77^\circ,\ \theta_{23} = 71^\circ,\ \theta_{30} = 71^\circ,\ \theta_{02} = 73^\circ,\ \theta_{13} = 61^\circ.$$

Hence it is seen that, with the exception of 11, the planes are inclined to one another in practically the same way as the faces of a regular octahedron, the interfacial angle for the latter being 70° 32′ approximately.

The markings on the plane faces of the cylindrical core, from which the measurements were taken, are shown in the accompanying photographs, figs. 2 and 3 (Plate 1), which are slightly less than natural size (actual diameter of core about 3·7 centims.). The relative position of the markings in space would be reproduced by rotating either of the photographs through 180° about the line 00 and then placing it behind, and about 1·8 centims. away from, the other photograph. The markings on the cylindrical part of the surface of the core are very distinct, but difficult to reproduce photographically owing to the curvature. On this part of the surface, the layers parallel to 11, which are not very clearly seen on the flat ends (see photographs), are very numerous, owing to the acuteness of the angle (29°) which these layers make with the flat ends, and are as conspicuous as the layers running in the other directions.

Since the layers parallel to 00 run practically perpendicular to the plane ends of the core, the true thicknesses of these layers are represented in the photographs. On the other hand, the thicknesses of the layers parallel to 11 are about one-half ($= \sin 29^\circ$) of the apparent thicknesses shown in the photographs. The thickness of a layer parallel to 22 is about three-quarters ($= \sin 50^\circ$) of the apparent thickness, whilst the layers parallel to 33 are about 5 per cent. thinner than they appear in the photographs. From these data it will be seen that the distribution of the layers is even more regular than appears from the photographs. At the same time, the want of symmetry in the numbers given, showing an apparent anomaly in the positions of the layers parallel to 11, is, I think, too great to be accounted for as arising from unavoidable errors of observation.

The chief importance, for the present purpose, of the numbers and description just given lies in the fact that they serve to define the geometrical distribution of the alloys of different composition in the ring of which the permeability was examined. It was proved directly by polishing and etching the ring at the conclusion of the experiments that the regularity of distribution observed in the core extended to the portion of the material of which the ring was composed.

§ 6. The micro-structure of the meteorite is shown in the four photographs (Plate 2), for three of which I am indebted to Mr. WRAIGHT.

The photographs *a* and *b* represent different portions of the etched surface magnified about 50 diameters. The duller portion of the surface (crossed by sets of fine parallel "Neumann" lines) is in each case the easily etched constituent "kamacite." The brighter less easily etched constituent is "taenite." In the photograph *a* the thin bands of taenite are almost rectilinear, and there are numerous subsidiary, discontinuous bands. The centre of fig. *b* shows that there is sometimes no taenite between contiguous layers of kamacite. Lower in the figure there is an unbroken band of taenite separating two layers of kamacite, while in the upper part of the figure more nickeliferous material occurs in the gaps between layers of kamacite. Fig. *c* shows a portion of the surface magnified about 80 times. It suggests, like *b*, that the crystallisation of the taenite is subsequent to that of the kamacite, and also that the former is not in reality homogeneous, since the comparatively thick band of taenite in the middle of the figure has obviously been unequally etched by the reagent (*cf.* COHEN, "Meteoritenkunde," I., p. 80 *et seq.*). Similar inequalities of etching are shown in the lower band of taenite in the negative from which fig. *b* was obtained.

In obtaining these three photographs the degree of etching was very slight—the minimum amount necessary to bring out the structure represented.

In the photograph *d* (magnification roughly 500 diameters), which I took later, the degree of etching was much greater. The surface of the meteorite was no longer approximately plane, and the different parts could not be simultaneously focussed. The dark parts of the field are the deeply etched and unfocussed kamacite. The regions partly dark and partly bright represent highly magnified portions of the bands of etched taenite, in one of which there are distinct traces of lamination.

§ 7. The nickel-iron alloy, of which the magnetic properties were compared with those of the meteorite, was kindly supplied to me by Mr. R. A. HADFIELD, M.Inst.C.E., and was a sample of the 5·81 per cent. nickel steel described by him in the 'Proceedings, Institute Civil Engineers,' vol. 138, p. 114, 1899, where its composition is given as follows :—

Ni = 5·81
C = 0·18
Si = 0·31
S = ...
P = ...
Mn = 0·65
Fe (by difference) = 93·05.

The ring was forged from the rod supplied and turned down until its dimensions were nearly the same as those of the meteoric ring.

The dimensions of the rings, before winding for the permeability measurements, were as follows :—

Ring.	External diameter.	Internal diameter.	Axial depth.
	centims.	centims.	centims.
Meteoric iron . . .	5·40	4·37	1·89
Nickel steel . . .	5·41	4·37	1·90

SECTION II.—PRELIMINARY MEASUREMENTS OF PERMEABILITY AT THE AIR TEMPERATURE.

§ 1. The determination of the permeability of the meteoric iron in its original state as received was made in the ordinary way by the ballistic method. The ring, of the dimensions given above, was wound with a primary and secondary of copper wire, each silk-covered and further insulated by a coating of shellac varnish. The inductive effects obtained from the ring were compared with those obtained from a standard inductor.

§ 2. The following numbers represent values obtained at a temperature of 19° C. for corresponding values of μ and H and of B and H when the values of the latter were taken through a cycle.

H.	B.	μ.	H.	B.	μ.
In C.G.S. units.			In C.G.S. units.		
0·089	9·16	103·2	−0·261	−30·03	—
0·175	19·26	110·3	−0·346	−42·57	—
0·261	29·63	113·7	−0·261	−35·15	—
0·346	41·08	118·8	−0·176	−26·95	—
0·261	33·40	—	−0·089	−17·51	—
0·176	25·19	—	0·0	− 7·68	—
0·089	15·63	—	0·089	3·91	—
0·0	5·25	—	0·176	15·22	—
−0·089	− 6·06	—	0·261	28·02	—
−0·176	−17·51	—	0·344	40·54	—

It is well known that for pure iron and for many iron alloys the values of μ and H in weak fields are connected by a linear relation of the form

$$\mu = a+b\text{H},$$

where a and b are constants.

Assuming that this relation may hold in the present case and calculating from the numbers just given, by the method of least squares, the most probable values of a and b, we find

$$\mu = 99{\cdot}5+55{\cdot}2\text{H}.$$

The following table shows how far the values of μ calculated from this equation agree with those actually found.

Observed.	Calculated.
103·2	104·4
110·3	109·1
113·7	113·9
118·8	118·5

It will be seen that the agreement between corresponding numbers is within about 1 per cent.

§ 3. The values of μ and H given above were deduced from the observations in the ordinary way by assuming that the intensity of the field in the ring (for a given current in the primary) was uniform and equal to that at the mean radius.

The assumption that μ is constant throughout the cross-section of the ring, and that H has the value corresponding to the field intensity at the mean radius is, of course, very nearly true when the radial width of the ring is small compared with the mean radius. But if this latter condition is not fulfilled, or if the permeability varies rapidly with the field, the error introduced by this method of calculation may be considerable.

Although the dimensions of the ring were such that the intensity of the magnetising field for a given current in the primary coil would be more than 20 per cent. greater at the inner than at the outer surface of the ring, it was thought, having regard to the nature of the material examined, that the ordinary method of calculation would probably be as appropriate as any other, and that the degree of concordance of the numbers already given was sufficient for the purpose in view. Nevertheless, it is of interest to notice that, if the relation $\mu = a+b\text{H}$ is approximately true, a close approximation to strictly corresponding values of μ and H can be easily obtained, even when the ratio of the radial width to the mean radius is considerable, or when the variation of μ with H is large. The inductive effect per turn of the ring secondary is $\int \text{B}\,ds = \int \mu\text{H}\,ds$, where ds represents an element of the cross-section of the ring, H is the intensity of the field at this element, and μ is the value of the permeability corresponding to H. Hence, assuming the linear relation between μ and H, stated above, we get

$$\int \mu \mathrm{H}\, ds = a \int \mathrm{H}\, ds + b \int \mathrm{H}^2\, ds,$$

from which it follows at once that $\int \mu\mathrm{H}\, ds / \int \mathrm{H}\, ds$, being equal to $a + b\int \mathrm{H}^2\, ds / \int \mathrm{H}\, ds$, represents the permeability of the material for a field of intensity $\int \mathrm{H}^2\, ds / \int \mathrm{H}\, ds$.

The value of $\int \mu\mathrm{H}\, ds$ is determined directly by experiment, and the values of $\int \mathrm{H}^2\, ds$ and of $\int \mathrm{H}\, ds$ can be calculated from the constants, geometrical and electrical, of the ring.

In the present case, the ring being nearly rectangular in cross-section, it was found that if μ_m and H_m represent strictly corresponding values of permeability and field, while μ and H represent approximately corresponding values as calculated in the ordinary way, then

$$\mu_m = \cdot 996\mu \quad \text{and} \quad \mathrm{H}_m = 1\cdot 006\mathrm{H}.$$

That is, values of μ and H calculated in the ordinary way would require to be reduced 0·4 per cent. and increased 0·6 per cent., respectively, in order to give the true corresponding values of permeability and field intensity.

The cross-section of the ring is frequently a rectangle terminated by semicircles, and we can then suppose the ring to be made up of a circular and a rectangular part. To complete the calculation in this case, according to the method just described, it is necessary to find the expressions for μ and H in the case of a ring of circular cross-section.

This is easily accomplished, since, as will be seen, in this case

$$\int \mathrm{H}\, ds = 4\pi \mathrm{N} i \left\{ r_2 - \sqrt{r_2^2 - r_1^2} \right\}$$

and

$$\int \mathrm{H}^2\, ds = 8\pi \mathrm{N}^2 i^2 \left\{ \left(r_2 / \sqrt{r_2^2 - r_1^2} \right) - 1 \right\},$$

where r_1 is the radius of the circular cross-section, r_2 is the mean radius of the ring, and N and i are the number of turns and the current, respectively, in the ring primary.

It may be noticed that the method of calculating corresponding values of μ and H, just described, would probably always give more accurate values than the ordinary method, even if the relation between μ and H, over a considerable range, were only expressible in the form

$$\mu = a + b\mathrm{H} + c\mathrm{H}^2 + \ldots,$$

for in many cases the assumption, that within the limits of H experienced in the ring a linear relation between μ and H is fulfilled, would not lead to appreciable error. All the values of permeability given later have been calculated according to this method.

§ 4. There is a further source of inaccuracy in the ordinary method of measuring permeability, of which the effects are usually small, but can on occasion become quite noticeable. It may be of interest to describe a method of procedure by which such effects can be eliminated almost entirely.

In the usual way of measuring permeability by the ballistic method the galvanometer circuit includes, in addition to the ring secondary, one of the two coils of an inductor not containing iron. The convenience of this arrangement arises from the fact that by its use measurements of resistance are avoided which otherwise would be necessary owing to the fact that the total flow of electricity in a circuit, in which a given change of induction is produced, depends upon its resistance. The method is especially convenient when, as in experiments of the kind described in this paper, the resistance of the secondary circuit has a succession of different values. But, unless certain precautions are taken, values of the permeability determined in the way just indicated are frequently liable to quite appreciable error owing to the effect of hysteresis in the ring secondary.

The quantity of electricity indicated by the galvanometer throw, when a current is established in the primary either of the inductor or of the ring, is a measure of the total change of induction in the secondary circuit. When a current is established in the primary coil of the ring the total change of induction in the secondary of the inductor is zero and the galvanometer throw therefore indicates the total change of induction in the ring secondary. But when a current is established in the primary of the inductor, the resulting total change of induction in the secondary circuit, indicated by the galvanometer throw, does not strictly represent the change of induction in the secondary of the inductor alone, because, owing to hysteresis, the total change of induction in the ring secondary is not zero. The induced current in the secondary, rising from zero to a maximum value and then again falling to zero, causes the iron in the ring to be subject to a magnetic force varying in the same way. In consequence the iron is left magnetised and the total quantity of electricity which circulates in the secondary circuit is less than would have been the case if there had been no hysteresis by an amount depending on the particular sample of iron and upon the magnitude of the changing field to which it is subjected in the way described.

The following numbers will serve to show the relative importance of the effect in question in the case of the experiments herein described. The meteoric iron ring was demagnetised by the method of continued reversal and diminution, and a current was then established in the primary of the inductor. This caused a galvanometer throw of 6·35 centims. The current was then broken and a deflection of 6·25 centims. was obtained in the reverse direction. The current was then again made and broken, and the respective throws were 6·3 centims. and 6·25 centims. The whole process was then repeated and the observed throws were 6·35, 6·15, 6·25 and 6·25 centims. The ring secondary was next cut out of the circuit and replaced by an exactly equal secondary containing no iron. On now making or breaking the current in the inductor primary the galvanometer throw was 6·43 centims.

The artificial nickel-iron ring showed a similar behaviour, but the differences between the various throws were much smaller than in the case of the meteoric iron, just as the observed hysteresis effect was much less.

The interpretation of these results is, of course, simple. The throw was greatest when the ring secondary was replaced by an equal resistance containing no iron because of the absence of hysteresis. This throw is that required for the correct calculation, in the usual way, of the value of the induction in the iron from which the permeability is deduced. The throw obtained on first completing the inductor primary circuit, after demagnetisation of the iron ring, was greater than the subsequent throws, which were practically equal, for a reason which is immediately obvious on consideration of the form of the curve showing the change of induction in an iron ring when subjected to a cyclic field.

Assuming the ring to be demagnetised, the effect of the transient current in its secondary when the inductor primary circuit is established is to change the induction in the iron in the way represented by the curves Ob_1, b_1b_2. The final induction in the ring secondary is indicated by Ob_2 and the magnitude of this ordinate is a measure of the difference between the first throw after demagnetisation and that obtained from a similar circuit containing no iron. When the current in the inductor primary is broken, the induction in the ring secondary changes in a way represented by $b_2b_3b_4$, and the line b_2b_4 represents the total change of induction in the ring secondary during the second step. Similarly b_4b_2 represents, approximately, the total change of induction when the inductor primary circuit is again completed, and so on. The length of b_2b_4 being approximately double that of Ob_2, the effect of hysteresis is more pronounced in the second and succeeding throws than in that first observed after demagnetisation.

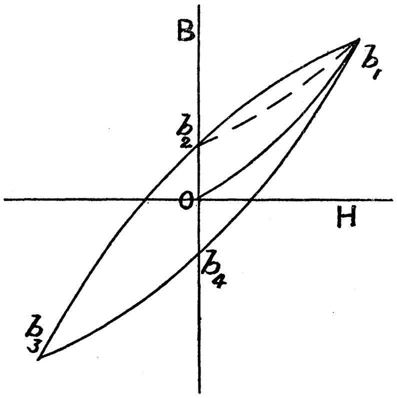


Fig. 6.

Assuming this to be the correct interpretation of the results, there follows at once a method of eliminating the effect of hysteresis directly without substituting for the ring secondary an equivalent resistance not containing iron. Suppose that, after demagnetising, the inductor primary circuit is completed. This causes a galvanometer throw which need not be recorded and leaves the induction in the ring secondary in the state represented by Ob_2. Now open the secondary circuit and then open the inductor primary circuit. Now close the secondary circuit again. The induction in the ring secondary will still be represented by Ob_2. Finally complete the inductor primary circuit again and observe the galvanometer throw. This throw will correspond truly with the change of induction in the inductor secondary and will be free from the effect of hysteresis in the secondary of the ring. This follows because the total induction in the ring secondary will be practically the same when the transient current has ceased as it was before the inductor primary circuit was completed for the second time. The induction in the ring will have changed in the way represented by the dotted curve b_2b_1 and by the full curve b_1b_2, *i.e.* its value at the end will be practically the same as at the beginning, viz., Ob_2.

This argument was verified by direct observation. The throw obtained by the method just described was indistinguishable from that obtained on replacing the ring secondary by an equivalent resistance not containing iron.

§ 5. The possible effects of external fields, constant or variable, existing during the measurements remain to be considered.

(*a*) The majority of the permeability measurements described were made while using magnetising fields comparable with that of the Earth, and it might seem that the observations could be influenced appreciably by the presence of the latter field.

Assuming the ring to be placed with its axis of figure in the direction of the Earth's field, it is of course seen at once that the effect of the external axial magnetising force upon the magnetic state of the ring is greatly diminished, owing to the shortness of the ring in the direction of its axis, by the demagnetising force which results from the magnetisation of the ring by the field. But it might be expected that if this axial field were such that it produced an intensity H_a within the ring, appreciable in magnitude compared with the intensity H of the magnetising field due to the ring primary, its presence would materially affect the amount of induction observed on establishing the field H.

(*b*) Another source of possible error, more likely to be serious in the measurements at the higher temperatures, was the field due to the current in the coil by which the ring was heated. Thus, to take a particular case, the current in the ring primary for permeability measurements was about 0·16 ampère; whilst in the bifilarly wound heating coil surrounding the ring a current of more than 2 ampères was required in order to keep the temperature of the ring at 700° C. It might seem therefore that if the bifilarity were not perfect, the permeability measurements, with a field corresponding to 0·16 ampère, taken at ordinary temperatures, would not be exactly comparable with those taken at high temperatures under the influence of the same primary field.

It was impossible of course to make the bifilarity perfect in practice. The following numbers, obtained by means of a ring wound as described later, serve to show the degree of approximation to bifilarity attained. A current of 0·23 ampère in the ring primary gave an inductive throw of 25·0 centims. of the galvanometer in the secondary circuit. A current of 0·66 ampère in the heating coil gave a throw of 0·48 centim. Hence the ratio of the fields produced by the same current in the primary and in the heating coil respectively would be approximately 150 : 1. Thus, assuming proportionality between induction throws and corresponding fields, the field due to the heating coil when the steady current was 2 ampères would be roughly $\frac{1}{15}$ of that used in the permeability observations.

§ 6. To find how far effects arising from either of the causes enumerated above were likely to influence the measurements, subsidiary experiments were made upon a wrought-iron ring of the same dimensions as the meteoric ring. These experiments showed that neither the influence of the Earth's field nor want of bifilarity in the heating coil would produce appreciable effect upon the form of the temperature-permeability curves, for a constant field, determined in the way described in the paper. A primary, a secondary, and a tertiary—the latter to represent a unifilar heating coil—were wound upon the wrought-iron ring. The ring was then placed at the centre of a large solenoid, so that its axis of figure coincided with the axis of the solenoid. By means of this "axial solenoid" a field of any desired magnitude could be produced in the direction of the axis of the ring.

The ring was taken through a succession of cycles under different conditions of steady current in the axial solenoid and in the tertiary coil. The demagnetisation of the ring previous to the determination of each cycle was performed in the ordinary way by the method of continuous reversal and diminution of a current in the ring primary.

The ordinary permeability-hysteresis cycle, with no current in the axial solenoid or in the ring tertiary, was first obtained. Cycles were then performed with currents of different magnitude in the axial solenoid. The axial field with the greatest current used was about 25 C.G.S. units. It was found that if this field was established *before* the demagnetisation process was performed, the permeability and hysteresis curves subsequently obtained were practically identical (for both directions of the axial solenoid field) with those of the "ordinary cycle." It was only when the axial field was established *after* demagnetisation that a perceptible difference in the forms of the curves could be noted.

Similar results were obtained with a steady current in the tertiary coil, the current in the axial solenoid being zero, and also with the axial solenoid and tertiary fields acting simultaneously.

SECTION III.—ARRANGEMENT OF THE APPARATUS FOR MEASUREMENTS OF PERMEABILITY OVER A WIDE RANGE OF TEMPERATURES.

§ 1. The method of carrying out the permeability measurements over a wide range of temperatures differed little from well-known methods, and needs only a very brief description. The current in the heating circuit was observed by means of a Weston ammeter reading to 5 ampères, and was derived from the main supply—of which the voltage (continuous) was about 100; it was regulated by means of incandescent lamps, of variable number, arranged in parallel, and by bare wire resistance boards of the ordinary type. The resistances of the ring secondary and primary were measured by means of a previously calibrated Callendar and Griffiths bridge. The demagnetisation circuit contained a shunted voltmeter similar to that used in the primary circuit (see below), and the current strength was varied by means of wire resistances and a zinc sulphate trough. The inductive effects in the secondary circuit were measured by the apparatus already mentioned in connection with the preliminary experiments. The primary currents were measured by a Weston voltmeter (reading to 5 volts) shunted by a resistance of 10 ohms, which was not heated appreciably by the currents traversing it. It was found, by calibration, that a deflection of 50 scale divisions on the voltmeter (30 divisions = 1 volt) corresponded very nearly to a current of 0·017 C.G.S. units in the primary circuit. The adjustment of the primary current to a constant value at different temperatures, notwithstanding variation in the resistance of the ring primary owing to temperature change, was accomplished by means of resistance boxes, and a stretched wire of variable length included in the primary circuit.

§ 2. The temperature of the ring at the time of each observation of permeability was deduced from the resistance of the secondary. The method of deduction was to assume the relation

$$R_\theta = R_0 (1 + a\theta - b\theta^2)$$

between the resistance of the ring secondary and its temperature. The values of a and b were determined, in the case of the meteoric iron, by constructing a platinum thermometer out of wire taken from the same reel as the secondary, and in the other cases by constructing a thermometer out of the secondary coil itself, re-wound for that purpose. In each case the resistances of the thermometer at the freezing- and boiling-points of water, and at the boiling-point of sulphur, were taken in the usual way, a previously calibrated bridge being used for the purpose.

Each of the three platinum thermometer observations, with each of the wires used, of corresponding values of temperature and resistance, was estimated to be measured correctly within 0·1 per cent. With this degree of accuracy the probable error in the estimation of a was about 1 per cent., and in the estimation of b about 15 per cent. The error in the estimation of a temperature of 700° C. would, under these circumstances, amount to about 5° C. The values of the higher temperatures given in the subsequent tables may therefore be regarded as subject to an error certainly less than 10° C.

§ 3. In the first experiments the heating coil was placed between the primary and secondary coils, but in the later experiments the heating coil was wound outside the other two. The method of winding was as follows:—Two strips of mica were cut of such size that one could be bent into the form of a hollow cylinder fitting inside the ring, and the other into a cylinder fitting outside. The depth of these cylinders was slightly greater than that of the ring, and equidistant notches were made along each edge of the two cylinders. The distance between consecutive notches in each edge was proportional to the circumference of each cylinder, and their number was equal to the number of turns of wire it was proposed to wind round the ring. Two annuli of mica were next cut of such size as to fit closely between the mica cylinders. The cylinders and annuli were then fitted over the ring and were kept in position finally by the windings of platinum wire which enveloped them. The second and third coils were wound in the same way as the first. The terminals of each coil were brought out through holes pierced in one of the annuli serving for the winding and insulation of the coil wound over it. In this way it was found to be easy, after practice, to wind the permeability coils and the heating coil fairly uniformly and with very perfect insulation from one another—nothing but mica being used in the insulation. In the earlier experiments, layers of thin asbestos ribbon were wound between each mica insulation, partly because under these circumstances it was easier to keep the mica of the next coil in position during the winding of that coil, and partly to diminish the possibility of short-circuiting between consecutive coils. The winding of the coils being completed, the ring was placed upon a sheet of mica through which holes for the passage of the terminals of the coils were pierced. This sheet of mica was then laid on a small wire tripod, which rested on a block of hard wood about 5 centims. thick. This block of wood was also supported on a tripod, and thick insulated copper leads projected through it vertically below the ring. The outer ends of these leads were provided with binding screws, while the inner end of each was connected to a coil terminal. (There were altogether eight of these leads, six for the coil terminals and two for the short platinum loop used for compensation when determining the temperature of the ring secondary by measuring its resistance.)

A large inverted beaker was placed on the top of the block of wood, and rested in a deep circular groove about half-filled with mercury. By this means the ring, which was nearly at the centre of the beaker, was kept out of contact with the outside air. There were, however, two glass tubes, leading from outside into the beaker through the wooden base, by means of which the air within the beaker could be withdrawn and replaced by dry air or other gas. The beaker was kept in a fixed position with respect to the baseboard by an asbestos disc placed above it and attached by wires to the board.

A rectangular cover of asbestos board was fitted on the top of the wooden baseboard, and by this means a layer of air about 5 centims. thick was enclosed between the beaker and the outer atmosphere. In most of the experiments a smaller asbestos box was placed inside the beaker and enveloped the ring.

§ 4. In this apparatus, with a given current in the heating coil, the temperature usually became practically constant in less than an hour, but in most cases the permeability measurements were not taken until about two hours after the heating was begun.

The relation between the steady temperature in the apparatus and the current required to produce it is interesting. It is shown for each of four series of experiments in fig. 7.

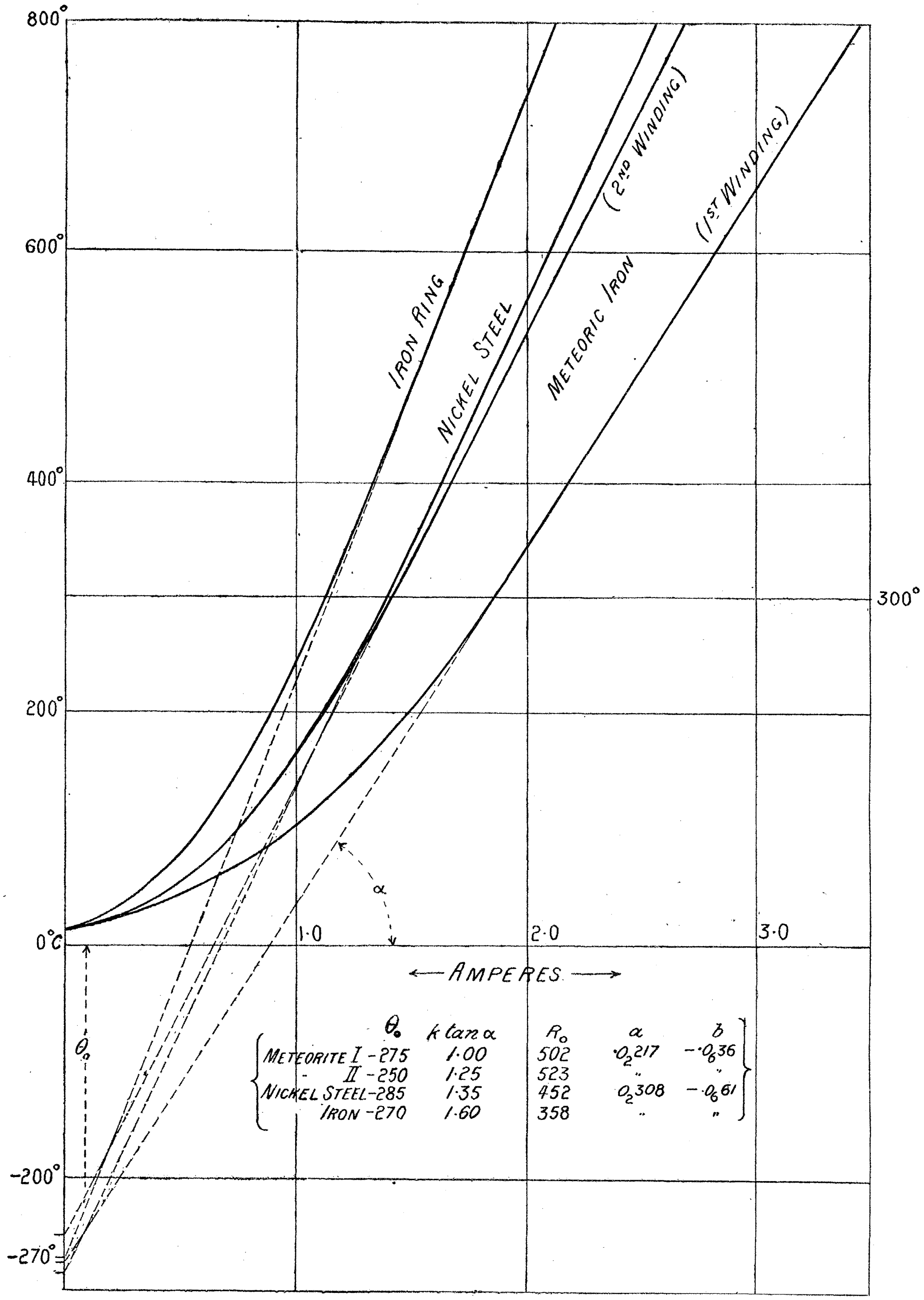


Fig. 7. Curves showing relation between heating current and temperature for each ring.

The conditions under which the heating took place differed appreciably in the different series. For example, in the experiments with meteoric iron (first winding) there was no asbestos box surrounding the ring within the beaker, and the heating coil was between the other two. But in every case, for temperatures above 300° C. and below 800° C., the relation between temperature and current is almost exactly linear and can be expressed as

$$(\theta+\theta_0) = m\text{C},$$

where m is the tangent of the angle which the θc line makes with the current axis, and θ is the temperature reckoned from 0° C. The values of m for the four series of experiments are in the approximate ratio :—

Meteoric ring (1st winding)	1
,, ,, (2nd winding)	1·25
Nickel-iron ring	1·35
Iron ring (see § 6, p. 39 below) . . .	1·60

whilst the corresponding values of θ_0 are 275°, 250°, 285°, and 270° respectively. From the latter numbers the curious result follows that the absolute temperature, between the limits specified, was directly proportional to the current producing it. In fact, it was seen from the data that the actual temperature between 300° C. and 800° C. produced by any current could be obtained correctly within a few degrees by determining a single temperature corresponding to a single given current, and then assuming in further experiments that the absolute temperature would be proportional to the current applied.

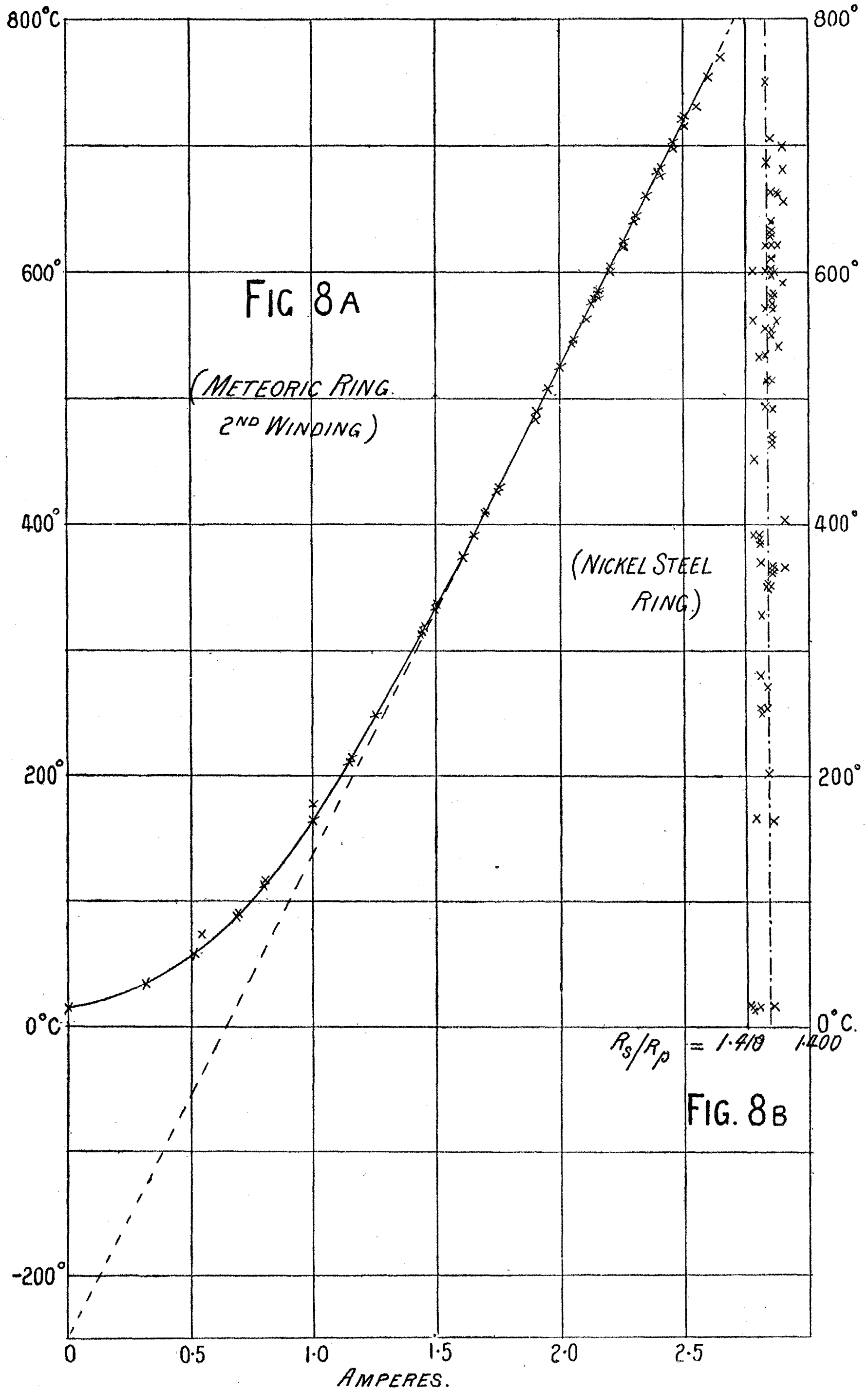
There were only a few measurements at temperatures above 800° C. The data seem to show that the θc curve slowly departs from linearity and becomes concave to the axis of temperature.

Below 300° C. the θc curve becomes convex to the axis of current. It would thus appear that the curve possesses an ill-defined point of inflexion somewhere between 300° C. and 800° C.

For temperatures below 100° C. the relation between θ and c is approximately parabolic.

§ 5. In practically all of the observations the resistance of the ring primary was measured in addition to that of the secondary. Corresponding values of the heating current were also tabulated. As it is impossible from want of space to give these data in the tables printed on pp. 42 to 47, the specimen curves shown in fig. 8 are reproduced to exhibit at a glance the degree of consistency attainable in the measurements. Fig. 8A, exhibiting the results of observations extending over three months, shows the extent to which the same heating current produced the same steady temperature on different occasions. Fig. 8B shows similarly the constancy of the ratio of the resistances of the primary and secondary at different steady temperatures, both coils being inside the heating coil and constructed of wire from the same reel.

§ 6. The dimensions of the rings used have already been given. In the first winding of the meteoric ring there were 34 turns of wire in the primary and 55 turns in the secondary, the diameters of the wires being 0·039 centim. and 0·033 centim. respectively. In the second winding the numbers of turns were 31 and 51 respectively. In the case of the nickel steel ring the primary had 30 turns and the secondary 51, and each consisted of wire 0·032 centim. in diameter.



The constants (calculated by the method already described) by means of which corresponding values of μ and H can be obtained in absolute units from the observations are, in the case of the meteoric iron ring (first winding), given approximately by the equations

$$\mu = 135{\cdot}5 \times i_o d/i_p d_o,$$

$$H = 28{\cdot}0 \times i_p,$$

in which d is the inductive effect (proportional to the sine of half the angle of throw) in the secondary circuit when the current i_p is established in the ring primary, and d_o is the corresponding inductive effect produced by a current i_o in the standardising solenoid. The corresponding constants in the other cases are :—Meteoric ring (second winding), 160·5 and 25·5; nickel steel ring, 166·4 and 24·8. (If the values of the constants were calculated in the ordinary way, the first would be about 0·6 per cent. higher and the second about 0·75 per cent. lower in each case.)

In the earlier experiments, of which the object was to examine how, for a constant value of H, μ varied with the temperature, the value of H chosen was 0·476, as being near the value of the Earth's field and corresponding with a convenient deflection—50 divisions—on the shunted voltmeter. In the experiments after the second winding of the meteoric ring the value of H used was unintentionally lower, viz., 0·433 instead of 0·476. This happened because the shunted voltmeter reading used was still 50 divisions, although the ring constant had become 25·5 instead of 28·0. In the experiments with the nickel steel ring, and also in some comparison experiments with a ring of nearly pure iron (of which further description is omitted for the present), the primary current was, in each case, adjusted so as to give a field as nearly as possible equal to that used with the meteoric ring after the second winding, and corresponded in each case to a field of 0·434 C.G.S. unit.

Owing to the difficulties of winding under the conditions necessary for work at high temperatures, the degree of accuracy of the constants calculated as above is not as great as is the accuracy, relative to one another, of the numbers proportional to μ. Consequently the actual values of the latter are not given, in most cases, in the tables showing the results of the measurements; but only the values of $i_o d/i_p d_o$, which are numbers proportional to them and which represent the direct results of the observations.

§ 7. In some cases, however, the actual values of the permeability, and not merely their relative values, are required approximately for the purposes of comparison. Thus the permeability of the meteoric iron was carefully determined at the conclusion of the experiments, after it had been subjected to repeated heatings, as described below, including a final annealing at 900° C. The permeability was also determined before the material received any thermal treatment beyond the slight warming that took place when the ring was cut out of the original block. The ring windings in these initial and final experiments were such that relatively accurate measurements could be made without difficulty. The resulting data show that, in round numbers, for H = 0·35 the permeability before heating was 120, while after heating it was 150; for H = 0·52 the corresponding numbers were 130 and 160. Hence there is no doubt that the permeability in weak fields was considerably higher after the thermal treatment than before.

The preliminary experiments (first winding) over a considerable range of temperatures show that the permeability at ordinary temperature can vary between considerable limits depending upon the thermal history of the specimen. Thus the greatest permeability observed was about 50 per cent. greater than the lowest. The approximate values of these extreme permeabilities were calculated to be 300 and 200 approximately (H = 0·48).

In the later experiments (second winding) the highest permeability observed at ordinary temperatures (H = 0·433) was about 278 (= 1·73 × 160·5), while the lowest was about 129 (= 0·8 × 160·5). Hence it is seen that the highest permeability at ordinary temperatures is more than double the lowest, and that the lowest corresponds approximately with the permeability of the meteorite in its original state.

From the same experiments it is seen further that the average value of the permeability at ordinary temperatures, after cooling from about 850° C., lies between the above values and is about 167 (= 1·04 × 160·5). This number is seen to be approximately correct from the results of the final measurements after annealing at 900° C., which gave $\mu = 154$ for H = 0·36, and $\mu = 164$ for H = 0·52.

The final measurements, after annealing at 900° C. in the case of the nickel steel, show also that the constant 166·4, calculated for the approximate conversion into absolute values of the data obtained during measurements over a wide temperature range, is not seriously in error. Thus the final measurements give $\mu = 179$ for H = 0·37, and $\mu = 184$ for H = 0·53, after annealing at 900° C.; while the earlier experiments fix the limits between which the permeability may lie after heating to about 800° C. as 174 (= 1·05 × 166·4) and 208 (= 1·25 × 166·4) for H = 0·43.

SECTION IV.—PERMEABILITY MEASUREMENTS BETWEEN 0° C. AND 850° C.

By S. W. J. SMITH *and* J. SATTERLY, *B.Sc.*

§ 1. In performing the experiments, of which the results are tabulated below, it was borne in mind that the permeability at a given temperature might not be free from a time effect. Hence, since in all probability the time rate of change of permeability at a given temperature would diminish fairly rapidly, and might become relatively small at the end of a comparatively short time, the ring was kept as long as was possible without prolonging the experiments unduly at a given temperature before the measurements were taken. Experience showed that consistent results were obtained if the material was allowed about two hours in which to acquire the temperature at which the measurements were to be made—the heating current being gradually increased to the necessary value. After the temperature, as shown by the resistance measurements, had remained practically constant for about half an hour, the throw due to induction in the standardising current was observed. The throws due to induction in the ring were measured after this, because they would be affected more by want of steadiness in the state of the ring. Finally the throw due to the standardising solenoid was checked and the temperature of the ring again noted.

In some of the later experiments, in which the time at disposal was more limited and it was necessary to get observations at a comparatively large number of points in succession, it was found that, if precautions were taken to reduce the rate of loss of heat by the ring, consistent results could be obtained, at moderately high temperatures, within an hour after the closing of the heating current circuit. In such cases the question whether there was a time effect was relatively unimportant.

§ 2. The majority of the temperature permeability measurements were performed under the influence of a constant field. In the earlier measurements the variation of μ with H was observed for values of H between 0·4 and 0·8 C.G.S. units; but the results of these observations, which are omitted from considerations of space, seemed to show that the information to be derived from them was not likely to be much greater than that derived from measurements under a constant field. The experiments were performed in the intervals between other work, and it would have been impossible to determine BH curves satisfactorily, over a wide range of values of H, in the time at disposal. It was therefore decided to aim only at fixing as accurately as possible, in the time available, the relation between the permeabilities at different temperatures, keeping the intensity of the field unchanged. The demagnetisation of the ring, observation of the inductive effect, and measurement of the resistance of the ring secondary were repeated in every case (sometimes as often as ten times) till there seemed no room for doubt that truly corresponding values of induction and temperature had been obtained.

§ 3. The data obtained from the experiments with the different materials are collected in the tables which follow.

METEORIC IRON (1st Winding).

First Experiments.

Number of experiment.	Temperature.	$\frac{\mu}{135\cdot 5}$ (H = 0·475) C.G.S.
	° C.	
a	16·5	1·615
b	158	1·54
c	272	1·515
d	464	2·29
e	678	4·37
f	717	1·52
g	752	0·26
h	816	—
i	589	0·13 (H = 0·71)
k	15	1·56
l	621	4·58
m	669	4·71
n	551	2·96 (H = 0·54)

At the point numbered *h*, temperature 816°, the induction throw had become imperceptibly small. The current was lowered gradually, causing gradual fall of temperature, and observations were made continuously to find when perceptible ferromagnetism reappeared. There was a perceptible throw, when the resistance showed a temperature of 591°, corresponding to a permeability, on the above scale, of 0·05. At 589° the permeability was approximately 0·13 for a field strength of 0·71 C.G.S. units.

The experiment *n* was not strictly comparable with the others, as the apparatus had been partially dismantled in the month intervening between this experiment and that numbered *m*.

METEORIC Iron (1st Winding).

Later Experiments.

Number of experiment.	Temperature.	$\frac{\mu}{135\cdot 5}$ (H = 0·475) C.G.S.	Number of experiment.	Temperature.	$\frac{\mu}{135\cdot 5}$ (H = 0·475) C.G.S.
	° C.			° C.	
1	12	2·065	10	173	1·73
2	174	1·805	11	388	1·695
3	315	2·025	12	102	1·715
4	463	2·01	13	247	1·655
5	574	3·60	14	286	1·675
6	12·5	1·91	15	336	1·68
7	310	1·985	16	305	1·655
8	461	2·055	20	14	1·80
9	572	3·50	21	309	1·715

METEORIC Iron (1st Winding) (continued).

Later Experiments.

Number of experiment.	Temperature.	$\frac{\mu}{135\cdot 5}$ (H = 0·475) C.G.S.	Number of experiment.	Temperature.	$\frac{\mu}{135\cdot 5}$ (H = 0·475) C.G.S.
	° C.			° C.	
22*	638	4·4	45	578	0·58
23	576	0·58	46	640	0·88
24	528	1·805	47	575	0·63
25*	664	4·85			
26	552	1·79	48*	18	1·495
27	503	1·67	49*	20	1·555
28	480	1·63			
29	17	1·595	50	465	1·405
30*	314	1·725	51	576	2·81
31	545	1·855	52	466	1·72
32	528	1·88			
33	17	1·625	53*	18·5	1·995
34	168	1·545	54	20	1·665
35	20	1·625	55	5	1·54
36	284	1·57			
37	576	3·52	56	20	1·54
38	23	2·31	57	-10	1·545
39	—	2·175	58	—	—
40	163	1·925	59	18·5	1·57
41	307	2·05	60	—	—
42	386	2·04	61	18	1·55
43	434	1·85	62	—	1·545
44*	464	2·125	63	—	1·55

* After each of the experiments marked by an asterisk the ring was raised to a temperature of about 830° C., at which its permeability became too small to be measurable.

METEORIC Iron (2nd Winding).

First Experiments.

Number of experiment.	Temperature.	$\frac{\mu}{160\cdot 5}$ (H = 0·433) C.G.S.	Number of experiment.	Temperature.	$\frac{\mu}{160\cdot 5}$ (H = 0·433) C.G.S.
	° C.			° C.	
1	17	1·405	11	18	1·095
2	137	1·335	12	21	1·08
3	433	1·465	13	821	—
4	11	1·49	14	587	0·72
5	18	1·67	15	537	0·93
6	588	2·69	16	475	0·96
7	—	1·63	17	19	0·97
8	734	3·37 ?	18	923	—
9	—	1·26			
10	798	—			

The ring was heated to 522° C. between (4) and (5); but the permeability was not observed.

After (17) the apparatus was re-arranged and the ring was supported in the beaker inside an asbestos box slightly larger than itself. The rate of escape of heat at a given temperature was much reduced by the addition of this box, as is seen by comparison of (10) and (18), in which the same heating current was used. In the earlier experiments the only covering of the ring, inside the beaker, was a layer of asbestos paper.

METEORIC Iron (2nd Winding).

Later Experiments.

Number of experiment.	Temperature.	$\frac{\mu}{160\cdot5}$ (H = 0·433) C.G.S.	Number of experiment.	Temperature.	$\frac{\mu}{160\cdot5}$ (H = 0·433) C.G.S.
	° C.			° C.	
19	19·5	1·305	60	410	1·40
20	722	2·36	61	582	2·97
21*	769	0·087	62	676	3·49
22	575	0·68	63	11	1·085
23*	13	1·04	64	428	1·61
24	590	0·40	65	600	2·99
25	583	0·615	66	658	3·41
26	604	0·92	67	12	1·18
27	697	1·53	68	754	0·90
28	603	1·075	69	681·5	1·12
29*	—	0·98	70	619	0·99
30	588	0·68	71	526	0·72
31	700	1·38	72*	14·5	0·80
32	602	0·94	73	625	0·06
33	696	1·38	74	546	0·96
34	602	0·95	75	643	1·935
35	13	0·93	76	545	1·25
36	584	0·73	77*	13·5	0·945
37	644	1·13	78	545	1·085
38	710	1·505	79	649	2·10
39	13·5	0·96	80	552	1·36
40	584	0·52	81*	15	1·04
41	676	1·31	82	493	0·995
42	730	1·57	83	584	1·79
43	577	0·68	84	489	1·195
44	12·5	0·91	85	579	1·835
45	693	2·86	86	489	1·215
46	729	1·845	87	18	1·125
47	769	0·54	88	12	1·135
48	13	0·83	89	112	1·13
49	681	2·76	90	216	1·18
50	715	1·96	91	334	1·36
51	639	1·85	92	449	1·495
52	524	1·12	93	621	2·98
53	337	0·87			
54	about 105	0·80	94	12·5	1·47
55*	12	0·83	95	625	2·91
56	561	0·78	96	450	1·45
57	524	0·98	97	333	1·41
58	434	0·95	98	212·5	1·265
59	12·5	0·98	99	118	1·23

* After each of these experiments the temperature of the ring was raised to about 850° C.

METEORIC Iron (2nd Winding) (continued).

Later Experiments.

Number of experiment.	Temperature.	$\frac{\mu}{160\cdot5}$ (H = 0·433) C.G.S.	Number of experiment.	Temperature.	$\frac{\mu}{160\cdot5}$ (H = 0·433) C.G.S.
	°C.			°C.	
100	12	1·465	149	15·5	1·560
101	700	3·58	150	165	1·555
102	661	2·71	151	389	1·555
103	507	1·37	152	249	1·505
104	9·5	1·11	153	15	1·525
105	667	3·16	154	722	3·065
106	605	2·715	155	601	1·915
107	480	1·39	156	715	2·645
108	394	1·21	157	17	0·96
109	178	1·185	158	719	2·81
110*	14·5	1·21	159	602	1·885
111	16	1·035	160	718	2·52
112	131	1·03	161	20	0·88
113	315	1·195	162	720	2·71
114	429	1·28	163	679	2·36
115	16·5	1·255	164	622	2·065
116	429	1·27	165	678	2·58
117	544	2·25	166	730	2·165
118	623	2·83	167	16	0·83
119	16	1·725	168	719	2·495
120	33·5	1·725	169	680	2·40
121	57·5	1·715	170	624	1·97
122	89·5	1·685	171	15·5	0·82
123	16·7	1·71	172	722	2·675
124	114	1·72	173	661	2·315
125	166	1·73	174	602	1·87
126	212	1·79	175	659	2·41
127	15·7	1·69	176	15	0·835
128	261	1·865	177	723	2·735
129	317	1·925	178	623	2·01
130	390	1·835	179	526	1·225
131	425	1·49	180	622	2·10
132	482	1·645	181*	14·7	0·845
133	17	1·66	182	587	0·965
134	391	1·56	183	604	1·20
135	319	1·50	184	624	1·42
136	17·5	1·60	185	680	2·11
137	430	1·485	186	622	1·62
138	375	1·315	187	564	1·24
139	250	1·465	188	16·7	0·845
140	19·5	1·575	189	430	1·39
141	624	2·815	190	683	3·10
142	427	1·345	191	432	1·085
143	390	1·320	192	681	3·06
			193	434	1·055
144	15	1·565	194	683	3·07
145	89·5	1·55	195	18	0·95
146	334	1·80	196	625	2·76
147	408	1·575	197	73·5	1·165
148	334	1·475	198	16	1·245

* After each of these experiments the temperature of the ring was raised to about 850° C.

Nickel Steel.

Number of experiment.	Temperature.	$\frac{\mu}{166\cdot4}$ (H = 0·434) C.G.S.
	°C.	
1	3·5	1·195
2	15·5	1·215
3	163	1·385
4	402	1·365
5	538	2·465
6	15	1·41
7	548	2·58
8	698	1·81
9	770	—
10	639	0·44
11	533	1·89
12	280	1·39
13	12·5	1·125
14	493	1·935
15	641	4·90
16	13	1·235
17	251	1·65
18	386	2·275
19	13·5	1·265
20	789	0·05
20*a*	799	0·015
20*b*	811	—
21	671	0·043
22	573	2·40
23	514	2·395
24	387	1·85
25	253	1·615
26	15·5	1·255
27	252	1·575
28	367	1·80
29	470	1·97
30	532	2·84
31	594	4·45
32	14·5	1·415
33	489	2·685
34	608	4·99
35	13·5	1·43
36	706	2·61 2·42
37	639	2·77
38	554	2·185
39	468	1·60
40	368	1·49
41	202	1·165
42	13	0·95
43	365	1·355
44	574	3·65
45	14	1·095
46	166	1·315
47	384	1·92
48	570	3·74

Number of experiment.	Temperature.	$\frac{\mu}{166\cdot4}$ (H = 0·434) C.G.S.
	°C.	
49	14	1·145
50	749	0·395
51	655	0·76
52	571	1·705
53	466	1·49
54	367	1·38
55	272	1·245
56	106	1·06
57	14	0·97
58	366	1·37
59	598	4·03
60	388	1·875
61	595	4·09
62	389	1·96
63	14	1·11
64	603	4·26
65	516	2·925
66	349	1·875
67	12	1·11
68	603	4·39
69	613	4·62
70	13	1·10
71	624	4·99
72	642	5·46
73	12·5	1·045
74	671	5·72
75	689	4·53
76	558	2·90
77	454	1·80
78	312	1·39
79	14	0·85
80	—	0·845
81	13	0·845
82	328	1·39
83*	663	5·24
84	554	2·55
85	14·5	0·945
86	558	2·985
87	662	5·95 5·84
88*	14·5	0·925
89	602	2·65
90	683	4·60 4·52
91	597	3·09
92	664	4·34
93*	10	0·765
94	624	1·88 1·91
95	686	3·005
96	620	2·33

* After each of these experiments the temperature of the ring was raised to about 850° C., at which the permeability was imperceptible.

NICKEL Steel (continued).

Number of experiment.	Temperature. °C.	$\frac{\mu}{166\cdot4}$ (H = 0·434) C.G.S.	Number of experiment.	Temperature. °C.	$\frac{\mu}{166\cdot4}$ (H = 0·434) C.G.S.
97	14	0·795	103	12	1·04
98	581	3·46	104	581	3·83
99	12·5	0·945	105	12·5	1·05
100	580	3·74	106	580	3·82
101	12·5	1·02	107	13	1·05
102	580	3·81			

In experiments 36, 87, and 90, the permeability seemed to fall, with lapse of time, from the higher to the lower value; but the temperature coefficient of μ is very large between 650° C. and 750° C.

In experiment 94 the permeability seemed to be rising gradually at 624° C.

§ 4. The series of curves, given below, figs. 9 to 22, show the results of the attempt to represent graphically, by continuous curves, the thermomagnetic properties of each material. The number of the experiment to which each point corresponds is shown in each of the curves drawn; but, because of the use made of the curves later and also because there are some relationships which cannot be represented graphically, it is necessary to state the connection between the tables and the curves at greater length than would otherwise be required.

§ 5. *Meteoric Iron* (1*st Winding*).—See fig. 9.

The sequence of all the experiments tabulated will be clearer if an account is given of the reasons why they were performed in the order shown.

The permeability at ordinary temperatures was determined, under my supervision, by Mr. W. H. N. JAMES, with the results already given (see Section II., § 2, p. 27). The experiments over a wider temperature range, after the coils had been rewound by Mr. JAMES and myself, had only extended to a few isolated measurements when it became impossible for him to take further part in the work. With a view to completing the experiments, I again set up the apparatus when time permitted and took the observations lettered *a*, *b*,...*n*, of which the record is given in the first table. The observations *a*, *b* and *c* showed the variation of μ at the lower temperatures. The region in which the permeability began to rise rapidly was marked by *d* and *e*; *f*, *g* and *h* marked the temperature range over which the permeability dropped from near its maximum value until it practically disappeared. The observations at *i* showed that the temperature lag in the reappearance of permeability, common to artificial nickel-iron alloys containing less than 25 per cent. of nickel, was shared by the

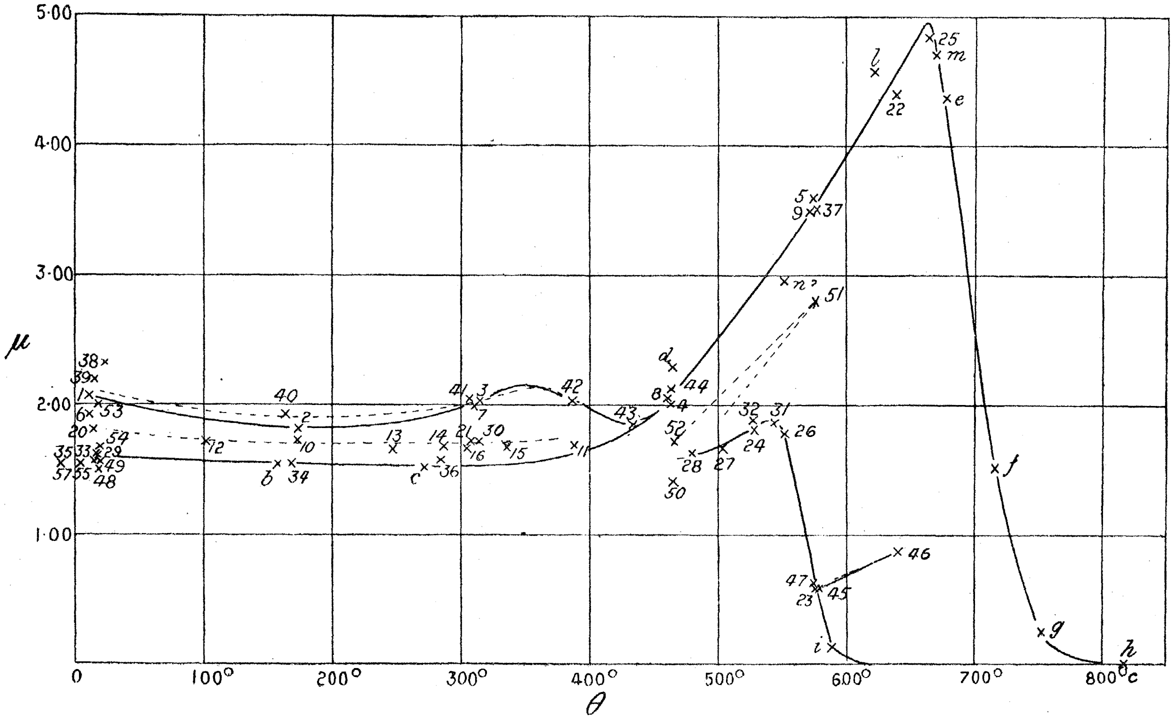


Fig. 9. Meteoric iron (1st winding).

Relation between permeability (H = 0·48 C.G.S. approximate) and thermal treatment.
C.G.S. values of μ = ordinates × 135·5 (approximate).

meteorite. The observation *k* showed that the permeability, after slow cooling from a temperature beyond the critical point, was nearly the same as that first observed. The observations *l* and *m* were next made in order to get values of μ near the temperature of maximum permeability.

After the experiments just described, no further measurements were taken until the isolated observation represented by *n* was made with the object of filling a gap, at about 550° C., in the previous observations. After being allowed to cool from the temperature just stated, the ring was left for about three months without further observation. The experiments represented by the numbers 1 to 63 were then begun. I was surprised to find that the permeability at ordinary temperature was about 30 per cent. higher than the value (*k*) last observed at that temperature, and it seemed as if the permeability had risen in that proportion in the three months during which the ring had been left undisturbed. It seemed advisable to examine whether this apparent time effect, so pronounced at ordinary temperature, was accompanied by any change in the variation of μ at higher temperatures. The experiments 2, 3, and 4, 5 showed an apparently anomalous position, with respect to one another, of the points 3 and 4. For this reason the observations at these temperatures were repeated (see 7 and 8), as was that at the higher temperature (see 9). It was found that although the permeability at ordinary temperature seemed to change appreciably, the permeabilities at 315° C., 460° C. and 575° C. (approximately) were subject to little variation under the treatment undergone.

The observations 10 to 16 were undertaken to find, if possible, how the permeability varied between 100° C. and 400° C. There seemed to be no sudden or irreversible changes; but the permeability was now intermediate between its earlier values and those observed after the lapse of 3 months. No experiments were made between those numbered 16 and 20, except to explore without success for a possible increase of permeability in the neighbourhood of 300° to 350° C.

The experiments 20 to 37 were undertaken with the object of finding again, under the apparently changed condition of the ring, the variation of permeability as the temperature was raised above the critical point, and, also, the manner in which the permeability reappeared as the ring was gradually cooled.

The observations 23, 24, and 26 to 28 seemed to show that there was an appreciable difference between the hysteresis in the reappearance of magnetism in the meteorite and that in nickel steel of similar composition examined by HOPKINSON. In HOPKINSON'S curve for a 4·7 per cent. nickel steel ($H = 0{\cdot}12$ C.G.S.) the portions of the $\mu\theta$ curve below 600° C. (for rising and falling temperatures respectively) would apparently be nearly superposable, whereas in the present case they were not. It was thought that the distance between the points 26, 24, &c., and corresponding points on the curve of rising temperatures might possibly have been less if the ring had been cooled more slowly. For this reason the observations were repeated (see 31 and 32), and the ring was kept for several hours at temperatures near 550° C., after cooling, in order to find whether a gradual rise in permeability could be detected. The value of μ at the end of two hours was, however, in each case not perceptibly different from its value after two hours more, and hence, if the change in question was actually occurring, it was of a much more gradual nature than those represented in the curves described here, and probably, also, in the curves described by HOPKINSON.

The observations 33 to 35, and also 29, showed that the state of the material (after gradual cooling from about 820° C.) was practically identical with its state at the beginning of the observations three months before. (A preliminary heating beyond the critical temperature had preceded the latter observations.)

The observation 37 showed that the permeability at 575° C. was practically the same as when heating took place from the state represented by Experiment 1, at which the permeability was much higher than at *a*, 29, 33, &c.

Thus it appeared that, although there was considerable uncertainty concerning the nature of the variation of μ with θ, especially at temperatures below 500° C., the material was not one in which the properties were continually changing in an arbitrary manner owing to gradual oxidation, to disintegration, or to some other effect increasing with time and arising possibly from an unassignable cause.

The permeability was next measured (38 and 39) after the temperature had again fallen (from 37) to that of the air. It was found now to be even greater than in Experiment 1. It thus became clear that the relatively great value of the latter was not due to a time effect lasting over three months (as was at first thought possible), but to the fact that the material had been allowed to cool uninterruptedly from a temperature of about 550° C. (see Experiment *n*). If the permeability had been measured immediately after this cooling it would apparently have been found to be as high as it was three months later.

An attempt was now made to find how the permeability of the ring in its new state altered with rising temperature. The result is shown in Experiments 40 to 44. These explained the apparently anomalous position of the points 3 and 4, which had been noticed at the time the latter were observed. The permeability varied slightly with rising temperature, falling at first and then rising. Between 300° and 400° C. it appeared to reach a maximum value, and then, beyond 400° C., it fell comparatively rapidly to a well-defined minimum value at about 435° C., beyond which the permeability quickly rose. It is obvious, therefore, from the data and the figure, that the points 3 and 4 lay on a $\mu\theta$ curve corresponding exactly with that just described. These experiments showed again that the behaviour of the material was definite, and, at the same time, that the permeability at a given temperature was strongly influenced by the previous thermal history of the material.

The effect of interrupted heating having been so pronounced, I next examined whether any noticeable effects resulted from interrupted cooling. After the ring had been heated beyond the point at which the ferro-magnetism disappeared it was allowed to cool gradually until a temperature was reached at which the ferromagnetism had begun to increase rapidly with fall of temperature. The permeability was measured at this temperature, and the ring was then heated through about 60° C. and kept at a constant temperature for about two hours, after which the permeability was again measured. The ring was then allowed to cool, and the permeability was measured a second time at the temperature at which the cooling was interrupted. The permeability rose considerably on heating, but on cooling it fell again practically to the same value as it had when the cooling was interrupted (see 45, 46 and 47). This result agreed with the qualitative diagram given by GUILLAUME as representing the behaviour of irreversible nickel steels under similar treatment (*cf.* C. E. GUILLAUME, 'Congrès International, Paris, 1900').

On cooling to the air temperature, the permeability was found to be a little lower than the lowest value previously recorded (see 48). Subsequent reheating beyond 820° C. and uninterrupted cooling restored the permeability at ordinary temperature to the normal value. Hence interrupted cooling had slightly lowered the subsequent ordinary temperature permeability (*cf.* § 7 below, p. 54, also Section VI., § 11, p. 90).

The object of the next experiments was to observe the effect of cooling interrupted at a temperature below that at which the permeability ceased to rise with falling temperature and began to diminish. The temperature chosen was about 465° C., at which the permeability was unexpectedly low, possibly because of insufficient preliminary heating (see later). On raising the temperature to about 575° C., the permeability rose rapidly, and on allowing the temperature to fall to 465° C. again it was found that, although the permeability fell considerably, it was now 25 per cent. greater than the value at this temperature when the cooling was interrupted. Subsequently, when the temperature had fallen to that of the air the permeability was much larger than it would have been if the cooling had been uninterrupted (see 53). It was, however, less than the value that would have been obtained by a further reheating to 575° C., as previously described (*cf.* 37 and 38).

The ring was now heated again above the critical temperature, and allowed to cool uninterruptedly when, as shown in the table, it showed the old permeability, at the ordinary temperature, corresponding with such treatment. (The first value, 54, was probably too high because the ring had not been allowed sufficient time to acquire a steady state.) The ring was then cooled to $-10°$ C. without showing any appreciable variation of permeability. The object of this cooling was to find whether there was any sign of the comparatively sudden increase of permeability observed by HOPKINSON in the case of a 25 per cent. nickel steel.

Finally the ring was left undisturbed for some weeks, and the permeability was found to be the same at the end as at the beginning of this period.

§ 6. The experiments just described showed that the permeability was subject to peculiar, but nevertheless definable, variation as the result of thermal treatment. Repetitions of a given process had led always to practically the same result, and hence, apart from the question of the interpretation of the data already obtained, it seemed worth while to study further, at various temperatures, those effects of interrupted heating and cooling which had been shown already, at some temperatures, to be accompanied by marked changes in the magnetic properties of the material. Thus, for example, it still remained to examine the effect of cooling from a temperature between that corresponding to the maximum permeability and that at which the permeability became imperceptible. I was anxious also to test more fully whether the remarkable reversibility between the two steep branches of the $\mu\theta$ curves, described by GUILLAUME in the case of artificial alloys, was shown by the meteorite. But at this point it became necessary, through want of time, to abandon the work or to enlist the services of another observer. Fortunately, Mr. J. SATTERLY, B.Sc., formerly a student and assistant at the Royal College of Science, volunteered to complete the examination of the meteoric iron on the lines proposed and also, if necessary, to test in a similar way a sample of artificial nickel iron, of nearly the same composition (see Section I., § 7, p. 26), which I had obtained for this purpose.

After Mr. SATTERLY had made a few preliminary observations corroborating those described above, the insulation of the ring secondary for some reason became defective, and it was decided to take off all the coils and re-wind them. The original wires were used for the primary and secondary coils, but a coil with a greater number of turns was substituted for the original heating coil.

Except for occasional assistance, nearly all the permeability observations after the second winding were made by Mr. SATTERLY.

§ 7. *Meteoric Iron (2nd Winding).*—See fig. 10, &c.

An attempt has been made, in the series of figures numbered 10 to 16, to represent the relations between the data obtained after the second winding. It required more consideration than might appear necessary at first sight to decide upon the form of some of the curves, and they may not be altogether free from such errors of interpretation as are difficult to avoid in the attempt to construct continuous curves from a set of discontinuous observations.

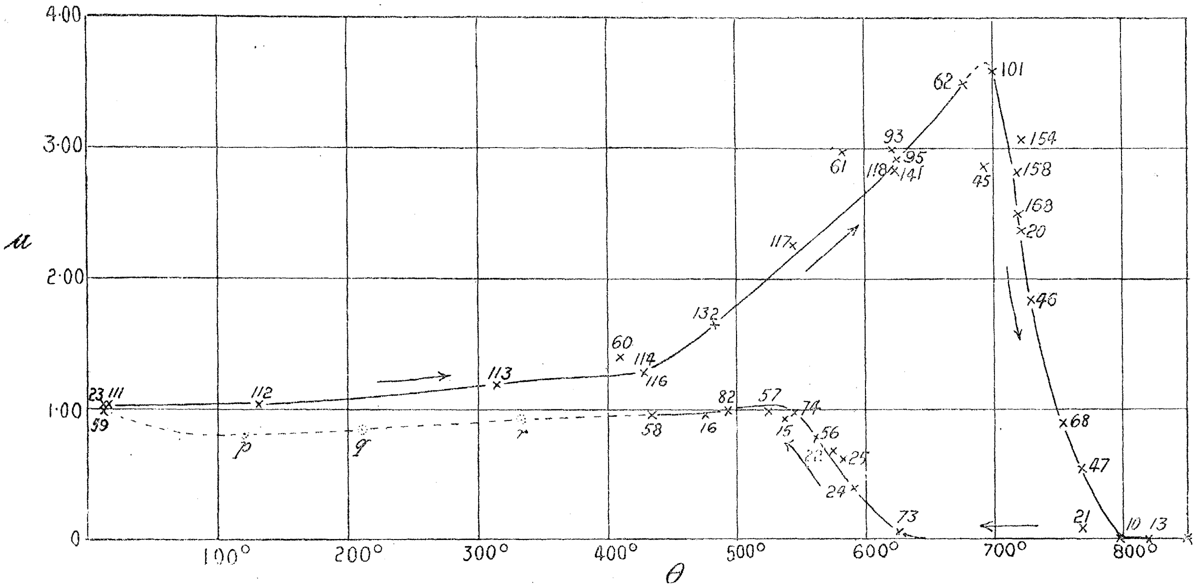


Fig. 10. Meteoric iron (2nd winding).

Field intensity = 0·43, C.G.S. values of μ = ordinates × 160·5 (approximate).

Variation of permeability with temperature during continuous cooling from about 850° C., and continuous reheating to same temperature.

Fig. 10 is intended to represent the variation with change of temperature of the permeability of the meteorite as it is cooled continuously from above the critical temperature to the temperature of the air, and then heated uninterruptedly until its ferromagnetism again becomes too small to be measurable. The numbers of the experiments upon which the curve is based are given in the figure. It will be seen that the greatest amount of uncertainty as to the form of the curve is in the part representing the cooling from 400° C. to 15° C. The similarity between 28 and 29 (1st winding), and between 58 and 59 (2nd winding) seemed to suggest that the permeability would not vary appreciably over this range. From subsequent data and from reasons given later it seems possible, however, that the permeability *may* become perceptibly less at intermediate temperatures than it was found to be at 400° C. and 15° C.

On a later occasion, after thermal treatment, to be described, the permeability variation was observed during cooling at a number of temperatures intermediate between those just stated. The initial and final permeabilities (see 96 and 100, fig. 13) in this case bear practically the same relation to one another as the permeabilities (at 58 and 59) represented in fig. 10. *The positions of the points p, q and r were calculated on the assumption* that the ratio of the permeabilities, at corresponding temperatures in the two cases, remained the same throughout the cooling as at 450° C. and 15° C. The lack of experimental data that might be of interest was not noticed until after the apparatus had been dismantled.

The general form of the $\mu\theta$ curve having been again approximately determined, the first experiments after re-winding were made to test, from points in the region where the permeability is rising rapidly during cooling, for the reversibility described by GUILLAUME (see above, § 6, p. 50). The experiments were not completely satisfactory on account of the difficulty of keeping the temperature absolutely constant for a considerable time. In the measurements given under the first winding the second value of the permeability at the original temperature of interrupted cooling was slightly greater than the first, but as both observations lay in a region where the permeability varied rapidly with temperature, it was difficult to decide whether the variation was not strictly reversible. In order to make the test less difficult

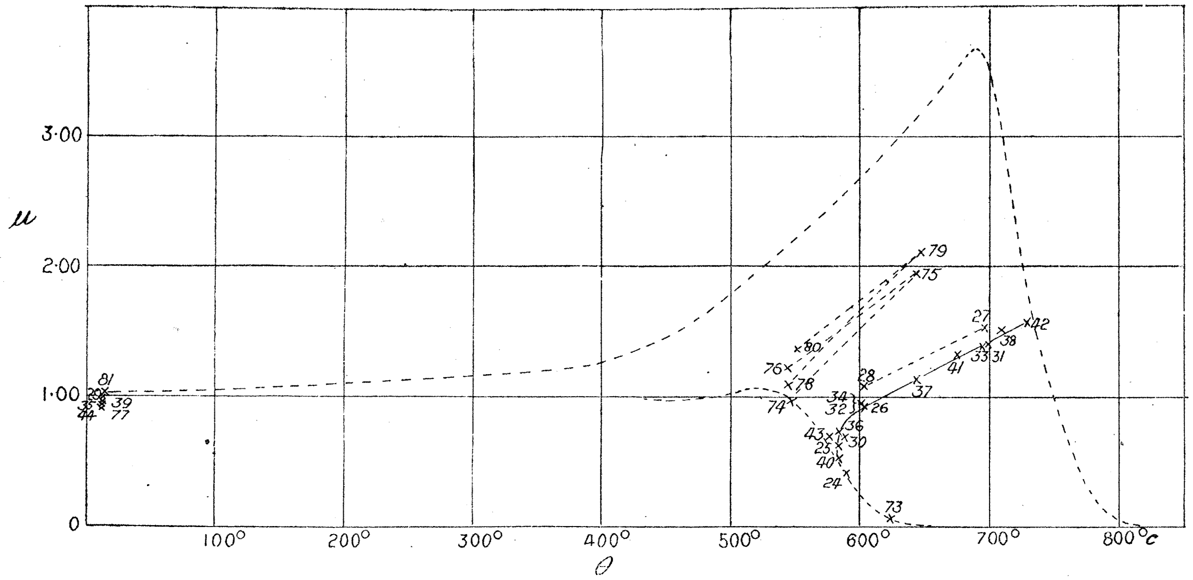


Fig. 11. Meteoric iron (2nd winding).
Cooling from 850° C. interrupted at 580° C. and at 550° C. (respectively).
Effect of subsequent reheating and cooling.

experimentally the observations were made at about 600° C. and 700° C., *i.e.*, at temperatures where the permeability was not subject to rapid variation. The experiments 26, 27 and 28 seem to show that there is distinct irreversibility on the first cooling from 700° C., but the experiments 31 to 34 seem to show that, after the first reheating and cooling, the subsequent variations are practically reversible—the permeability being subject at most to a very slight rise.

An attempt was made to determine how the curve of alternate heating and cooling just described departs from and returns to the steeper curve of continuous cooling. It was here that the uncertainty arising from the difficulty of maintaining a constant temperature became most pronounced, but from the experiments 40 to 42, in conjunction with those just quoted, it would seem that at the beginning of the first reheating the permeability rises more rapidly than it does subsequently (fig. 11), and that the changes in permeability variation are certainly less abrupt than in the qualitative diagrams given by GUILLAUME. (Experimental magnetic data are not given in any of the papers by GUILLAUME to which I have had access. It is worth notice that permeability measurements may reveal changes of internal structure too small to be detectable by other methods. *Cf.* Section VII., § 12, p. 101 below). The data of fig. 11 are not sufficient to show how the curve of falling permeability, passing through 42 and 43, meets the curve of continuous cooling, but it is noteworthy, as in the first winding, that interrupted cooling and subsequent treatment as above is followed, in every case, by a lower permeability at ordinary temperatures than if the cooling had been continuous from beyond the critical point (see later, Section VI., § 11, p. 91).

It was next intended to test for reversibility, on cooling and reheating, from a point in the region (between 700° C. and 800° C.) in which the permeability falls rapidly with rising temperature. For this purpose the points 45 to 47 (see also fig. 10) were taken in order to get the general position of the region in question. The heating was not continued beyond about 770° C. (47) owing to want of time. It was noticed that, as the result of uninterrupted cooling from 770° C., the permeability at ordinary temperature was lower than any value previously obtained, and 20 per cent. lower than that obtained after uninterrupted cooling from temperatures above that at which ferromagnetism becomes imperceptible.

The ring was then reheated to a point on the falling branch of the curve (about 720° C.) and then allowed to cool without intermediate reheating. Measurements of permeability were taken from time to time until the air temperature was reached. The results are shown in Experiments 50 to 55. The permeability at ordinary temperature was again exceptionally low and practically identical with that obtained just previously after uninterrupted cooling from 770° C.

The permeability at ordinary temperature was now raised, by treatment similar to that described under the first winding (see 67), and the ring was then heated to about 755° C. and again cooled uninterruptedly (except for stoppages at three temperatures for the measurement of permeability) to the temperature of the air. The resulting permeability was again very low (see 72) and practically equal to that obtained after cooling from 770° C. and 720° C. respectively (see fig. 12).

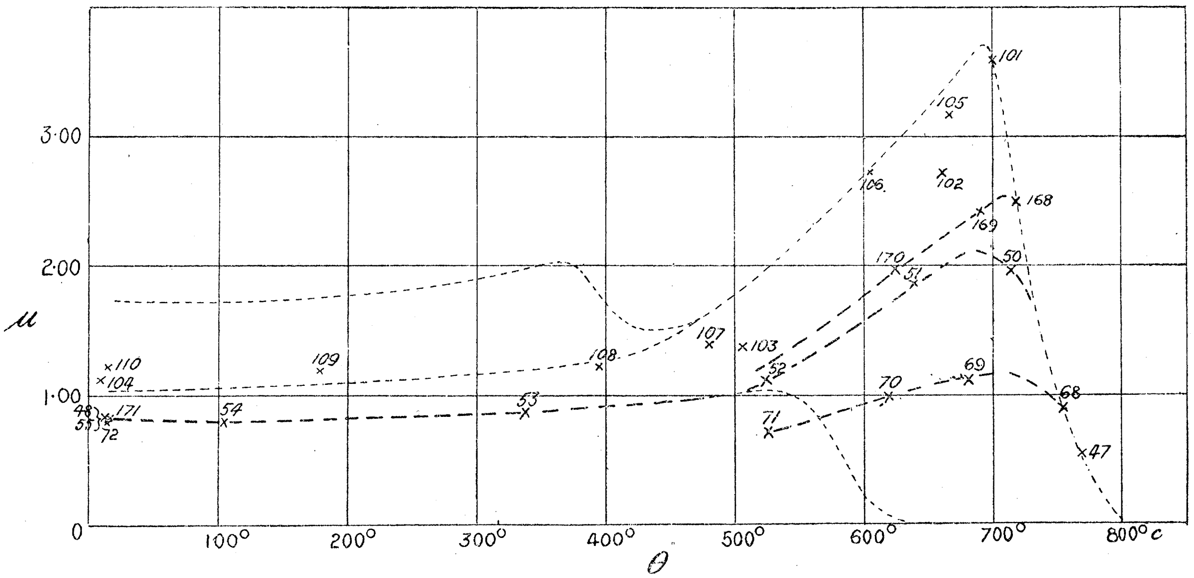


Fig. 12. Meteoric iron (2nd winding).

Reheating to 850° C. interrupted at temperatures between 700° C. and 800° C.

Variation of μ during subsequent continuous cooling to air temperature.

On fig. 12 there are plotted also the results of a much later set of observations (168 to 171) which lead to the same result as the above sets. They serve further to show the constancy in the behaviour of the material.

Apart from showing that very low and nearly equal values result from uninterrupted cooling from a temperature between 700° C. and 800° C., the numbers just given show that GUILLAUME'S qualitative diagram does not represent exactly what happens in the present case; since, if it did, the permeability at ordinary temperature in each of the above cases should be the same as that obtained after uninterrupted cooling from above 850° C.

The experiments 74 to 80 (shown in fig. 11) prove that, when cooling from 850° C. is interrupted near the temperature at which the permeability ceases to rise, subsequent reheating is accompanied by irreversible change of permeability. The nature and extent of this irreversibility is shown further in fig. 13. From the experiments 82 to 86 it is seen that, after a second reheating, the state of the material is practically reversible and the hysteresis with respect to temperature has almost disappeared, being ten times smaller after the second reheating from 490° C. than after the first (*cf.* 31 to 34 and also experiments described later).

Fig. 13 shows also the result of the first attempt to trace exactly how heating interrupted in the neighbourhood of 600° C. results in an exceptionally high

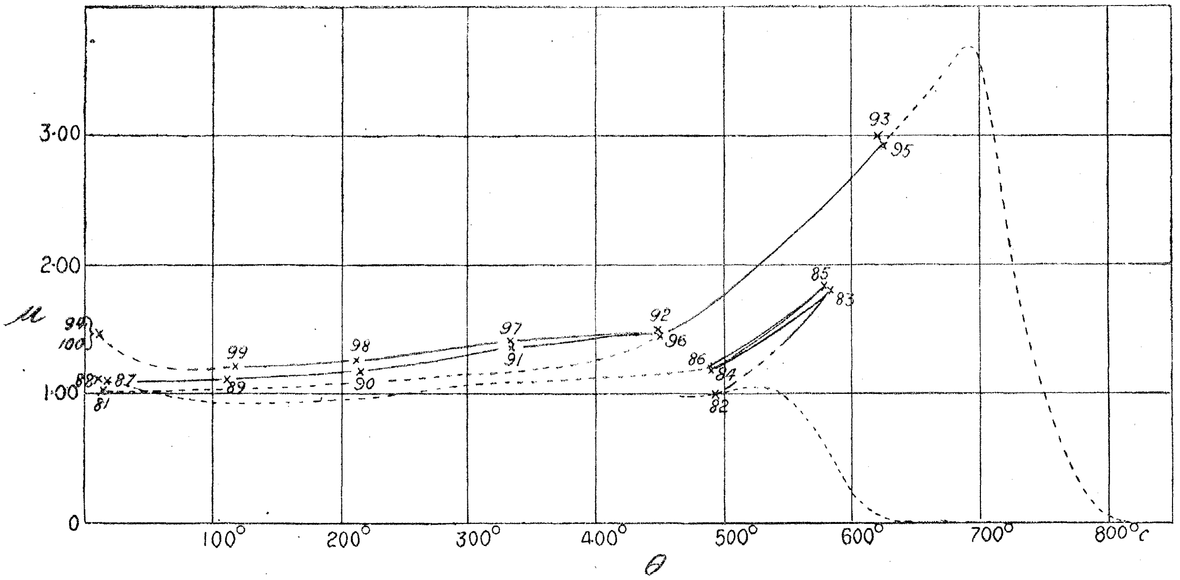


Fig. 13. Meteoric iron (2nd winding).

Variation of μ with θ below 500° C.—

(i) when cooling from 850° C. is interrupted at 500° C.

(ii) when reheating to 850° C. is interrupted at 625° C.

permeability at ordinary temperature (*cf.* 1st winding). From the data 88 to 100 it is seen that the greater part of the increase takes place during the time that the material is cooling from below 100° C. to the temperature of the air (*cf.* 99 to 100).

The experiments 101 to 110 (fig. 12) seem to show that uninterrupted cooling from

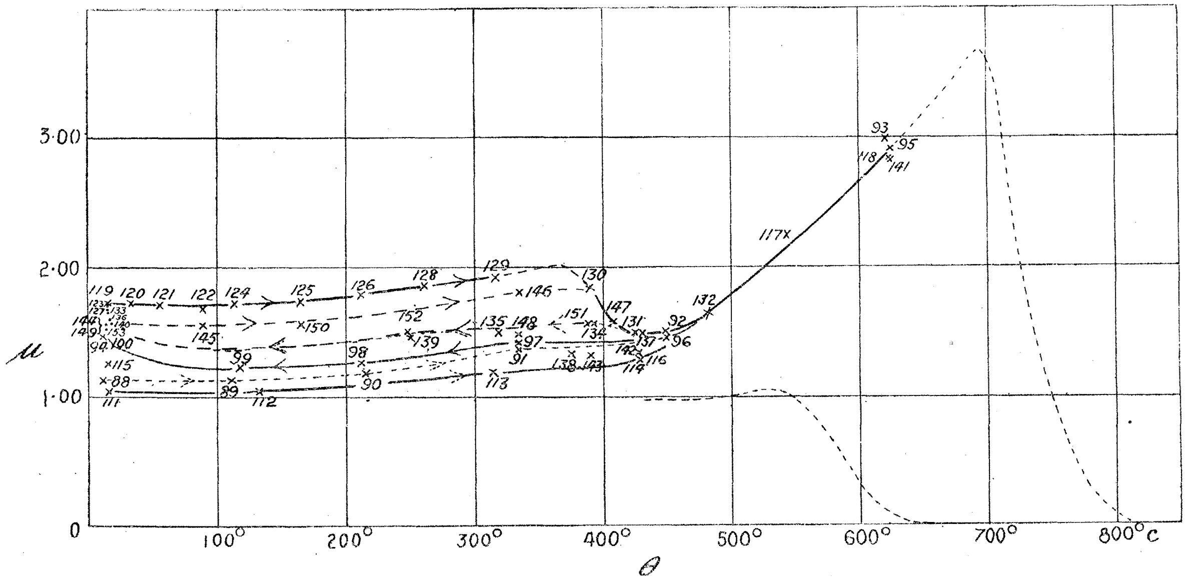


Fig. 14. Meteoric iron (2nd winding).

Curves showing the variation, at temperatures below 500° C., of the permeability obtained after cooling from about 600° C.

a point on the rapidly descending part of the $\mu\theta$ curve is accompanied by a lowering of permeability at ordinary temperature which a single reheating to 670° C. is not sufficient to remove (see, however, Section VI., § 8, p. 88 below).

The experiments 111 to 119 (fig. 14) show the full effect of heating interrupted at about 620° C. on the ordinary temperature permeability—the point 111 having been obtained after uninterrupted cooling from beyond the critical point, and the point 115 after heating interrupted at about 430° C.

The experiments 119 to 129 (fig. 14) show how the permeability now changes with rising temperature, 123 and 127 showing that the change is reversible, and 121, 122 and 124 that there is apparently a minimum permeability in the neighbourhood of 100° C. The experiments 130 to 132 corroborate the sudden fall and subsequent rise, with a minimum permeability at about 440° C., noticed after similar treatment in the case of the first winding (*cf.* fig. 9).

Observation 133 shows that on cooling from 480° C. (132), after the permeability has begun to rise again, the air temperature permeability is practically the same as at the outset. The observations 134 to 136 were made to examine the effect of cooling from a point near 400° C., at which temperature the permeability of the ring in its new condition was falling rapidly with rising temperature. These show that there is a well-marked temperature lag, the returning permeability at 300° C. being much below the permeability at the same temperature during heating, although the permeability eventually rises, at the air temperature, nearly to its original value. Experiments 137 to 140 show a similar effect, with a further slight decline in the ordinary temperature permeability. A subsequent heating to 625° C. (141) did not have much effect upon the air temperature permeability (144). The experiments 144 to 153 corroborate those already made.

The result of the experiments plotted in fig. 14 is, therefore, to show that reheating to 625° C. is followed by a large increase in the permeability at ordinary temperature. The greater part of this increase takes place, irreversibly, below 100° C. The permeability remains high upon subsequent reheating until a temperature of about 400° C. is reached; but beyond 500° C. the permeability is the same as it was before the treatment which resulted in the relatively high permeabilities at lower temperatures. Further, the additional permeability produced as above is subject to approximately reversible variations, over temperatures between those of its appearance and disappearance, of the same kind as those observed at higher temperatures (*cf.* figs. 11 and 15).

An attempt was made next to determine whether the variation of permeability, as the temperature fell from between 700° C. and 800° C., was reversible in the meteorite, as it is stated to be by GUILLAUME in artificial alloys. The results of the experiments are difficult to represent in a single diagram (fig. 15); but the correct conclusion seems to be that in each case there is not strict reversibility and that the permeability is greater on reheating than it was at the corresponding temperature during cooling

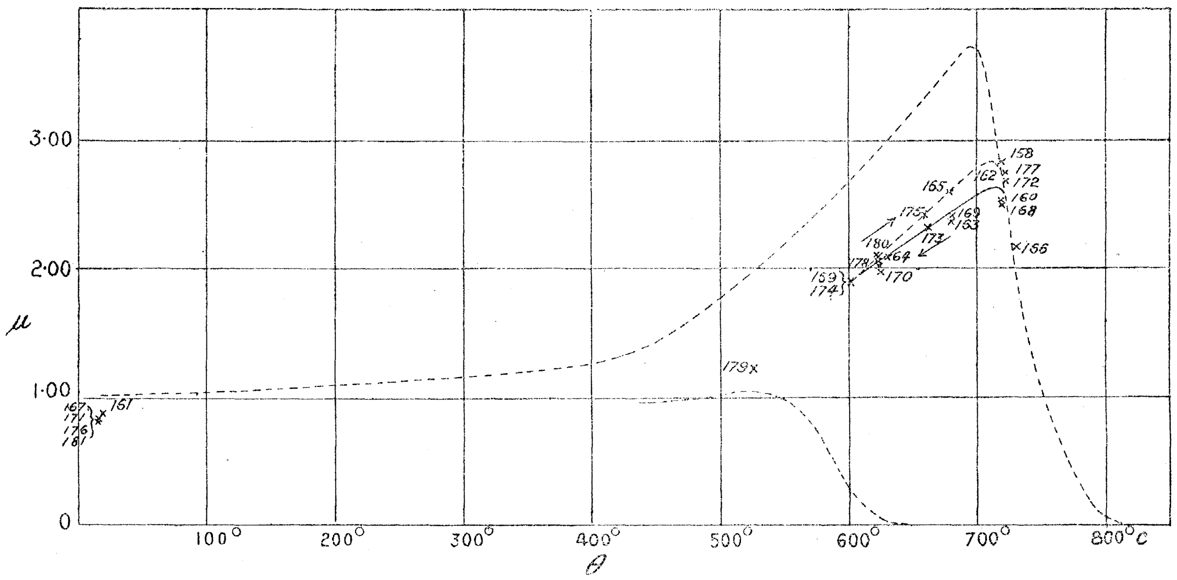


Fig. 15. Meteoric iron (2nd winding).
Reheating to 850° C. interrupted between 700° C. and 800° C.
Effect of subsequent cooling and reheating.

(*cf.* 163 to 165, 173 to 175, and 178 to 180). It is noticeable, corroborating this view, that the readings at the air temperature (167 and 171) after continuous cooling are practically identical with previous values (*cf.* 48, 55, 72) obtained under similar treatment, while the values at 176 and 181 (after interrupted cooling) are each slightly larger, showing that the effect of reheating to a temperature in the

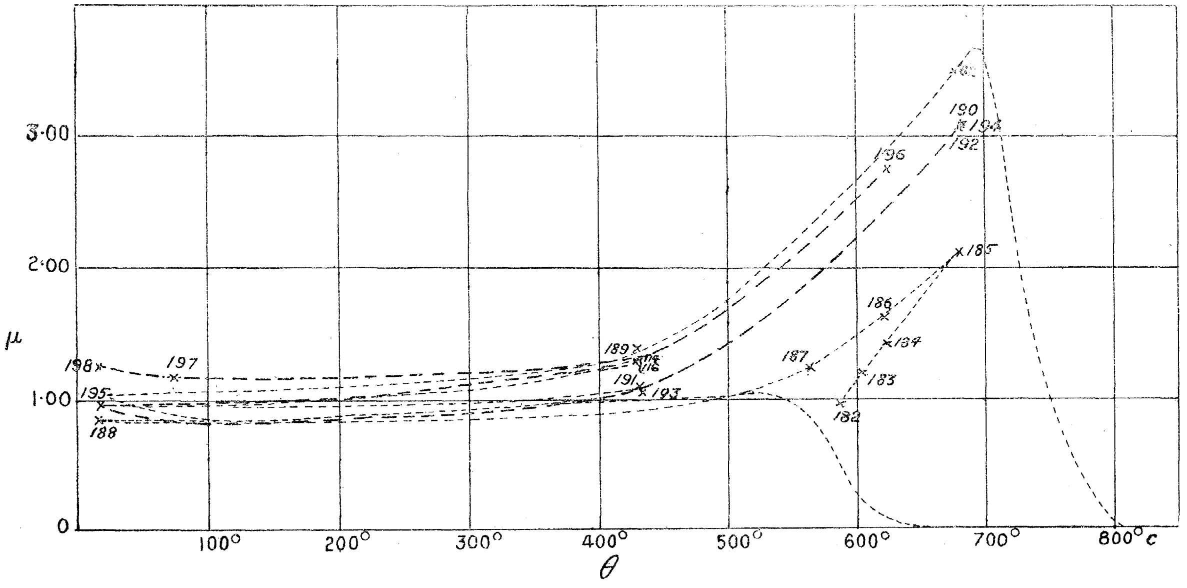


Fig. 16. Meteoric iron (2nd winding).
Effect upon permeability of temperature change alternating between (i) 430° C. and 680° C., (ii) 15° C. and 625° C.

neighbourhood of 650° C. has the effect of slightly raising the air temperature permeability obtained on subsequent continuous cooling. Hence, under the conditions described, it may be said that the change in question is not strictly reversible, although by analogy, from results already given, it is probable that a few reheatings and coolings would result in subsequent practical reversibility.

The final experiments, 182 to 198, show the effect of alterations over various ranges of temperature. The points 182 to 187 (fig. 16) show the irreversibility already noted (*cf.* 78 to 80). Points 190 to 194 show, over a wider range than 85 and 86, that the permeability becomes reversible under repetition of heating and cooling between about 430° C. and 680° C. It is not until the temperature is lowered beyond 430° C. that the permeability shows any further rise on heating. The observations 195 to 198 show, over a wider range, the same irreversible effect as occurs between 182 and 187.

§ 8. *Hadfield* 5·8 *per cent. Nickel Steel.*—(See fig. 17, &c.)

The object of the experiments on the nickel steel was to enable a comparison to be made, under conditions as far as possible identical, of the thermomagnetic properties of natural and artificial nickel-iron alloys of similar percentage composition. The rings were almost identical in size, were heated in the same way, and had primary and secondary coils as nearly as possible alike.

The nickel steel contained almost the same percentage of iron as the meteorite, but about 1 per cent. less of nickel. It contained about 0·7 per cent. of manganese and smaller quantities of carbon and silicon. All these substances were absent in the meteorite, which contained, however, about 0·4 per cent. of cobalt.

The experiments 1 to 8, in the table of results, were made with the ring in the unannealed condition in which it was after construction, and serve only to show that the permeability begins to rise rapidly at about 500° C., and that the maximum had been passed at 700° C. It seems worth while to note (although the data upon which the inference is based are few in number) that the positions of the points 1 to 7 (see fig. 17) suggest a closer resemblance, below 550° C., between the properties of the nickel steel in its unannealed state and those of the meteoric iron than was found after the annealing of the former. The possible significance of this will be seen later (*cf.* Section VI., § 12, p. 92, and Section VII., § 14, p. 102).

The experiments 9 to 13 were made to find the effect of annealing, and those from 14 to 16 to show the effect of reheating interrupted at a temperature in the region in which the permeability is increasing rapidly with rise in temperature. The results are shown in fig. 17, in which the outer dotted curve, running from 15° C. to 810° C., is drawn in order that the relation between the present data and those obtained later may be represented in the figure.

The ring was next annealed at a higher temperature (see 20*b*), as it was doubtful whether, in Experiment 9, the ring had been heated to a temperature at which

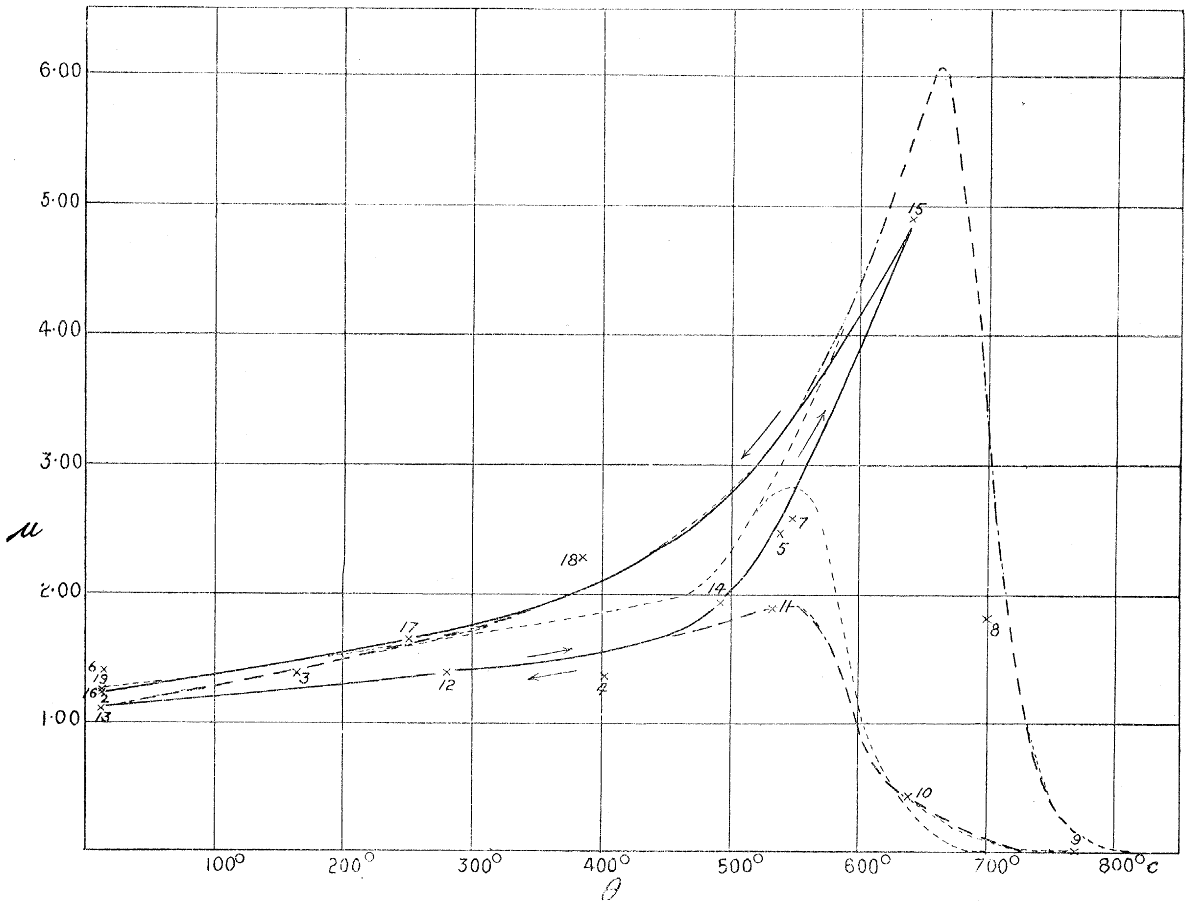


Fig. 17. Nickel steel.

Field intensity = 0·43, C.G.S. values of μ = ordinates × 166·4 (approximate).
Effect of cooling from 770° C. and of subsequent reheating to 640° C.

ferromagnetism had completely disappeared. The temperature of reappearance and the subsequent variation of permeability during cooling were again observed (see fig. 18, 21 to 26) and the variation of permeability during subsequent reheating to 600° C. is shown by the observations 27 to 31.

It is seen from the observations 21 to 31 that the rising and falling permeability curves are practically superposable (below about 550° C.) as in the curves given by HOPKINSON, which, as already described, differ from those for the meteoric iron.

The permeability at air temperature resulting from heating interrupted at 600° C. is shown in 32, and the value upon subsequent heating to 490° C. is shown in 33. The air temperature permeability is seen to be raised comparatively little by treatment identical with that which produced a large increase in the case of the meteorite; but the permeability at 490° C. (33) is notably larger than the values obtained previously at about the same temperature (*cf.* 23 and 29). A second cooling from about 600° C. produced a slight further rise in the air temperature permeability (*cf.* 32 and 35). The other data shown in fig. 18 will be referred to later (see Section VI., § 10, p. 90).

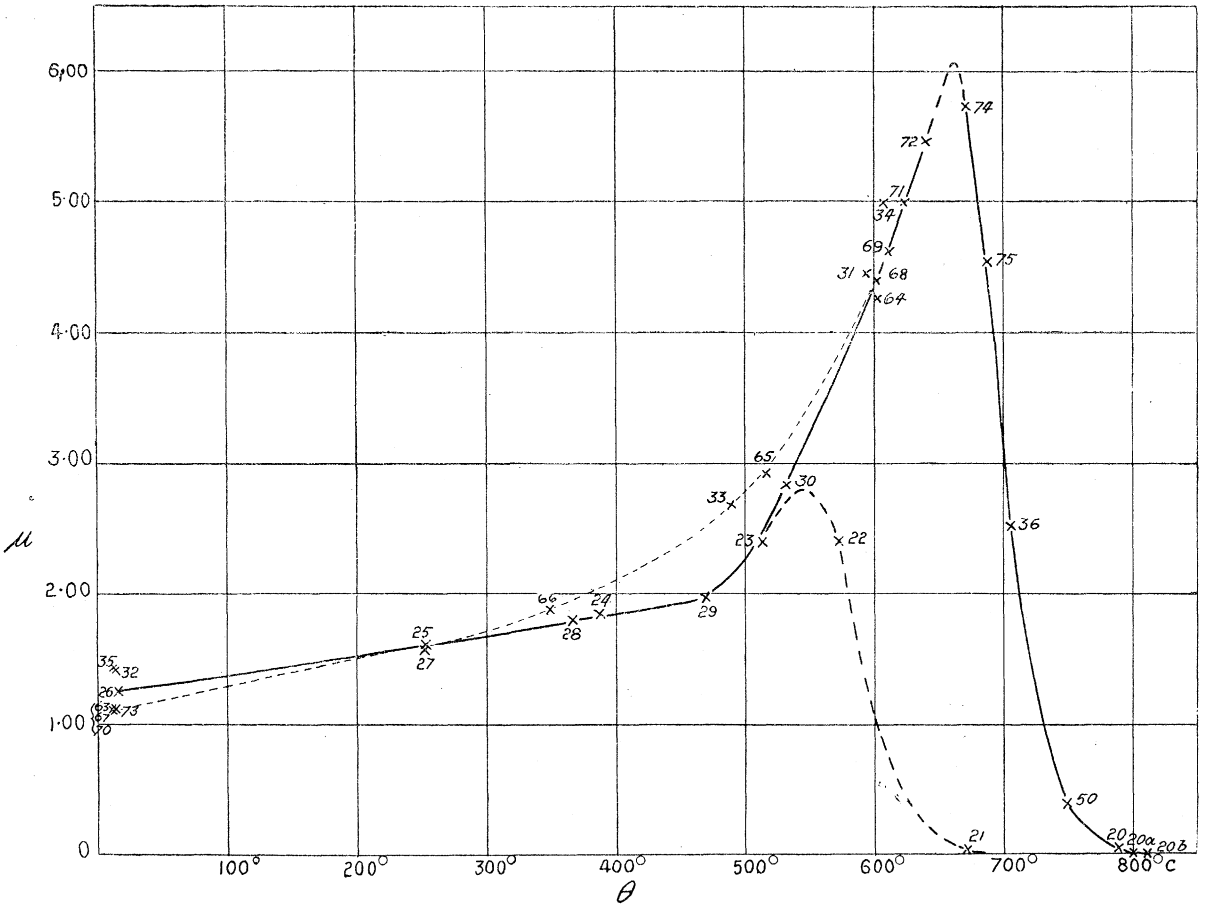


Fig. 18. Nickel steel.

Curve showing relation between permeability and temperature during continuous cooling from about 810° C. and continuous reheating to same temperature.

The next experiments were made to find what happened on cooling from a temperature (705° C.) in the region (about 680° C. to 800° C.) in which the permeability is falling rapidly with increase in temperature. The results are shown in fig. 19 (observations 36 to 42). It is seen that the air temperature permeability is reduced by this treatment, as in the case of the meteorite (*cf.* 26 and 42). The ring was next reheated to 570° C., when it is seen that the permeability rose rapidly beyond 450° C. as before (*cf.* fig. 18), and then allowed to cool to the air temperature. This procedure raised the air temperature permeability about 15 per cent. A subsequent reheating caused a further rise of 5 per cent. (*cf.* 45 to 49). Hence the effect of alternation of temperature between given limits is of the same character as in the case of the meteorite.

Fig. 20 shows the effect upon the subsequent permeability of heating interrupted at a higher temperature than in fig. 19, but at which the permeability was still measurable, viz., 750° C.

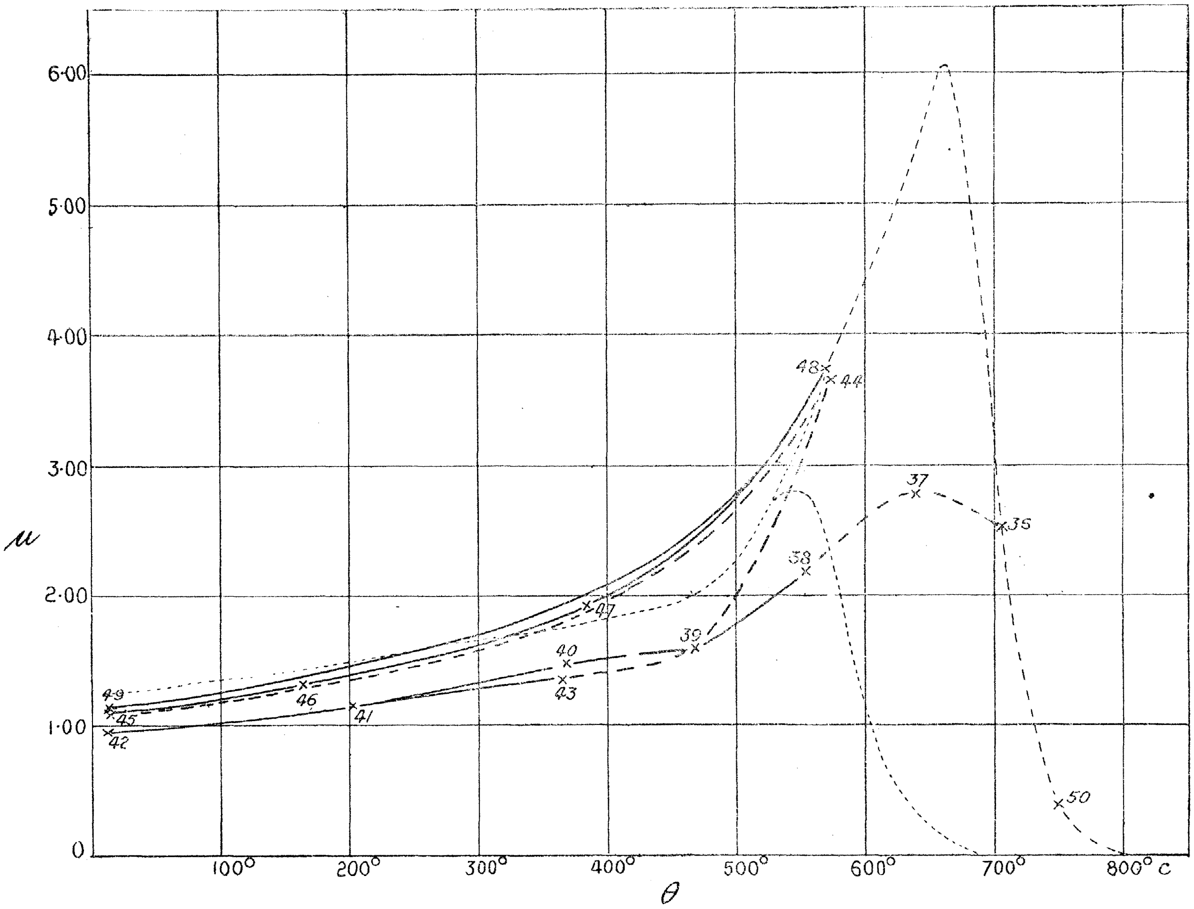


Fig. 19. Nickel steel.

Reheating to 810° C. interrupted at 705° C.

Variation of μ during subsequent continuous cooling to the temperature of the air.

Effect of two subsequent reheatings to 570° C.

The air temperature permeability was again very low and, although slightly greater than that previously obtained (42), was about 28 per cent. lower than the value obtained after cooling from beyond the temperature at which the ferromagnetism becomes imperceptible. The ring was now reheated to about 600° C., as in the previous case, when the permeability seemed to vary reversibly below 400° C. (*cf.* 54 and 58), as it did under similar circumstances in the previous experiments, and to rise rapidly between 400° C. and 600° C. [It will be seen (Section VI., § 10, p. 90) that the points 53 to 58 lie nearly in a straight line, as do the points 24 to 29, fig. 18, and 41 to 43, fig. 19, and that these lines meet approximately at the same point on the axis of temperature produced.] The ring was next subjected to alternate heating and cooling between 400° C. and 600° C. (*cf.* 59 to 62) with the result, as shown in fig. 20, that the permeability rose at first rapidly and then, during subsequent alternation, very slowly (*cf.* 58, 60, and 62).

The ring was then allowed to cool to the air temperature, when its permeability

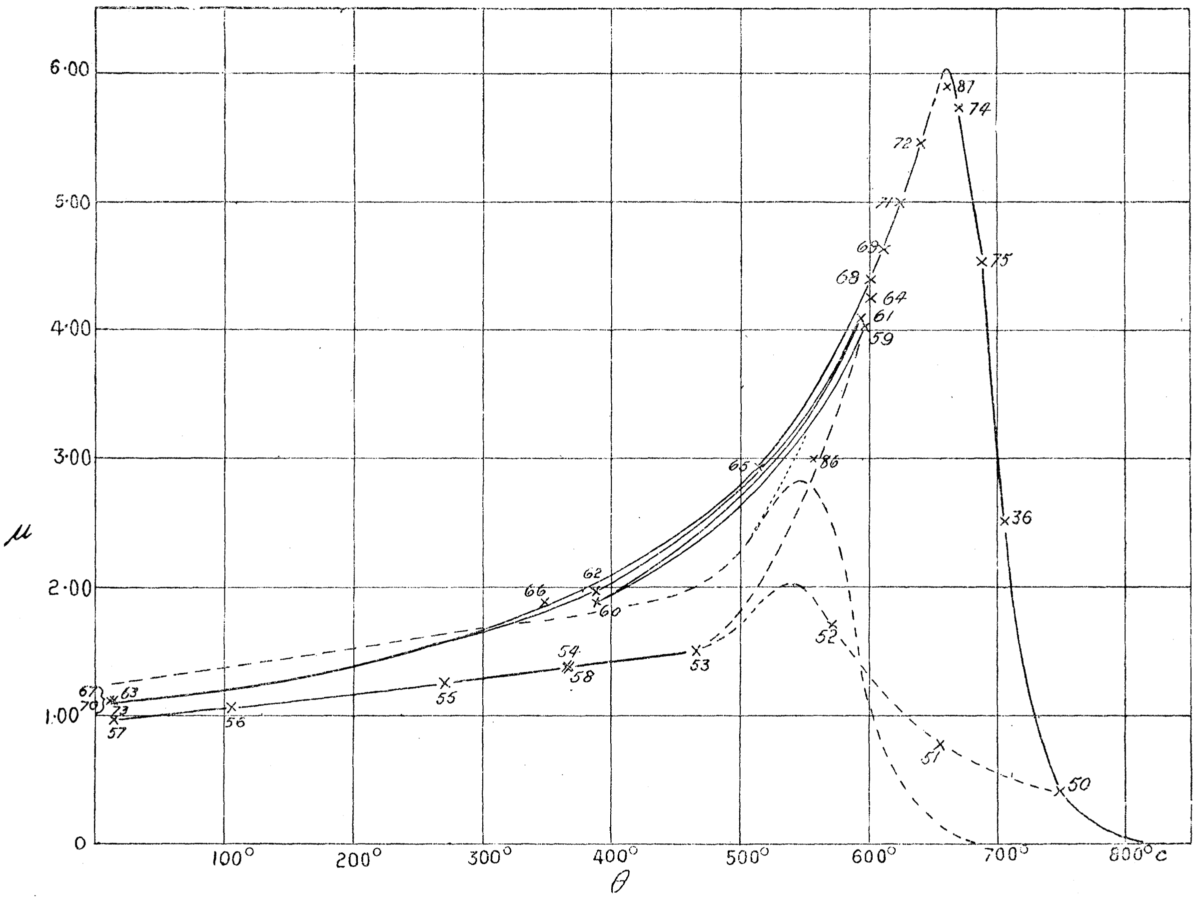


Fig. 20. Nickel steel.

Reheating to 810° C. interrupted at 750° C.

Variation of μ during subsequent cooling.

Effect of reheating to 600° C. and of subsequent alternation of temperature between 400° C. and 600° C.

Effect of subsequent alternation between 15° C. and 650° C.

was found to be practically the same as it was under corresponding circumstances previously (*cf.* 45 and 63).

The ring was next subjected to alternation of temperature between 15° C. and 600° C. and finally between 15° C. and about 650° C., the permeability being measured at various intermediate temperatures as shown. It is seen that, as a result, the permeability acquires a practically steady state at all temperatures below that of maximum permeability. This state is represented by the curve passing through the points 63 to 73, fig. 20, and shown by dotted lines in the other figures. (It is noticeable that, if the ring is heated nearly to its temperature of maximum permeability, the subsequent air temperature permeability is slightly less than when the temperature is not raised beyond 600° C.—compare 63, 67, and 70 with 73. A possible interpretation of this will be found later, see Section VI., § 8, p. 88.)

The ring was now heated to a temperature (690° C.) not far beyond the maximum

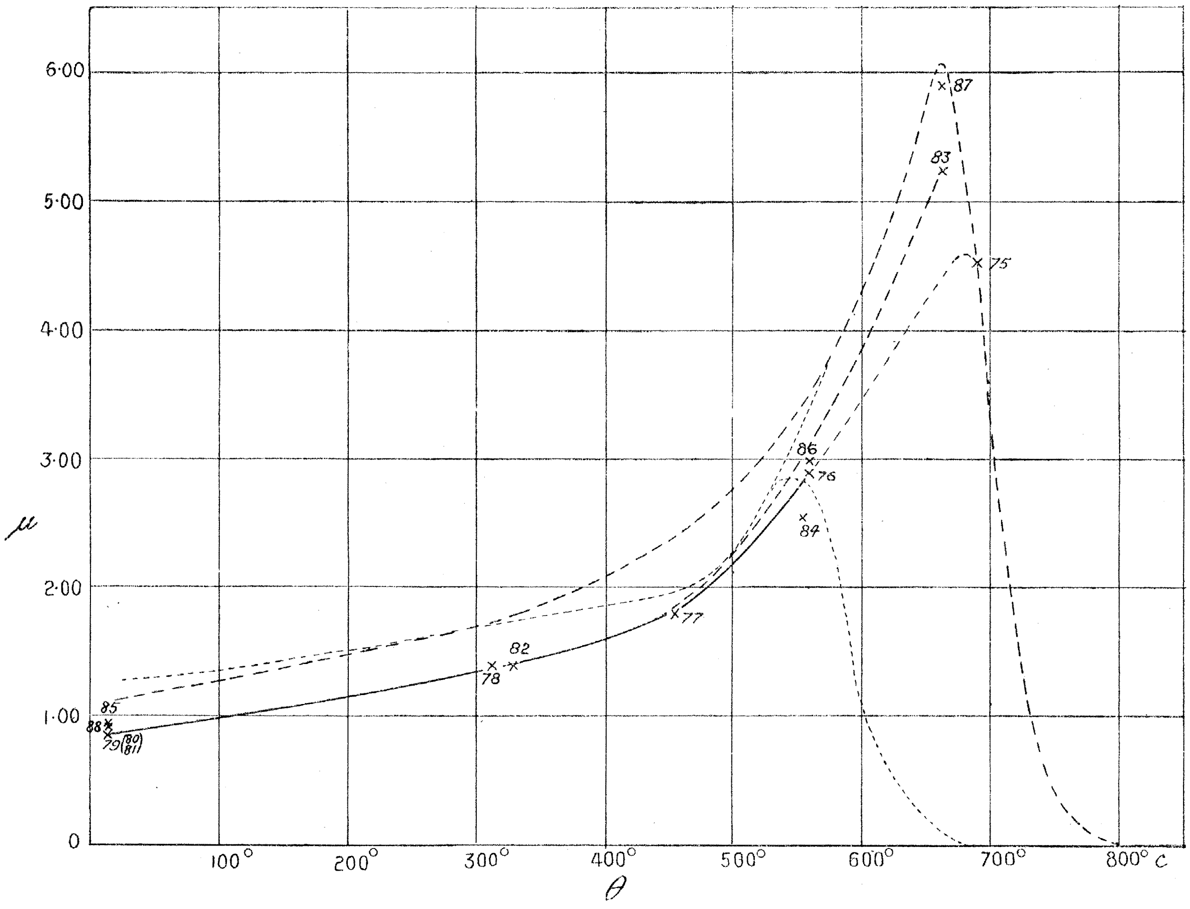


Fig. 21. Nickel steel.

Reheating to 810° C. interrupted at 690° C.

Variation of μ during subsequent cooling to 15° C. and reheating to 660° C.

and then allowed to cool, with stoppages for the measurement of permeability. The results are shown in the points 76 to 79 (fig. 21). The air temperature permeability was now even lower than after previous coolings from 705° C. and 750° C. respectively (*cf.* 79, 42, and 57). The ring was then heated beyond the critical point and then allowed to cool to the temperature of the air. The permeability was raised about 10 per cent. by this process, but was still comparatively low. Reheating to 660° C. did not seem to raise the permeability (*cf.* 85 and 88), but the effect of heating to a lower temperature, *e.g.*, 600° C., was not observed. The latter treatment, as can be inferred with certainty from the earlier and later experiments, would have raised the permeability at the air temperature.

The sets of observations 75 to 79, 36 to 42, 50 to 57, 9 to 13, and 20 to 26 show that the air temperature permeability after cooling from beyond the temperature of maximum permeability is greater in proportion as the temperature from which the cooling begins approaches that at which ferromagnetism has disappeared.

From the above results it can be inferred that the permeability does not vary

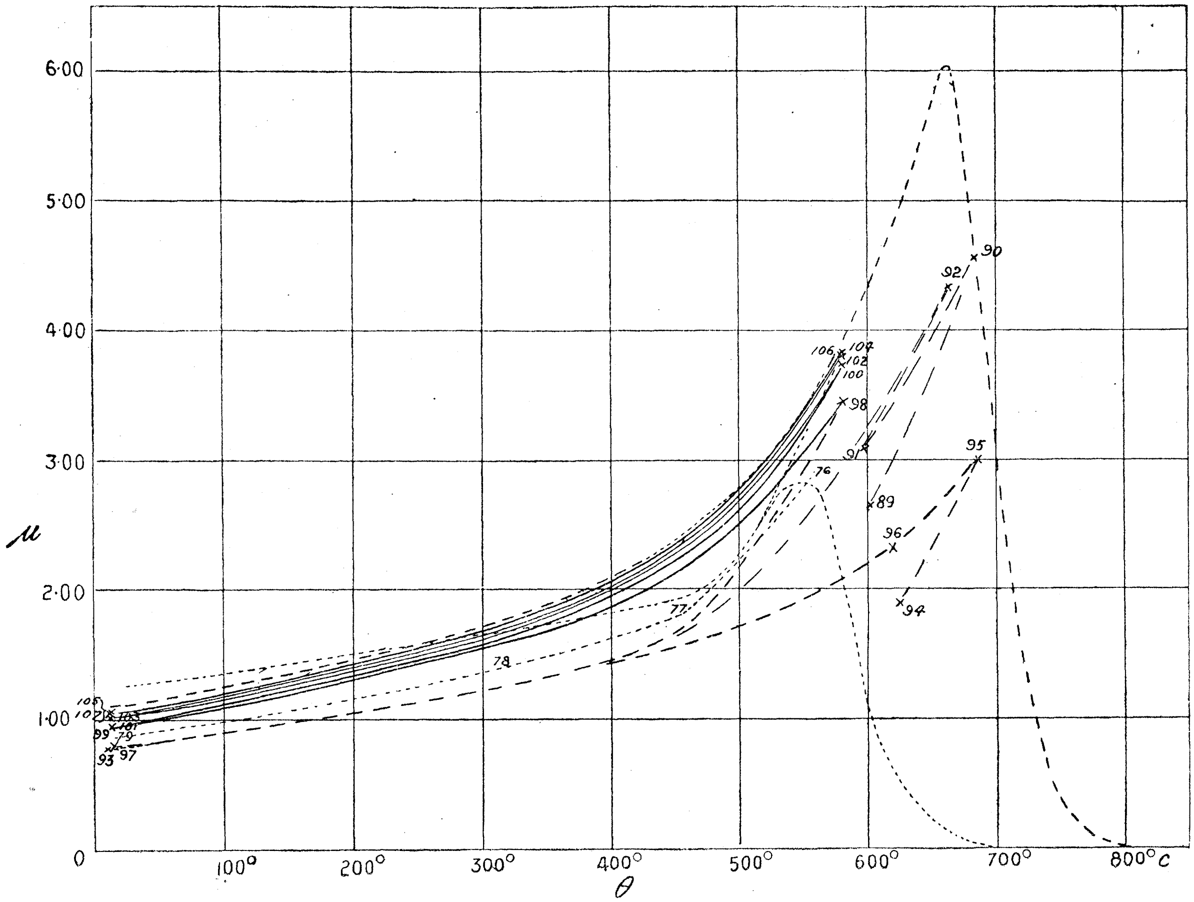


Fig. 22. Nickel steel.

Effect of interrupted cooling and of subsequent alternation of temperature between 15° C. and 580° C.

reversibly (in the time occupied by the experiments) over temperatures between those of the rising and falling permeability curves of fig. 18. This inference is seen to be correct from the results of the observations 89 to 92 and 94 to 96. It is noticeable (fig. 22) that, as in the case of the meteorite, but to a greater extent, alternation of temperature between the falling and rising permeability curves is followed by a relatively low permeability at the air temperature (see 93 and 97). (*Cf.* Section VI., § 11.) The effect of a single reheating to 580° C. upon the air temperature permeability is shown in the experiments 97 to 99, and the effect of subsequent alternation of temperature between 13° C. and 580° C. is shown in the observations 99 to 107. As in all previous cases, the permeability change produced by alternation diminishes rapidly from one alternation to the next, and, in the present case, after three alternations further change was imperceptible. The observations are also consistent with the inference from previous experiments that the irreversible increase of permeability does not begin until, on the first reheating, some temperature between 400° C. and 500° C. is attained.

The permeabilities finally obtained at 580° C. and 13° C., after five alternations between these limits (see 106 and 107), lie only slightly below the curve, already determined, which represents the condition of the material when its permeability varies reversibly between the air temperature and a temperature not far below that of maximum permeability. (There is evidence of a slight diminution of permeability, during the course of the experiments, possibly due to oxidation or to some other cumulative effect.)

SECTION V.—THE RELATIONS BETWEEN THE PROPERTIES OF NICKEL-IRON ALLOYS CONTAINING DIFFERENT PERCENTAGES OF NICKEL.

§ 1. A study of the relations between the temperatures of appearance and disappearance of magnetism in nickel-iron alloys containing different percentages of nickel (*cf.*, *e.g.*, **OSMOND**, 'Revue Générale des Sciences,' vol. XIV., p. 865, 1903) shows that as the percentage of nickel increases up to some value not far from 27, the temperatures of appearance and disappearance become continuously lower and more widely separated from each other.

When the percentage of nickel exceeds 30 the temperature of appearance is only slightly below the temperature of disappearance of magnetism, and **OSMOND** is of opinion, in agreement with **GUILLAUME**, that the temperatures would practically coincide if the rate of change of temperature were made sufficiently slow to avoid possible difference between the temperature of the thermocouple and that of the bar of the alloy under examination. According to this view the alloys can be divided into two classes, namely, those containing not more than 27 per cent. of nickel, which are *irreversible,* and those containing more than 27 per cent., which are *reversible.*

§ 2. These results suggest that the percentage at which transition occurs from one class of alloys to the other corresponds with a eutectic point. Following **ROOZEBOOM**, **OSMOND** represents the "equilibrium curves" for the nickel-iron alloys diagrammatically, as in the figure below (*cf.*, however, § 19, p. 77).

The curve ABCD is obtained from the magnetic measurements above described. The dotted curves AE, FCD are theoretical in the first instance, and their positions are not assumed to be more than qualitatively correct. Their properties may be indicated briefly by supposing a line drawn through any temperature θ, parallel to the axis of temperature, and cutting the different curves of the figure in p, q, r, s, t, and u respectively. At this temperature θ solid solutions containing θq, θr, and θu per cent. of nickel are, respectively, in equilibrium with "mixed crystals" of iron and nickel containing θp, θs, θt per cent. of the latter.

The curves are drawn in accordance with the theorem, confirmed by experiment on mixed substances which deposit mixed crystals, that when the transition temperature of a substance (*e.g.*, Fe) is reduced by the addition of a second substance (*e.g.*, Ni) with which it forms mixed crystals, the crystals in equilibrium with the solution must contain a less percentage of the second substance than the solid solution—the

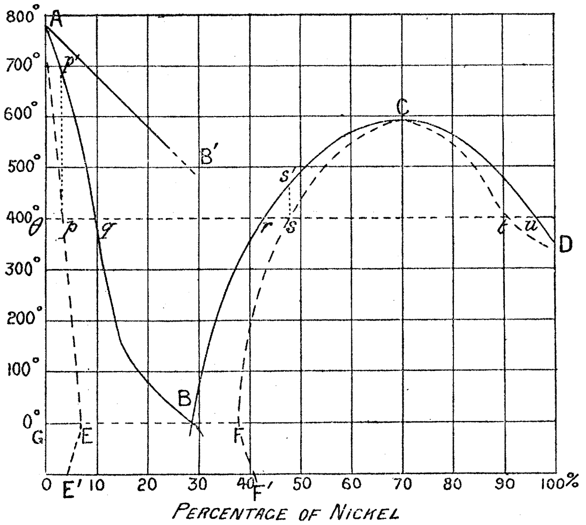


Fig. 23.

converse being true when the transition temperature is raised (*cf.* θt and θu, representing the case in which the transition point is that of nickel raised by addition of iron).

The fundamental ideas represented in the diagram may be summarised as follows :—

(1) When an alloy contains less than GB per cent. of nickel, the crystals which separate first contain less nickel than the remainder of the alloy, and are richer in iron the less the percentage amount of nickel in the material.

(2) When GB per cent. of the nickel is present, crystals of two kinds, one relatively rich and the other relatively poor in nickel, can exist in equilibrium with the (non-magnetic) solution containing GB per cent. of Ni and separate simultaneously when the temperature corresponding to GEF is reached.

(3) When the percentage of nickel exceeds GB the crystals which first form on cooling are those of the second type, relatively rich in nickel.

(1*a*) The ultimate state, at the temperature represented by GEF, of an alloy containing less than GB per cent. of nickel is different according as the percentage of nickel present is less than or exceeds GE.

If the alloy contains less than GE per cent. of Ni, it will be crystallised completely before GEF is reached, and will contain crystals of one type only, of which the percentage composition will be the same as that of the originally uncrystallised alloy. The alloy will be homogeneous at the temperature represented by GEF.

If the alloy contains more than GE per cent. of nickel, the percentage of Ni in the crystals will increase, at the same time that the total amount increases, until the eutectic temperature is reached. Here the last of the solid solution (containing GB per cent. of Ni) crystallises, but partly in the form of crystals weak in nickel (containing GE per cent.) and partly in the form of crystals stronger in nickel (containing GF per cent.). Hence any alloy containing more than GE per cent. and less than GB per cent. of Ni will be heterogeneous when completely crystallised at the eutectic temperature.

(2*a*) When the alloy contains GB per cent. of Ni, the material will be, when completely crystallised at the eutectic temperature, a mixture in definite proportions of the two types of crystals, one relatively rich and the other relatively poor in nickel.

(3*a*) The ultimate state, at the eutectic temperature, of an alloy containing more than GB per cent. of nickel will be different according as the percentage of nickel is less than or exceeds GF.

If the alloy contains less than GF per cent. of Ni, the eutectic temperature will be reached before the whole of the solution has crystallised. The final crystals will form from a solid solution containing GB per cent. of nickel, and will be a mixture of the two types containing respectively GE and GF per cent. of nickel. When completely crystallised at the eutectic temperature the alloy will be heterogeneous.

If the alloy contains more than GF per cent. of nickel, it will be crystallised completely before the eutectic temperature is reached, and will contain crystals of one type only, of which the percentage composition will be the same as that of the originally uncrystallised alloy. The alloy will be homogeneous at the eutectic temperature.

In all the cases described above, with the exception of that in which the alloy contains GB per cent. of nickel, the composition of the crystals changes continuously during the process of cooling to the eutectic temperature. When the percentage of Ni is less than GB the crystals become continuously richer in nickel; when the percentage is greater (but less than that represented by C) they become continuously poorer. If, however, the alloy contains the percentage of nickel represented by the dystectic point C, the crystals and the solid solution from which they form will be of the same composition from the beginning to the end of the crystallising process.

§ 3. As stated above, the crystallised material is homogeneous at the eutectic temperature if the alloy contains originally less than GE or more than GF per cent. of nickel. This result need not apply, however, to lower temperatures if the equilibrium curves below the eutectic temperature are (as they may be by analogy with fluid solutions) of the form represented qualitatively by EE′ and FF′ respectively. Under such circumstances alloys containing slightly less than GE per cent. or slightly more than GF per cent. of Ni might become heterogeneous at temperatures not very far below the eutectic temperature.

§ 4. There are various experimental data which are explained by the views above summarised of the relation between the structure and temperature of a nickel iron alloy of given composition.

That the formation of crystals of varying composition can occur in an alloy has been proved by direct experiment, and that this crystallisation occurs in a way analogous to that in which it takes place in liquid solutions has also been shown.

The distribution in space of the chemical constituents of a homogeneous alloy is analogous to that which exists in a solution, and the redistribution on crystallisation is the same phenomenon in each case, although the conditions under which the redistribution occurs in a fluid medium must be different from those in which it takes place when the medium is solid. Experiment has shown, however, that interdiffusion of metals can take place even at low temperatures, and hence to postulate the interdiffusion of the nickel and iron, as in the above theory, does not involve the introduction of an *ad hoc* hypothesis.

The theory involves the result that in any nickel-iron alloy—assuming the magnetisability to be a function of the state of crystallisation—the magnetism will not appear and disappear at one definite temperature. Thus in alloys containing θp, θs per cent. of nickel, crystallisation will begin at temperatures corresponding to p', s' respectively, and will not be complete until temperatures corresponding to p, s are reached.

Hence over the range of temperature represented by $p'p$ in the one case and by $s's$ in the other the amount of magnetic material will be increasing. In only one alloy, viz., that corresponding with C, in which the composition of the crystals is the same as that of the solid solution, will it be possible for the magnetism to disappear or reappear completely at one temperature. The data given by OSMOND (*loc. cit.*) are qualitatively in agreement with this deduction. The curves which he gives show that in the alloy containing 76·75 per cent. of nickel the magnetism reaches its full value very rapidly, after the temperature of reappearance is reached, just as it does in pure iron. It is further clear on inspection of the curves ('Rev. Gén.,' vol. XIV., pp. 868 and 869, 1903), that the range over which the permeability reappears becomes wider as the percentage of nickel increases from A or diminishes from C. Similarly with percentages above C, the range over which the magnetism reappears at first widens, but, as D is approached, again becomes restricted (*cf.* also Section VI., § 8, p. 88).

§ 5. The connection between permeability and the state of crystallisation is directly suggested in an experiment by GUILLAUME ('Comptes Rendus,' vol. 134, p. 596). A non-magnetic specimen of nickel steel, part of the surface of which was polished, was cooled down, with the result that visible crystals were developed and that the material become magnetic. According to GUILLAUME ('Journ. Iron and Steel Inst.,' vol. II., p. 297, 1905), the first observation of this kind was made by OSMOND.

By observation of the changes of volume (which are accompanied by the appearance of magnetism) in certain nickel-iron alloys, GUILLAUME has shown (see 'Rev. Gén.,' 1903, *loc. cit.*) that these changes agree quantitatively with the view that the presence of the nickel merely alters the temperature at which the transition of the iron in the alloy, from the non-magnetic to the magnetic state, takes place. The simplest interpretation of his results is that the nature of the change is the same in all the alloys, while the temperature at which the change begins, and the rate at which it proceeds, depends upon the percentage of nickel. The experiments are necessarily comparatively restricted and the argument is based partly upon a process of extrapolation.

It is known that there is no appreciable change in the density of nickel when it passes from the non-magnetic to the magnetic state, and hence the metrological method used by GUILLAUME (depending upon observation of the change in length of a bar of the nickel iron) affords no information concerning the changes that may take place in the nickel during the crystallisation of the iron by which it is accompanied in the alloy.

§ 6. The marked change in the magnetic properties of nickel-iron alloys when the percentage of nickel passes through a value between 25 and 30 is shown clearly in the data given by HOPKINSON ('Roy. Soc. Proc.,' vol. 48, 1890), and confirmed by the work of subsequent observers (*cf.*, *e.g.*, BARRETT, 'Trans. Roy. Soc. Dubl.,' 1902–1905).

The change in the magnetic properties corresponds closely with a well-marked change in crystalline structure which has been studied in detail by GUILLET ('Metallographist,' vol. 6, 1903). This change takes place, according to GUILLET, when the percentage of nickel is 27, if the percentage of carbon in the alloy is small.

Other data of a similar kind might be cited in support of the hypothesis that the permeability is intimately related to the crystalline structure, and of the deduction therefrom that observation of the permeability variation may be valuable as a means of tracing continuously variations in the state of crystallisation of the material.

It will be seen that the experiments described in this paper bear directly upon this point; but before considering the evidence of the validity of the theory of solid solutions, which they convey, it seems well to indicate how, as it appears to me, the value of the theory as an explanatory hypothesis can be exhibited by consideration of certain data already known.

The method of presentation of the facts enumerated and discussed in §§ 7–17, below, was suggested to me by a consideration of those thermomagnetic data of Section IV. which are discussed in Section VII.

§ 7. As already stated, the positions of the dotted curves AEFCD in fig. 23 above are in the first instance purely qualitative. The values of GE and GF, for example, which represent the compositions of the two components of the supposed eutectic are not known from direct experiment upon artificial alloys; but a study of the structure of nickel-iron alloys of natural origin ("meteoric" and "terrestrial") strongly supports the view that the equilibrium curves are of the general form given in the figure.

The results of the chemical analysis of meteorites (see, *e.g.*, COHEN, 'Meteoritenkunde,' 1894–1903) show that the amount of nickel (together with cobalt) found in meteoric iron is seldom less than 6 per cent. or more than 11 per cent. It is probably for this reason, as will be seen, that Widmanstätten figures are usually regarded as a characteristic of meteoric iron. But while the occurrence of *large* and almost perfectly symmetrical figures may, in the present state of knowledge (since the means of producing such figures artificially has not yet been discovered), be regarded as a sign of "meteoric" origin, yet the absence of such figures does not prove that the iron is not meteoric. There is a considerable number of specimens of iron which, judged by their mode of occurrence and general appearance alone, would be accepted as of similar origin to those classed as meteoric, but of which the origin, on account of the absence of the Widmanstätten figures, is regarded as doubtful. In each of these doubtful cases the percentage of nickel is either appreciably lower than 6 per cent. or appreciably higher than 11 per cent., and the composition is in consequence described sometimes as "anomalous." But it is clear that this point of view is conventional.

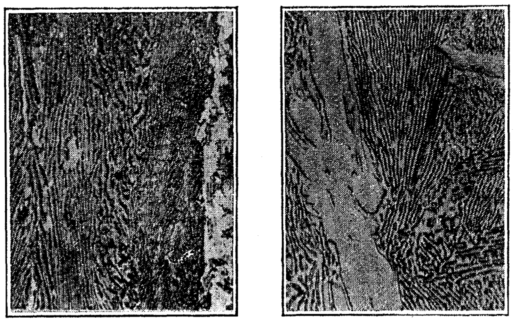
The essential fact is that no nickel-iron alloy, meteoric or terrestrial, is known which gives Widmanstätten figures when the percentage of nickel, in the portion of the material showing the figures, is less than about 6 or more than about 15. Neither of these limits has been fixed precisely, because the structure of an alloy which gives the figures is heterogeneous and the amount of the meteorite used for the analysis is generally small (*cf.* COHEN, I., p. 86).

§ 8. Numerous analyses are available of meteoric irons, poor in nickel, which are practically homogeneous (COHEN, I., p. 97). From these it is seen that the percentage of nickel may be as high as 7 per cent. without occurrence of Widmanstätten figures. Moreover, the crystalline characteristics and other physical properties of "hexahedral" iron (the commonest of the homogeneous types) are practically identical with those of the kamacite of octahedral iron (COHEN, I., p. 85), and, finally, although such iron may contain only 4 per cent. of nickel or less (*cf.* COHEN and BREZINA, 'Akad. Sitzungsb. Wien,' vol. 113, 1904; MOISSAN, 'Comptes Rendus,' vol. 139, p. 773, 1904), those specimens richest in nickel contain practically the same percentage of nickel as the kamacite of octahedral iron. Hence it seems clear that the percentage of nickel can reach some value between 6 and 7 without occurrence of heterogeneous crystallisation in the material from which the meteorite is formed; and that when the amount exceeds this value, the whole of the material cannot crystallise as kamacite. Another alloy richer in nickel (taenite) then makes its appearance, and the production of Widmanstätten figures by etching becomes possible.

At first, when the percentage of nickel only slightly exceeds 7, the structure is relatively coarse. The layers of less nickeliferous alloy (kamacite) are broad and the thin lamellæ of the alloy richer in nickel (taenite) which border the layers of kamacite are sometimes absent. But as the percentage of nickel rises, the kamacite layers become narrower and the layers of taenite more abundant. The kamacite is gradually displaced from its position of predominance and the figures eventually become too fine to be visible except when highly magnified (COHEN, I., pp. 100, 101) (*cf.* Section VII., § 15, p. 103).

§ 9. Data are not available by which to decide the question whether there is a definite percentage of nickel at which the Widmanstätten figures disappear. Modern methods of micrographic analyses have not yet been applied to the material at disposal.

Of particular interest, however, in connection with the theory of solid solution is the San Cristobal meteorite. It contains about 26·5 per cent. of nickel (**Cohen**, 'Sitzungsb. Akad. Wiss., Berlin,' p. 608, 1898), and this, as will be seen from the previous diagram (fig. 23, p. 67), is approximately the percentage contained by the supposed eutectic corresponding to the point B of the diagram. The structure of this meteorite is described by **Cohen** (*loc. cit.*), and also, more recently, by **Brezina** (Wien, 'Denkschr. Akad. d. Wiss., math.-naturw. Classe,' vol. 78, p. 638, 1905).* In the photograph given by the latter (Plate II., fig. 12), representing a portion of the meteorite magnified 23 times, the left half of the field shows a remarkable resemblance in structure to the eutectic of iron-carbon alloys of the type known as *lamellar pearlite.* This resemblance is shown in the annexed figure, in which are placed side by side a portion of **Brezina**'s figure and of one given by **Osmond** ('Microscopic Analysis ot Metals,' p. 85. Compare also 'Roberts-Austen Reports, Alloys Research Committee,' 1899 and 1904).



San Cristobal Meteorite.
(**Brezina.**)
(?) contains eutectic
percentage of nickel.

Lamellar Pearlite.
(**Osmond.**)
Contains the eutectic
percentage of carbon.

×23. ×1000.

Fig. 24.

§ 10. The present state of knowledge concerning the general structure of nickel-iron alloys of natural origin (omitting those in which carbon, phosphorus, and other elements are present in considerable quantity) can be summarised as follows :—

(1) Meteoric iron is, in general, homogeneous when it contains less than 7 per cent. of nickel. (2) It is heterogeneous when the percentage of nickel lies between 7 and 14. (3) It becomes practically homogeneous again when the percentage of nickel exceeds some value, apparently between 15 and 35 per cent., which could possibly be fixed by further careful microscopic investigation.

It is clear that these facts can be interpreted if we assume that the taenite (thin layers of nickeliferous material), which appears when the percentage of nickel exceeds 7, is a eutectic consisting of (1) "mixed crystals" containing about 7 per cent. of Ni, and (2) "mixed crystals" containing the considerably higher percentage of Ni corresponding to that at which the structure of the alloy again becomes homogeneous.

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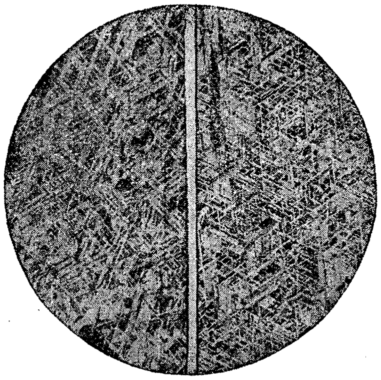
* I am indebted to Mr. L. **Fletcher**, F.R.S., for drawing my attention to this paper.

§ 11. With respect to the evidence that taenite is a eutectic there is to be noted, first, its mode of occurrence and distribution (already indicated), next, its microscopic and chemical characteristics, and, in conclusion, as will be seen, the magnetic properties of the meteoric iron in which it occurs.

In connection with the distribution of taenite mention should be made of a very striking photograph given by ARNOLD and McWILLIAM ('Nature,' vol. 71, p. 32, 1904. Similar photographs have been given by OSMOND, 'Annales des Mines,' vol. 17, Plate III., 1900—and by others). From this photograph it is evident that a steel containing about 0·4 per cent. of carbon gave, on comparatively rapid cooling after casting, a micrographic structure practically identical in form with that of octahedral meteorites. The two constituents "ferrite" and "pearlite" are distributed in the same way as the "kamacite" and "taenite" in the meteoric iron.

To indicate the degree of similarity, there are placed side by side in the accompanying figure the photograph given in 'Nature' (*loc. cit.*) and a reduced copy of the photograph given by COHEN and BREZINA ('Structur der Meteoreisen,' Plate X., fig. 3) of a specimen of meteoric iron (Tazewell meteorite) containing between 12 and 15 per cent. of nickel.



Cast Steel.
× 22 diameters.

0·4 per cent. Carbon.
Ferrite (light).
Pearlite (dark).

Meteoric Iron.
× 2 diameters.

13 per cent. nickel (approx.).
Kamacite (light).
Taenite (dark).

Fig. 25.

In the one photograph the darker constituent is pearlite (ARNOLD and McWILLIAM, *loc. cit.*) and in the other taenite (COHEN and BREZINA, Erklärung der Tafeln, *loc. cit.*). In the one the constituent of lighter colour is ferrite, and in the other kamacite. The section is cut parallel to an octahedral face in the meteoric iron, but the plane of section is evidently slightly inclined to an octahedral face in the steel.

Now a reference to the equilibrium curves for carbon-iron alloys shows that when a 0·4 per cent. carbon steel cools from a temperature above 780° C., ferrite will form in gradually increasing amount, in the state α from the state γ, until the eutectic temperature (690° C.) is reached. At this temperature the remainder of the iron will recrystallise as pearlite, a eutectic mixture of ferrite and cementite.

In the same way, by hypothesis, when a nickel-iron alloy containing, say, 10 per cent.

of Ni cools from a temperature above 700° C., kamacite will form in gradually increasing amount until the eutectic temperature (below 100° C.) is reached. At this temperature the remainder of the material, containing the percentage of Ni represented by GB (fig. 23, p. 67), will separate as taenite, an intimate mixture of kamacite containing GE per cent. of Ni and of a more nickeliferous alloy containing GF per cent. As will be seen, the extraordinary similarity between the structures of the iron-carbon and iron-nickel alloys above described would follow as a natural consequence of this hypothesis. Hence the way in which taenite is distributed relatively to the kamacite strongly supports the view that taenite is a eutectic.

§ 12. The microscopic characteristics of taenite, when examined under high magnification, are in accord with this view. All observers agree that it is not homogeneous (*cf.* Tschermak, 'Denkschr. Akad. Wiss. Wien,' vol. 31, p. 187, 1871; Osmond, 'Comptes Rendus,' vol. 137, p. 1057, 1903).

§ 13. The chemical analyses of taenite confirm the view that it is not homogeneous. Different analyses of the kamacite of octahedral iron do not vary much among themselves and show that this alloy usually contains between 6 and 7 per cent. of nickel. It is otherwise in the case of taenite. References are given by Cohen (*loc. cit.*, I., p. 102, II., p. 217) to the published analyses of taenite and I have arranged these in three groups in the following table.

Percentage of Ni (Co).	Meteorite.	Observer.	Reference.
13·56	Cosby Creek	Reichenbach	'Pogg. Ann.,' 1861, vol. 114, p. 258.
14·0	Caille	Meunier	'Ann. Chim. et Phys.,' 1869 (4), 17, p. 31.
15·0	Caille	Meunier	'Ann. Chim. et Phys.,' 1869 (4), 17, p. 32.
16·68	Casas Grandes	Tassin	'Proc. U.S. Nat. Mus.,' 1902, 25, p. 73.
19·6	Kenton	Nichols	'Field Columb. Mus.,' 1902, p. 314.
24·65	Welland	Davison	'Amer. Journ. Sci.,' 1891 (3), 42, p. 64.
26·70	Welland	Davison	'Amer. Journ. Sci.,' 1891 (3), 42, p. 64.
25·73	Staunton	Cohen and Weinschenk	'Ann. Nat. Hofm. Wien,' 1891, vol. 6, p. 146.
27·0	Cosby Creek	L. Smith	'Comp. rend.,' 1881, vol. 92, p. 843.
28·41	Magura	Weinschenk	'Ann. Nat. Hofm. Wien,' 1889, vol. 4, p. 97.
29·74	Cranbourne	Flight	'Phil. Trans.,' 1882, p. 888.
30·33	Misteca	Cohen	'Ann. Nat. Hofm. Wien,' 1892, vol. 7, p. 152.
31·54	Cañon Diablo	Florence	'Amer. Journ. Sci.,' 1895 (3), 49, p. 101.
34·00	Medwedewa	Berzelius	'Pogg. Ann.,' 1834, vol. 33, p. 133.
34·46	Wichita	Cohen and Weinschenk	'Ann. Nat. Hofm. Wien,' 1891, vol. 6, p. 155.
34·61	Chupaderos	Manteuffel	'Ann. Nat. Hofm. Wien,' 1892, vol. 7, p. 150.
34·74	Toluca	Cohen and Weinschenk	'Ann. Nat. Hofm. Wien,' 1891, vol. 6, p. 137.
35·66	Cañon Diablo	Fahrenhorst	'Ann. Nat. Hofm. Wien,' 1900, vol. 15, p. 376.
36·96	Glorieta	Cohen and Weinschenk	'Ann. Nat. Hofm. Wien,' 1891, vol. 6, p. 157.
37·31	Bischtübe	Cohen	'Ann. Nat. Hofm. Wien,' 1897, vol. 12, p. 54.
38·13	Youndegin	Fletcher	'Mineral. Mag.,' 1899, 12, p. 174.
48·43	Beaconsfield	Sjöström	'Sitzungsb. Akad. Berlin,' 1897, p. 1041.

§ 14. The earlier data contained in the above table are doubtful, since they represent the results of the first attempts at analysis of taenite. For instance, in some of MEUNIER'S experiments the kamacite and taenite were separated by means of the difference in colour, blue in the one and yellow in the other, produced by superficial oxidation of a powdered sample of the iron. Since careful microscopic examination shows that taenite and kamacite can occur in alternating layers, each not more than a small fraction of a millimetre in thickness, it is clear that such a method of separation cannot be relied upon. The difficulty of completely separating nickel and cobalt from iron by chemical analysis has, moreover, been realised more fully since the date of these experiments.

Of the two later analyses giving a percentage of nickel in taenite less than 20, it is not claimed for the second that it is more than "fairly correct." Only 0·02 gramme of material was used in the analysis, and this amount was obtained by a laborious mechanical selection from the rest of the iron.

With respect to the analysis by TASSIN, it is not certain from the description how the separation was effected.

A later analysis by TASSIN of a sample of taenite from another meteorite yielded 36 per cent. of nickel ('U.S. National Museum,' vol. 28, p. 215, 1905).

§ 15. In the second group of the table are collected the analyses which give values for the nickel (together with cobalt) content ranging between 25 per cent. and 30 per cent.

In three at least of the seven analyses (those by DAVISON and FLIGHT respectively) the method of separation was mechanical. No chemical solvent was used. In the paper describing the analysis of the Cosby Creek (Sevier) meteorite no details are given, but the material was apparently picked out of portions of the iron which had been disintegrated by oxidation. It is significant to note that this taenite and that analysed earlier by REICHENBACH (and giving 13·56 per cent. of Ni) were obtained from different specimens of the same meteoric iron (see COHEN, I., p. 103). Of the two analyses given by DAVISON, one refers to the comparatively broad bands of taenite (thickness $\frac{1}{15}$ to $\frac{1}{30}$ millim.), and the second to the narrower bands (thickness about $\frac{1}{100}$ to $\frac{1}{200}$ millim.) picked from the so-called "plessitic" layers of the iron.

With respect to the specimens of taenite in this group, which were separated chemically by the continued action of dilute hydrochloric acid, it is noteworthy in connection with the interpretation which follows below, (1) that the physical properties of the Magura taenite agree closely with those of the plates picked by FLIGHT from the Cranbourne meteorite, and that the iron is described by WEINSCHENK as soluble with difficulty; (2) that the plates of Staunton taenite were relatively thick and rich in carbon; (3) that the physical properties of the Misteca taenite were intermediate between those of the Staunton taenite and those of several almost carbon-free taenites referred to below.

§ 16. In the third group of the table the percentage of nickel lies, in round numbers, between 35 and 40.

A distinguishing feature of the analyses collected in this group is the length of time during which the solvent action of the acid upon the material was continued. In each case dilute HCl was used of such strength (usually 1 of acid to 10 or 20 parts of water) that the solvent action upon the nickel-rich alloy (taenite) was very slow compared with that upon the nickel-poor alloy (kamacite). The acid was, in each case, frequently renewed, and the action extended over three months in three cases, and over two months in another. One analysis only (Cañon Diablo, Florence) gave a less percentage of nickel than 34, viz. 31·54, and against this must be placed a subsequent analysis of a specimen of the same meteorite performed, purposely with the greatest care as a check upon the first, by FAHRENHORST and giving the value 35·66.

It is important to notice that the total percentage of taenite in the iron varied greatly from one meteorite to another. Thus, for example, COHEN obtained from about 70 grammes of Bischtübe iron enough taenite to enable him to use 0·4 gramme in his analysis; while out of 100 grammes of the Youndegin meteorite FLETCHER obtained less than 0·1 gramme. The Glorieta meteorite was especially rich in taenite (containing apparently more than 10 per cent. of the latter) and was characterised by extremely thin alternating layers of kamacite and taenite. The removal of the kamacite (which was relatively very difficult) left a sponge-like skeleton of taenite, and during the action of the acid it was noticed that plates not more than 0·15 millim. thick sometimes consisted of alternating layers of kamacite and taenite.

Under the circumstances of the analyses, as indicated above, the agreement amongst the numbers obtained by different observers is remarkable, and it seems difficult to avoid the inference that the ultimate residue, after the action of the acid, was in every case the same.

But for the analysis of the Beaconsfield taenite, which is anomalous in more respects than its percentage of nickel (*e.g.*, its specific gravity), the data so far considered agree with the view that the percentage of nickel in the nickel-rich constituent of taenite is not very different from 40.

§ 17. The last point in connection with the chemical data, regarded in this way, is the information they afford concerning the percentage composition of the eutectic as a whole.

If taenite is the eutectic, the action of the acid during long continued treatment of meteoric iron is twofold. In the first place it removes the layers of kamacite adjacent to the taenite, and in the second, when the action is sufficiently long continued, it removes the portion of the eutectic that consists of kamacite from the taenite itself; but *if the taenite can be separated mechanically from the adjacent kamacite and analysed, the percentage of nickel found will be that contained by the eutectic.* In the Welland and Cranbourne meteorites the mechanical isolation of the taenite was undertaken on account of the comparative ease with which it could be performed. The average of the percentages of nickel obtained in this mechanically isolated taenite is approximately 27—almost identical with that obtained in the Cosby Creek taenite, which was probably also separated mechanically. It is remarkable that this percentage should agree so nearly with that suggested by thermomagnetic data to be contained by the eutectic; but the interpretation from the present point of view is obvious.

The chemical data can thus be explained simply if it is assumed that octahedral iron consists of two nickel-iron alloys, one (kamacite) nickel-poor but homogeneous and easily soluble in very dilute hydrochloric acid, the other (taenite) nickel-rich but heterogeneous and consisting of alloys nickel-richer and nickel-poorer, of which the poorer is much the more soluble in the dilute acid.

§ 18. In the classification of the constituents of octahedral iron, proposed originally by Reichenbach, it is usual to include a third constitutent, "plessite." It is distinguished by its mode of occurrence; but, on account of the difficulty of isolation, no complete analysis has been made. Unless the meteorite is comparatively rich in nickel, plessite is not abundant; in many octahedral meteorites it is scarce, and in some it is apparently absent (*cf.* Cohen, *loc. cit.* II., p, 219).

This section of the paper in its original form included a discussion of the nature of plessite and of the point of view advocated by Osmond that plessite is the eutectic; but this discussion, to some extent a digression and involving also the question of nomenclature, is omitted from considerations of space.

§ 19. In discussing the question of the composition of meteoric iron from the point of view of the theory of solution, Osmond suggests that the curve showing the temperature of disappearance of magnetism in the irreversible alloys should be regarded as the true equilibrium curve marking the beginning of crystallisation (accompanied by the appearance of magnetism) in these alloys. On the assumption that the irreversibility would disappear if the cooling were excessively slow, and that the rate of cooling of the meteoric iron may have been such as to satisfy this condition for reversibility, Osmond infers that the eutectic temperature could be as high as 360° C., and also that the compositions of the constituents of the eutectic could be explained from the curves (*cf.* fig. 23, p. 67) if it appeared subsequently (from chemical or other evidence) that the eutectic found in meteorites contained as much as 40 per cent. of nickel and was composed of alloys containing possibly 5 per cent. and 50 per cent. of nickel respectively.

The work on carbon-iron alloys above referred to (Arnold and McWilliam, *loc. cit.*) shows incidentally that although slow cooling *may* be essential to the production of large-scale Widmanstätten figures, this is not the case—as far as mere form is concerned—when the figures are small.

Further, it is doubtful (see below, Section VII., § 15, p. 103) whether infinitely slow cooling would cause crystallisation to proceed in the way which Osmond suggests.

Again, if it cannot be said that the chemical evidence disproves the view that the eutectic contains 40 per cent. of nickel, it can at least be said that there is as much in favour of the view that it contains between 25 and 30 per cent.

It would be unwise to generalise from the thermomagnetic analysis of a single specimen; but, as will be seen below, the Sacramento meteorite certainly possesses a constituent containing between 25 and 30 per cent. of nickel, of which the internal structure is complex and, as seen above, a consideration of the chemical data in detail distinctly supports the view that there is a constituent *in all octahedral meteorites* which contains between 25 and 30 per cent. of nickel and which consists of components unequally attacked by acids.

Finally, the presence of a 25 to 30 per cent. Ni constituent can be explained naturally, on the assumption that it is a eutectic, by means of the already known thermomagnetic properties of nickel-iron alloys; while the existence of a 40 per cent. Ni eutectic requires, for its explanation from the experimental curves, hypothetical extrapolation.

SECTION VI.—AN INTERPRETATION OF THE "IRREVERSIBILITY" OF NICKEL-IRON ALLOYS.

§ 1. From the point of view of the theory of solution, considerable interest attaches to those experiments of the present paper in which the nature of the thermal hysteresis of the nickel-iron alloys is examined.

The qualitative resemblance between the thermal hysteresis in the return of magnetism in nickel-iron alloys and the phenomena of supersaturation has already been commented upon (*cf.*, *e.g.*, GUILLAUME, 'Recherches sur le Nickel et ses Alliages,' 1898).

A comparison of the properties of nickel-steel with those properties of supersaturated solutions recently described by MIERS ('Nature,' August 24, 1905, vol. 72, p. 412) suggests that the analogy is even closer than has appeared hitherto. MIERS finds that a solution of a salt of given strength, saturated at a temperature θ_1, remains supersaturated, when the temperature is lowered, until a definite temperature θ_2 is reached. Throughout the range θ_1 to θ_2, crystallisation will not begin, however long the solution be allowed to stand (if surface evaporation is prevented), unless crystals of the salt are added from without. The value of θ_2, like that of θ_1, depends upon the strength of the solution. If crystals are introduced at temperatures between θ_1 and θ_2, they grow at the expense of the salt in solution; but the growth proceeds slowly even if, in order to facilitate uniform distribution of the salt, the solution is kept stirred.

When, however, the temperature reaches θ_2, a change in the condition of equilibrium of the solution occurs, which is accompanied by spontaneous generation of crystalline nuclei. The solution, saturated at θ_1, may be said to pass from the metastable to the labile state at θ_2. The immediate effect of the formation of the crystalline nuclei is, of course, to reduce the concentration of the salt left in solution. Hence, since the temperature of transition from the metastable to the labile condition decreases when the concentration is diminished, the remaining solution is metastable at the temperature θ_2, and further crystallisation can ensue only in the way already described as characteristic of the metastable state, viz., round the crystalline nuclei formed. It will be assumed for simplicity that any thermal effect accompanying the formation of crystals can be ignored.

If the temperature is kept constant at θ_2, there will be a very slow crystallisation of the salt in solution. The amount taking place will be very small if the time during which the temperature is maintained constant is short—even if, as before, the solution is kept stirred. If the temperature is maintained at θ_2 for a sufficient length of time, crystals will continue to grow round the original nuclei until the amount of salt left in solution is that required to produce a saturated solution at θ_2. If the temperature is now assumed to fall slightly, the solution becomes supersaturated and metastable. Crystallisation will proceed slowly round the crystals already formed until the solution again becomes saturated, and will then cease. Hence extremely slow cooling from the temperature θ_2 at which the labile condition first appears will be such as to favour the growth of the largest and most symmetrical crystals it is possible to obtain.

If, however, the rate of fall of temperature below θ_2 is rapid compared with that just contemplated, it is easy to see that the process of crystallisation will be different. The temperature will fall below θ_2 before the solution has deposited enough crystals to become saturated at that temperature. It is still supersaturated and, if the amount of crystallisation round the nuclei, since the advent of the labile condition at θ_2, has been small, it will pass almost immediately from the metastable to the labile state. A fresh deposition of crystalline nuclei will then ensue. This process will be repeated again and again as the temperature falls—the growth round each set of nuclei being a very slow process will not proceed far before, by reduction of temperature, the solution has again reached the labile condition. Hence comparatively rapid cooling will cause the growth of a succession of sets of small crystals.

An important deduction (of which the significance in the supposed analogous case of solid solution will be seen below) from the behaviour during comparatively rapid cooling, as set out above, is that at any temperature below θ_2 the amount of crystallisation will reach, practically at once, a value which will not increase appreciably until the temperature suffers a further fall. The rate of growth round the nuclei will be so small compared with the rate of formation of the nuclei themselves that the amount of crystallisation at a given temperature will appear to be approximately a single-valued function of the temperature.

Again, for the purposes of the analogy which it is sought to develop between a crystallising solution and cooling nickel-steel, suppose that the comparatively rapid cooling below θ_2 is interrupted and that the temperature of the mixture of solution and crystals is raised. The crystals will not begin to go into solution again at once, for the solution surrounding them is already supersaturated. They will not begin to re-dissolve until the temperature is attained at which the solution is saturated, and this temperature will be higher in proportion as the temperature from which the reheating begins is nearer θ_2. (It is, of course, supposed throughout that the salt is one of which the solubility increases with the temperature.) Hence, if the temperature is subject to variation between that at which the cooling was interrupted and that at which the solution ceases to be supersaturated, there will be no solution of the crystals formed during the first cooling from above θ_1.

On the other hand, if the temperature is kept constant at any value between the limits in question, there will be a slow growth of crystals around those already formed and the concentration of the solution will approach slowly, from near the crystals outwards, to that corresponding with saturation at the temperature considered.

Further, when the reasons why the rate of growth round the nuclei is slow are considered, it is seen that the alternation of temperature between limits θ'_2 and θ'_1 (where $\theta'_2 > \theta_2$ and $\theta'_1 < \theta_1$) will cause the growth to occur more rapidly than if the temperature were kept constant at θ'_2. The salt crystallises round the nuclei because at the temperature θ_2' the solution in contact with them is supersaturated. By removal of the salt this solution approaches the normal saturation strength at θ'_2, and further crystallisation does not occur until the concentration loss is made good by the diffusion of salt inwards from the more concentrated layers of solution further away from the crystals. Increase of temperature will increase this rate of diffusion and hence, also, the rate of crystal growth. The effect of increase of temperature will be most pronounced at first because the concentration gradient in the solution will have then its maximum value—the crystals being then surrounded by an extremely thin layer of solution saturated at θ'_2, immediately beyond which is the supersaturated solution. At each alternation of temperature the distance over which the concentration varies between saturation at θ'_2 and that of the main bulk of supersaturated solution will become larger and the concentration gradient will consequently become smaller. Hence each successive heating to θ'_1 will be accompanied by the approach of a smaller amount of crystallisable material, to the crystallising nucleus, than the last, assuming each reheating to occupy about the same length of time as the one preceding it. Effects of the kind here contemplated will be most pronounced in solutions of which the viscosity is not only large, but subject to rapid decrease with rise of temperature. They may be represented qualitatively by a diagram, such as that given below (fig. 26, I.), in which the ordinates represent the amount of crystals present in contact with the solution and the abscissæ are temperatures.

It is assumed that an amount of crystals, represented by OA, is present originally in contact with a solution saturated at θ_0, and that when the solution and crystals are heated—the solution being allowed to become saturated at any temperature—the amount of crystals present gradually diminishes, following the upper curve ABC. At θ_1 all the crystals have dissolved, and above this temperature the solution is unsaturated. When the solution is allowed to cool, crystals reappear at θ_2 and, if the cooling continues at such a rate that there is no appreciable growth of crystals except by successive deposits of nuclei, the amount of crystals present at any temperature below θ_2 will be represented diagrammatically by the lower curve C′B′A′.

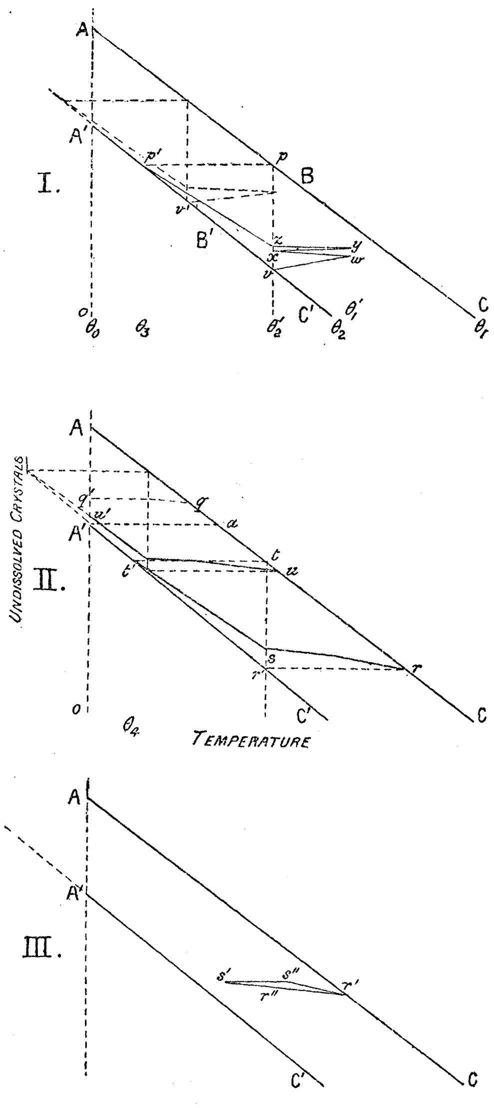


Fig. 26.

If the cooling is interrupted at θ'_2, and the system is re-heated to θ'_1, the amount of crystals present may increase as represented by the curve *vw*. This will not be, in general, a straight line, but a curve of which the slope will vary in a way depending upon the relative magnitudes of the effects of the decrease in the concentration gradient due to deposition and of the increase of the rate of diffusion due to rise of temperature. During cooling from θ'_1 to θ'_2, the growth is represented by the curve *wx*, which is flat compared with *vw*, because the rate of diffusion gets less as the temperature falls. The next curve *xy* may be steeper than *wx*; but the succeeding element *yz* will be flatter. Finally, on account of the continuous decrease in the gradient, crystallisation will proceed so slowly that alternation of temperature between θ'_2 and θ'_1 will be without appreciable effect upon its amount.

Assuming the effect of alternations of temperature carried out comparatively rapidly to be represented by *vwxyz*, the effect of allowing the material to cool below θ'_2 may now be considered. With the exception of the layers surrounding the crystals, the solution will have the same concentration as it possessed when the cooling was first interrupted at θ'_2. It is metastable at θ'_2, but a small lowering of temperature is sufficient to reduce it to the labile condition. Hence crystallisation will begin at θ'_2, and will continue at lower temperatures in this solution exactly as in the case of uninterrupted cooling. Through *p*, the point in which the ordinate at θ'_2 cuts the curve ABC, let *pp'* be drawn parallel to the axis of temperatures and cutting the curve A′B′C′ in *p'*. Then below the temperature corresponding to *p'* (θ_3) the crystallisation curve will coincide with the corresponding part of A′B′C′; between θ'_2 and θ_3 the curve will follow a course represented diagrammatically by *zp'*. This follows because, by hypothesis, the process represented by *vwxyz* caused the strength of the solution round the crystals to become practically equal to the saturation value at θ'_2. From the curves ABC and A′B′C′ it is seen that a solution of this strength does not pass into the labile condition until the temperature θ_3 is reached. Hence there is no further deposition of nuclei from this solution until θ_3 is reached. Further, a solution labile at θ'_2 deposits crystals during cooling at such a rate that it also is labile at θ_3. Hence both the solution which lost salt by deposition round crystals already present and that which lost salt by the continuous formation of nuclei reach θ_3 in the labile condition, and thus, at the end of the process represented by *vwxyzp'*, there will be practically the same amount of labile solution remaining as after uninterrupted cooling along C′B′*p'*. All the solution is again labile at θ_3, and the curves of interrupted and uninterrupted cooling will coincide below this temperature. From the figure (26, I.) it is clear that if the cooling is first interrupted at some temperature lower than θ'_2, like that corresponding with *v'*, the solution round the crystals present, originally, at *v'* may still be metastable when the temperature θ_0 is reached.

Other effects of thermal treatment may be exhibited diagrammatically in a similar way. Thus, to consider the possible effects of interrupted heating following the saturation curve ABC, suppose first that the heating is discontinued before the temperature reaches the value corresponding to the line A′*a* (*e.g.*, at *q*, fig. 26, II.), *i.e.*, before the solution is concentrated enough to become labile, during cooling, at θ_0. Then it is clear that no crystallisation by formation of nuclei will occur during subsequent cooling to θ_0. The crystal growth during cooling, which can occur only round crystals already present, may be represented by the curve *qq'*.

Next suppose that the heating is first interrupted at some temperature above that represented by *a*. In this case the strength of the solution is such that on cooling it will become labile before θ_0 is reached. Let *r* be the point at which the heating is interrupted. Crystals will grow round those already present comparatively rapidly at first, on account of the relatively high concentration gradient and temperature, but the rate of growth will diminish subsequently, because the temperature effect and the effect of the gradient now conspire to retard it. When the temperature reaches the value corresponding to the ordinate *r't* the supersaturated solution at a distance from the crystals will pass into the labile state, and the formation of nuclei within it will begin. The solution in the immediate neighbourhood of the crystals, being more dilute, will still be metastable, and the last portion of it—that corresponding to saturation at the temperature represented by *r'*—will not become labile until the temperature θ_4 (represented by *t'*, fig. 26, II.) is reached. At θ_4 all the solution will be in labile equilibrium, and the growth of crystals subsequently will be along C'B'A'. (For the sake of simplicity it has been tacitly assumed that crystallisation round crystals is inappreciable below the point *s*.)

It is easy to see that if the heating along ABC is interrupted at some point between *q* and *r*, such as *u*, the solution round the crystals will not become labile until some temperature lower than θ_0 is reached.

Finally, consider the case in which the cooling from the curve ABC is interrupted before any of the solution has reached the labile state and the system is reheated. Crystals will grow during the cooling round those present, as already described. When the reheating begins, assuming the solution round the crystals to be still supersaturated, crystals may continue to grow, but, obviously, before the outer curve ABC is reached the temperature will reach a value at which the solution round the crystals is not supersaturated. Beyond this temperature the crystals will begin to re-dissolve and the solution round the crystals will become saturated at the expense of the crystals which were deposited from it during cooling. When the temperature from which the cooling began is reached, practically all the solution will again be saturated at this temperature, and the result of further rise of temperature will be that the crystals will dissolve, following the curve ABC. If the zone in which loss of salt by the solution takes place during cooling is of considerable extent, there will be a perceptible lag in the return of the state in which all the solution is saturated. In such a case the temperature at which the heating was first interrupted will be reached before the whole solution is saturated again at this temperature, and the amount of crystallisation may therefore, for some degrees above this temperature, exceed that corresponding to the saturation curve ABC.

These conclusions rest upon the assumption, which is apparently justified by the experiments of MIERS (*loc. cit.*), that the temperature at which a supersaturated solution becomes labile is a single-valued function of its concentration. It remains to show how many of the results described in Section IV. can be explained on the assumption that crystallisation occurs in nickel steel from a solid solution, in accordance with a similar law.

§ 2. The irreversible phenomena discovered by HOPKINSON can be interpreted at once in terms of the theory outlined above. Thus, whilst magnetism is disappearing during heating, magnetic crystals are, by hypothesis, dissolving in solid solution, and, finally, when all the crystals have disappeared, the material consists of a solid solution only. It is a homogeneous mixture, of which the constituents may be crystalline, but are not magnetic. Further, just as in a mixture of crystals and water, the temperature at which the last of the crystals dissolve rises when the relative amount of crystals originally present is increased, so the temperature of the disappearance of magnetism, in a mixture of iron crystals and nickel, rises when the percentage amount of iron present increases.

When the magnetism has just disappeared, a saturated solid solution remains. If this is allowed to cool it becomes supersaturated and metastable, but eventually it becomes labile. The temperature of lability, at which spontaneous recrystallisation begins, is definite and depends upon the relative amounts of nickel and iron present in the material. It decreases as the percentage of nickel in the alloy increases, just as the temperature at which lability is reached in a supersaturated salt solution decreases as the percentage of water which it contains increases.

Thus, qualitatively, the manner of disappearance and reappearance of magnetism in nickel-iron alloys corresponds with that of disappearance and reappearance of crystals in fluid solution.

§ 3. The applicability to the case of solid solutions of the fundamental hypothesis discussed in § 1 with respect to fluid solutions seems to receive remarkable confirmation from the experiments already described. The general characteristics of the thermomagnetic curves and the quantitative relations between them, when a numerical comparison can be made, are in accord with the theory.

The changes in the alloy when heated will differ slightly from those in the hypothetical case of an aqueous salt solution considered above. They will correspond more nearly with those which would occur in a crystallised salt which can go into solution in its own water of crystallisation. Referring to fig. 27, IV., the amount of crystalline material will remain constant (following the horizontal line) until a temperature is reached represented qualitatively by B. Gradual solution of the crystals will then begin and will continue until, at the point C, they have disappeared.

If the percentage of nickel in the alloy is less than that contained by the eutectic, the changes that take place in the material in the region BC will be (according to the theory of mixed crystals) as follows :—

Considering a small element of the material at first magnetically crystalline, when the temperature is slightly above B, a small quantity will change its state. There will be a redistribution of the components chemically as well as physically, since the composition of the crystals is different from that of the solution. The small quantity of solid solution first formed will be richer in nickel than the mixed crystals which remain. A larger fraction of the total amount of nickel than of the total amount of iron will go into solution.

But as the relative amount of the solution increases, the percentage amount of nickel it contains will diminish, until, finally, when the last of the crystals disappear, the composition of the solid solution will be the same as that of the original crystallised material.

During recrystallisation the reverse process will occur. The crystals first formed will be relatively weak in nickel, but as their amount increases so also will the percentage of nickel they contain. A larger fraction of the iron than of the nickel goes into the crystals, however, and the solution gets richer in nickel also, although it diminishes in amount.

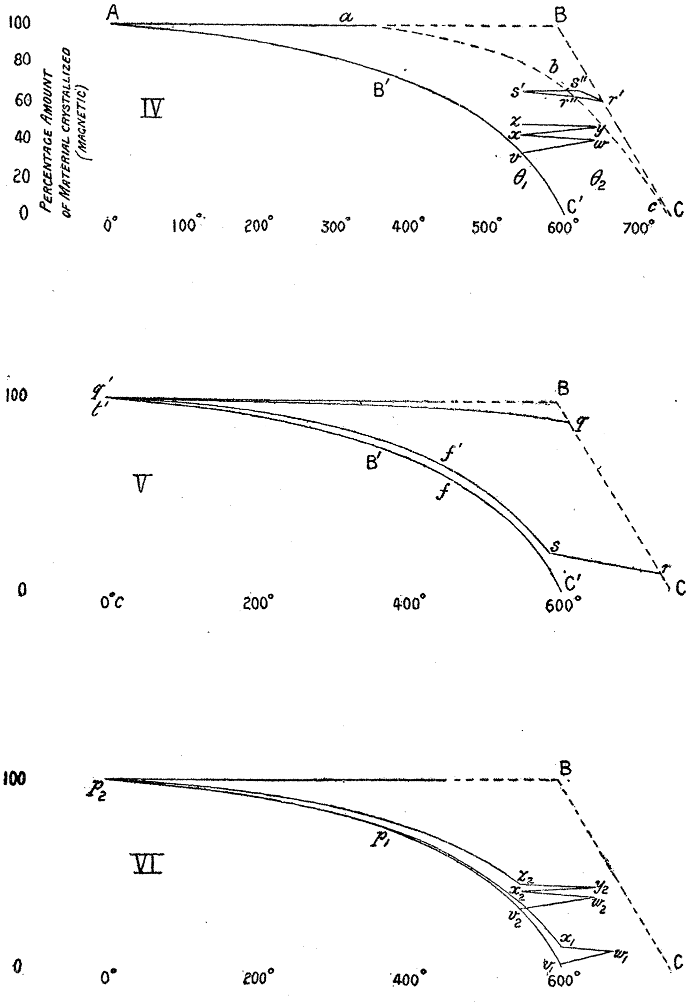


Fig. 27.

§ 4. To show how closely the permeability measurements agree with the view that the phenomena assumed above really occur, consider first fig. 27, IV.

Assume that the nickel-iron alloy contains about 6·5 per cent. of nickel. Crystals will begin to disappear at a temperature which has not yet been accurately fixed. Their solution will be complete at a temperature not far from 750° C.

The change may be represented qualitatively by the curve *a*BC (the ordinate giving the percentage of the material that is still crystalline at the temperature corresponding to the abscissa), although the curve for extremely gradual heating is more probably of the form represented diagrammatically by *abc*.

The curve of crystallisation during cooling can be calculated roughly from the data at disposal. Thus, at any temperature θ, the percentage of nickel in the labile solid solution is known approximately, since it is, by hypothesis, the same as the total percentage of nickel contained by that alloy in which magnetism reappears at θ.

It may be assumed as a first approximation from the experimental data that θ decreases linearly from $\theta = 780°$ C. when the percentage of nickel is negligible to $\theta = 0°$ C. when the percentage of nickel is 27, *i.e.*, that the curve AB of fig. 23 on p. 67 is approximately a straight line.

The percentage of nickel in the crystals in equilibrium with the labile solid solution in question is θp (fig. 23), θq being the percentage of nickel in the solution. Again assume, as a first approximation, that the curve AE showing the variation in the percentage composition of the crystals is a straight line. For reasons already given, suppose that E corresponds roughly to 6·5 per cent. of nickel.

If a is the total percentage amount of Ni in the alloy, and if x is the percentage amount of the alloy which is crystalline at the temperature θ, we have

$$\frac{\theta p}{100} x + \frac{\theta q}{100} (100 - x) = a,$$

from which, assuming that θp and θq can be calculated roughly as above, it is possible to find the value of x for any value of θ.

The curve C′B′A of fig. 27, IV., is plotted from numbers calculated in this way for $a = 6{\cdot}5$. It is assumed that the rate of cooling is sufficiently slow to ensure that all the crystals at any temperature contain the same percentage of nickel.

§ 5. The first conclusion from the curve C′B′A is that, in an alloy containing 6·5 per cent. of nickel, the amount of magnetic iron will increase rapidly at first as the temperature falls below 600° C., and then more gradually. The final portions of the alloy will become magnetic very slowly, and the return to the magnetic state of all the iron in the alloy will not be complete until the temperature is below the ordinary temperature of the air. This accounts for the fact, carefully examined in the first experiments with the meteoric iron (1st winding) and corroborated subsequently, that the permeability during cooling, *e.g.*, at 550° C., is considerably below that shown at the same temperature during reheating from 15° C. The fact is less obvious in the case of the artificial nickel steel. Thus, considering only the curves given by HOPKINSON and the corresponding curves of fig. 18, it would appear that all the iron had become magnetic when, during cooling, the temperature had fallen to about 550° C. But the later measurements show that the material is not in a state of final equilibrium at temperatures below 600° C. until it has undergone successive alternations between that temperature and 15° C., and that, when this state is considered, the behaviour of the steel is analogous to that of the meteoric iron (*cf.* § 12 below, p. 92).

§ 6. If the cooling is interrupted at some temperature below that at which magnetism appears and if the temperature is then varied between this and some higher temperature (*cf.* fig. 26, I.), the amount of magnetic iron should increase at first relatively rapidly and finally very slowly, as already explained. The slope of *vw* (figs. 26, I., and 27, IV.) should be greater than that of *xy*, and that of *wx* should exceed that of *yz*. In the same way the permeability change corresponding to *vw* should exceed that corresponding to *xy*, and that corresponding to *wx* should be greater than that corresponding to *yz*. If diffusion can only take place slowly, the increase in permeability will become imperceptible after a few alternations; *xy* and *yz* will be practically horizontal, and the temperature coefficient of permeability between the temperatures θ_1 and θ_2 (fig. 27, IV.) will become practically identical with that observed when all the iron is magnetic.

Examination of the data given in the tables shows that after the first alternation between given temperature limits in the meteoric iron and in the nickel steel, the change produced by subsequent alternations (during the time occupied by the experiments) is practically inappreciable, *i.e.*, *xy*, *yz*, &c., are practically superposed. An example of this is given in the data 30 to 34, meteoric iron, 2nd winding, fig. 11. A similarly rapid approach to a steady state is shown in the data 82 to 86, fig. 13.

Besides these examples of the process *vwxyz*, there are also numerous examples of the process *vwx* in the tables, which incidentally lead to the conclusion that if *y* and *z* had been observed in these cases the results would have been the same as in the experiments above mentioned. For the temperature coefficient of permeability over the range represented by *wx* has, within the limits of experimental error, in each case reached almost the same value as that over the same range when the material is fully magnetic. This is seen by comparing Experiments 51 and 52, 1st winding, with 8 and 9, and also Experiments 27 and 28, 75 and 76, 79 and 80, &c., 2nd winding, with 92 and 93. Also 90*b* and 91, 95 and 96, nickel steel, with 64 and 65.

§ 7. The observations upon the nickel steel when fully magnetic between 350° C. and 600° C. lie very approximately on a parabola in which the relation between the constants is such that $1/\mu \,.\, d\mu/d\theta$ has a maximum value at about 570° C., but varies so slowly with change of θ that its value is ·0041 at 500° C. and ·0042 at 650° C.—the maximum value being about ·0044. On account of the peculiarities of the meteoric iron curves a comparison cannot be obtained over this range, but the observations 92 and 93, fig. 13, correspond with a mean value of $1/\mu \,.\, d\mu/d\theta$ equal to

·0039. It is curious that for a sample of nearly pure iron, examined in the same way as the nickel-iron alloys, the mean temperature coefficient between approximately the same temperatures was found to be nearly the same as those of the alloys, viz., ·0037 (between 630° C. and 480° C., $H = {\cdot}43$), although the mean permeability of the iron was more than four times that of the meteoric iron and more than double that of the nickel steel.

§ 8. The data 63 to 69, &c., nickel steel, show that the reversible fully magnetic state of the material extends between the air temperature and 610° C. If the heating is continued beyond 610° C.—for example to 640° C. as in 72—irreversible effects are produced (shown by the magnetic behaviour on cooling). This is interesting as showing that the change of internal structure begins below the temperature of maximum permeability of the material as a whole. (*Cf.* Section IV., § 8, p. 63.)

The fact that the loss of magnetism is very gradual in nickel-iron alloys instead of being very sudden as in nearly pure iron is clearly in accord with the theory of the process by which the alloys lose their magnetism. In iron the temperature at which the permeability becomes practically indistinguishable from that of the air is only a few degrees above that at which $d\mu/d\theta$ first becomes negative. In each of the alloys there were about 130° C. between the corresponding temperatures. (*Cf.* Section V., § 4, p. 69.)

§ 9. If the heating is interrupted at some temperature between that at which the magnetism begins to disappear and that at which it has become inappreciable, and if the temperature is then varied between this temperature and some lower temperature above that at which the solution becomes labile (*cf.* fig. 26, III.), the changes in the amount of crystallisation can, as already explained, be represented graphically by the curve $r'r''s's''$ (figs. 26, III., and 27, IV.).

The agreement between this deduction and the permeability data is shown by the experiments r'' (163), s' (164), s'' (165); r'' (173), s' (174), s'' (175), meteoric iron, 2nd winding, fig. 15.

§ 10. The cases in which heating, interrupted at some temperature between B and C (fig. 27, IV.) is followed by uninterrupted cooling to the air temperature may next be considered (*cf.* fig. 26, II.).

The two cases which will differ most from each other are represented in fig. 27, V.

In the first (qq'), the heating is interrupted soon after solid solution has begun to form, *i.e.*, soon after magnetism has begun to decrease.

In the second (rst'), the heating is not interrupted until the magnetism has nearly disappeared.

In the former case, in accordance with the explanation already given (*cf.* fig. 26, II.), the solid solution, rich in nickel, will deposit crystals (at a decreasing rate) as the temperature falls. It will become still richer in nickel during crystallisation (*cf.* Section V., § 2, p. 67) and will itself not become labile until a low temperature is reached. Hence, over a considerable range of falling temperatures, the state of the material will differ from that of complete crystallisation represented by AB (fig. 27) only in the respect that very thin layers of solid solution will be present. All of the alloy will be magnetic, with the exception of thin intervening gaps of non-magnetic material. The permeability variation for a considerable range (below a temperature at which the rate of crystallisation has become inappreciable) will be precisely the same as when the material is in the state corresponding to the curve Aα. At each temperature the permeability will be less in a constant proportion than when the material is wholly magnetic.

The extent to which this conclusion is verified is shown by the following data :—

NICKEL Steel (see Curves, fig. 21) Cooled from 689° C.

Number of experiment.	(75).	(76).	(77).	(78).	(79).	(82).
μ	4·53	2·90	1·80	1·39	0·85	1·39
μ_0	—	3·58	2·42	1·74	1·11	1·8
μ/μ_0	—	0·81	0·75	0·80	0·77	0·77

The values of μ_0 were obtained from the curve joining points 63 to 69 (Nickel Steel, fig. 18), by interpolation, for temperatures corresponding to (76), (77), &c.

In the second case of fig. 27, V., in which the heating is interrupted at a comparatively high temperature, the change in the degree of crystallisation will proceed in a different way. There is at first a considerable amount of solid solution comparatively weak in nickel, and the temperature is relatively high. During the early stages of the cooling there will be a considerable amount of crystallisation round the existing nuclei, and the solution round these nuclei will become comparatively rich in nickel. The main portion of the solution will, however, remain weak in nickel, and will become labile when that temperature is reached which is represented by the point of intersection of the horizontal line through r and the curve C′B′A (*cf.* fig. 26, II.). Subsequently crystallisation will proceed from this solution exactly as when uninterrupted cooling took place from a temperature higher than C.

But the portions of the solution from which crystallisation took place during the stage represented by rs will have become of similar content in nickel to the solution existing at q in the first case, and will not become labile until a low temperature is attained. The permeability variation, for a considerable range below a temperature such as f (fig. 27, V.) will be the same on cooling from r as on cooling from C, but the permeability itself will be less in a constant proportion at each temperature in the former case than in the latter. This will happen, in spite of the greater amount of total crystallisation represented by the curve rst' in comparison with the curve

C′B′A, because of the well-known effect of gaps in a magnetic circuit. The amount of crystallisation at *f′* is greater than at *f*, for example, but the excess results from crystallisation round nuclei, which is accompanied by the production of layers of non-magnetic material which surround these nuclei.

These conclusions can be tested by examination of the relation between the permeability data obtained during the cooling of the nickel steel from 810° C. and from 750° C. respectively.

The data are given in the tables (p. 46) in the experiments from 20*b* to 28 and from 50 to 58. The relation between the permeability variations in these two series of observations is shown graphically in fig. 20 (nickel steel), in which the unnumbered dotted curve corresponds with that drawn through the points 21 to 29 in fig. 18.

The quantitative relation between the data is shown in the table below :—

NICKEL Steel (see Curves, figs. 18 and 20).

Number of experiment.	(50).	(51).	(52).	(53).	(54).	(55).	(57).	(58).
μ	0·395	0·76	1·705	1·49	1·38	1·245	0·97	1·37
μ_0	—	0·1	2·45	1·96	1·80	1·63	1·255	1·80
μ/μ_0	—	7·6	0·70	0·76	0·77	0·76	0·77	0·76

The values of μ_0 were obtained, by interpolation from Experiments 21 to 29, for the temperatures corresponding to 51, 52, &c.

From these data it is seen that below 460° C. the permeability variations in the two cases are practically identical, and that the value of the permeability in the one case is about three-fourths of the corresponding value in the other (*cf.* Section IV., § 8, p. 62).

It is also seen that the observations 50, 51 (fig. 20) agree with the view that crystallisation round crystals already present takes place above 650° C. The rapid rise of permeability between 51 and 52 is consistent with the hypothesis that the bulk of the solution present at 50 began to crystallise from the labile state at about 650° C. This temperature is approximately that at which a permeability curve, corresponding to a constant amount of crystallisation and passing through 50, would cut the curve through 21 and 22 (see fig. 18).

§ 11. The explanatory value of the theory is still further confirmed by the measurements, after interrupted cooling, of the permeability at the temperature of the air.

It was noticed frequently (see Section IV., §§ 5, 7 and 8) that the permeability at the air temperature was less after interrupted cooling than when the cooling from beyond the critical point was continuous. That such effects are to be expected will be seen on consideration of fig. 27, VI. If the cooling is interrupted at a comparatively high temperature such as v_1, crystallisation will proceed from the metastable solution during subsequent reheating to w_1 and cooling to x_1. At the latter point the bulk of the solution has again reached the temperature of lability, and crystallisation proceeds by generation of fresh nuclei. But the solution from which crystals separated, during the treatment $v_1w_1x_1$, has become relatively rich in nickel and will not become labile until a temperature lower than x_1 is reached. The value of this temperature will depend upon the amount of crystallisation that ensues during the process $v_1w_1x_1$.

If it is comparatively small, the whole of the solid solution remaining at p_1 may be in the labile state, and crystallisation during further cooling will take place in the same way as when the cooling from C is uninterrupted.

If, however, there is a considerable amount of re-crystallisation during the process $v_1w_1x_1$, or if the amount is increased by repetition of the process as in the case $v_2w_2x_2y_2z_2$, then the solution from which crystals have been deposited round nuclei may have become so rich in nickel that it does not become labile until a low temperature, such as p_2, is attained. The mean permeability of the material at the air temperature may then be relatively low.

Examples of the correspondence between these conclusions and the experimental data are given below.

Meteoric Iron I. v (45), w (46), x (47).

Here the range of the alternation is about 60° C. and the permeability x is about $8\frac{1}{2}$ per cent. greater than the permeability v.

The subsequent air temperature permeability (Experiment 48) is about 4 per cent. less than that obtained after continuous cooling (*cf.* Experiment 49).

Meteoric Iron II. (Curves, fig. 11). v (26), w (27), x (28).

Here the range of the alternation is about 100° C. and the permeability x is about 16 per cent. greater than the permeability v.

The subsequent air temperature permeability (29) is about 6 per cent. less than that obtained after continuous cooling (111).

v (30), w (31), x (32), y (33), z (34).

Here, after two alternations over a range of about 100° C., the subsequent air temperature permeability (35) is about 11 per cent. less than after continuous cooling (Experiment 111).

Nickel Steel (see Curves, fig. 22). v (94), w (95), x (96).

Here, after a single alternation over about 60° C., the permeability x is about 23 per cent. greater than v, and the subsequent air temperature permeability (97) is about 16 per cent. less than that after continuous cooling (85).

It is important to notice that even in a case like $v_1w_1x_1p_1$, in which it is assumed that all the solution remaining at p_1 is simultaneously labile, just as when the cooling is uninterrupted, the permeability may be less below p_1 than after continuous cooling. For, in the former case, if the cooling has not taken place sufficiently slowly, the portions of the solution of which the crystallisation has been retarded (by the deposition from them of crystals less rich in nickel than themselves) may give rise eventually to crystals containing an appreciably greater percentage of nickel than is contained by the original nuclei which they surround.

Thus interrupted cooling may, on account of the incomplete equilibrium due to difficulty of diffusion, be followed by a less homogeneous crystallisation of the material as a whole than when the cooling is continuous. If this does occur, the permeability will be less in the less homogeneous material, because (*cf.* HOPKINSON, 'Roy. Soc. Proc.,' *loc. cit.*, p. 70, above) the permeability of a nickel-iron alloy in a given weak field decreases as the percentage of nickel increases towards 25.

§ 12. Owing to the comparative lowness of the temperatures at which the last stages of the crystallisation occur, it is probable that the greatest degree of homogeneity will not be attained unless the cooling is extremely slow and that, if the cooling is comparatively rapid (occupying only a few hours), the formation of mixed crystals will be incomplete at ordinary temperatures. A subsequent alternation of temperature between that of the air and a higher temperature (below that at which solid solution begins to re-appear) will then produce a perceptible effect upon the permeability-temperature curve. It will accelerate the passage of the material into the state of final equilibrium, to be expected theoretically, in which the crystallisation is complete and the composition of the crystals is uniform.

The experiments 97 to 107 (nickel steel, p. 47) may be cited as an example of the effects of such alternation. The data are shown graphically in fig. 22 (nickel steel). Precisely similar effects are shown also in figs. 17, 19, and 20. From each of the curves it seems that, during reheating, little effect is produced until the temperature exceeds 450° C.; but, beyond this, there is a considerable accession of permeability (*cf.* Section VII., § 11, p. 101). The effect is most noticeable in those cases in which the previous value of the permeability at the air temperature is low.

SECTION VII.—THE COMPOSITION OF THE SACRAMENTO METEORITE AS DETERMINED BY THERMOMAGNETIC ANALYSIS.

§ 1. A comparison of the thermomagnetic curves of the meteoric iron with those of the artificial alloy, and with the data given by OSMOND and others, shows, in the first place, that the iron consists largely of an alloy containing about 6 per cent. of nickel. This agrees with the result derived from chemical analysis, that the kamacite of octahedral iron contains between 6 and 7 per cent. of nickel. As already shown (see, *e.g.*, the magnified photograph of the core, Plate 1, fig. 4), the present meteorite consists mainly of kamacite.

§ 2. The thermomagnetic behaviour of the meteorite at temperatures below 500° C. shows, however, that its structure is complex, that it does not consist wholly of the $6\frac{1}{2}$ per cent. alloy, kamacite. This is seen in the curves for the first winding (fig. 9), and again very clearly in fig. 14, second winding. The latter shows, in greater detail than the former, that there is an irreversible alloy present in which magnetism disappears at about 480° C., and reappears near the temperature of the air. It is seen that this alloy behaves, on interrupted heating, in the way characteristic of irreversible alloys.

Inspection of the available experimental data shows that the alloy having the thermomagnetic properties just stated is the richest in nickel of the irreversible alloys, and contains about 27 per cent. Ni.

The results thus point to the conclusion that the thin bands of nickel-rich alloy which occur in the meteorite contain between 25 and 30 per cent. of nickel. The geometrical distribution of the taenite in the ring has already been described (Section I., § 5, p. 25) and its loss of magnetism would clearly produce gaps in the magnetic circuit and consequent diminution of permeability.

The amount of nickel-rich alloy in the material is proved to be small not only by inspection of the etched surface, but also by the chemical analyses (Section I., §§ 2, 3, pp. 23, 24) of the meteorite as a whole. If the meteorite contains m per cent. of Ni, and the kamacite and taenite k and t per cent. of Ni respectively, then the number of grammes of taenite in 100 grammes of the meteorite is

$$x = 100\,(m-k)/(t-k).$$

This assumes, of course, that the distribution of the kamacite and taenite is uniform (*cf.* the analyses by Foote, p. 23, and Wraight, p. 24).

If we assume that in the present case, in round numbers, $m = 7{\cdot}3$, $k = 6{\cdot}5$, and $t = 27$, then $x = 4$ approximately, *i.e.*, only about 4 per cent. of the meteorite can consist of taenite.

Inspection of the curves of fig. 14 (see p. 56) shows that when the nickel-rich constituent is magnetic the permeability of the ring is over 60 per cent. greater than when it is not magnetic, but 4 per cent. of the nickel-rich constituent is quite sufficient to account for this difference. Thus, if a ring contains x per cent. of an alloy of permeability μ_2 arranged as a single transverse gap in the rest of the material (which is of permeability μ_1), the equivalent permeability of the whole ring will be

$$\mu = \mu_1\mu_2 \Big/ \left\{\mu_2 + \frac{x}{100}(\mu_1-\mu_2)\right\}.$$

If $x = 1$ and $\mu_1 = 100$, then, when $\mu_2 = 1$, the permeability will be

$$\mu = 50{\cdot}25,$$

i.e., the presence of 1 per cent. of a non-magnetic alloy would reduce the permeability to half the value it would have if the non-magnetic alloy were replaced by material of the same permeability as the rest of the ring.

If $\mu_2 = 5$, then, when $x = 1$,

$$\mu = 84 \text{ approx.},$$

i.e., the permeability in the case just considered would be increased nearly 70 per cent. if the permeability of the material in the gap rose from $\mu_2 = 1$ to $\mu_2 = 5$.

The permeability of the kamacite in the field used in the experiments is more than 100 (Section III, § 7, p. 40), and that of a 27 per cent. alloy when magnetic is at least 5 in the same field (*cf.* HOPKINSON'S curves, 'Roy. Soc. Proc.,' 1890). Hence the loss or gain of magnetism by the small quantity of the richer alloy known to be present, occurring transversely in the ring, would produce an effect of the kind and relative magnitude shown in fig. 14.

§ 3. The curves of fig. 14, in conjunction with the other data, prove that, at the end of the experiments, the meteoric iron consisted almost entirely of two irreversible alloys, viz., a small quantity of an alloy containing between 25 and 30 per cent. of nickel and a relatively large quantity of an alloy containing between 6 and 7 per cent. of nickel. After the experiments the ring was polished and etched and showed a distribution of the kamacite and taenite which, as far as careful examination through a lens could decide, was identical with that existing in the core in its original state.

Hence, although the internal structure of the taenite may have changed during the course of the experiments, its distribution with respect to the rest of the meteorite remained practically unaltered. At the end of the experiments it was an irreversible alloy containing about 27 per cent. of nickel.

But a careful examination of the data obtained at different times after the beginning of the thermal treatment seems to show conclusively that the taenite was subject to alteration of internal structure during the course of the experiments and did not, at the outset, possess the same properties as the artificial alloy containing 27 per cent. of nickel.

The evidence, as will be seen, supports the hypothesis that the taenite was originally a mixture, thermomagnetically discernible, of a nickel-poor alloy such as kamacite and of a much richer alloy containing not less than 37 per cent. of nickel.

If, as before, we assume that the taenite contains t per cent. of Ni and that it is a mixture of kamacite containing k per cent. of Ni and of an alloy containing t' per cent. (where t' is greater than t), the number of grammes of kamacite in 100 grammes of the eutectic will be

$$x = 100\,(t'-t)/(t'-k),$$

and if we assume that, in round numbers, $t' = 40$, $t = 27$ and $k = 6{\cdot}5$, then

$$x = 39 \text{ approx.},$$

or, roughly, 40 per cent. of the eutectic will consist of kamacite.

Having, for the sake of directness, stated this view at the outset, the arguments in its favour may now be given.

§ 4. A preliminary experiment was performed soon after winding of the ring to find approximately the maximum permeability of the material. It gave the following numbers :—

Temperature.	H.	μ.
658° (approx.)	0·20 0·31	7·91 8·23

Previously, the ring had been heated only once to a high temperature, viz. to a dull red, during a preliminary testing of the heating apparatus. The permeabilities are given in the same arbitrary units as those of the figure for the first winding (see Section III., § 6, p. 39).

After the above measurements the ring was heated twice to a temperature above 800° C. Some months later the permeability was again measured, at temperatures comparable with the above, with the following results :—

Temperature.	H.	μ.
622°	0·43	4·72
661	0·445	5·17
678	0·44	4·38

Making every allowance for possible error of experiment and for the isolated character of the experiments first cited, it would seem to be proved that heating above 800° C., in the early stages of the heat treatment, is followed by a considerable lowering of the maximum permeability.

This conclusion is supported by the numbers given in the previous tables (pp. 42 to 45). The maximum permeability seems to have become gradually smaller as the experiments proceeded. Thus, whereas the maximum permeability first quoted above corresponds approximately to $\mu = 1000$ C.G.S., the highest value observed towards the end of the experiments during the first winding did not exceed 700 C.G.S. ($H = 0{\cdot}48$). The data obtained during the second winding show that at the end of the experiments the maximum permeability of the ring probably did not exceed 600 C.G.S. ($H = 0{\cdot}43$).

Although part of the decrease may have been due to oxidation of the ring, the results are clearly in accord with the hypothesis of a conversion of the nickel-rich and nickel-poor constituents of the taenite into a mixture which becomes non-magnetic at a temperature below that at which the permeability of one of the original constituents is a maximum. Similarly, if the maximum permeability observed during cooling is compared with the value observed at the corresponding temperature during heating it will be seen that it is relatively less in the second winding than in the first. Thus in the one case the ratio (at 540° C.) is about 1 : 2 and, in the other about 3 : 5. It is possible that part of this difference is due to the more gradual cooling in the first experiments; but part of it is possibly also due to decrease in the total amount of the nickel-poor alloy.

§ 5. If the values of permeability obtained below 500° C. during the 1st winding (when the meteorite had been heated only a few times to a high temperature) are compared with those of fig. 14 (representing the behaviour of the material after a large number of heatings), it will be seen that there are notable differences.

The field strengths (·48 and ·43 respectively) are different in the two cases; but the data already referred to show that the permeability variation with the field strength is not rapid enough to make this difference very important (*cf.* Section IV., § 2, p. 41). It is seen from the curves, however, that the percentage differences between the greater permeabilities at temperatures below 400° C. and those obtained at corresponding temperatures after continuous cooling from 800° C. are much less in the earlier than in the later experiments. The maximum value at the air temperature (assuming that the calculated constants of the two windings are substantially correct) is about the same at the end as at the beginning of the experiments, viz., about 280 and 270 respectively. But, in accordance with the statement above, the permeability at the air temperature after continuous cooling from 800° C. (about 220 C.G.S.) is considerably greater in the earlier than in the later experiments (about 170 C.G.S.).

These results agree with the interpretation (see below) that, after continuous cooling from 800° C., the gaps in the magnetic circuit at 15° C. (due to the taenite) are less at first when the taenite contains an appreciable amount of nickel-poor alloy and of nickel-rich alloy, separately magnetic at that temperature, than later, when practically the whole of the taenite may be non-magnetic.

§ 6. Upon heating from 15° C. the permeability decreases continuously in the earlier experiments until a temperature of about 300° C. is reached—the decrease being especially marked in the curves of greatest permeability (see fig. 9, 1st winding)—while in the later experiments the decrease is scarcely perceptible in the lowest curve and ceases below 100° C. in the curve of greatest permeability (see fig. 14, 2nd winding).

Thus in the first case the maximum decrease between 15° C. and 160° C. is about 12 per cent. and the minimum about 5 per cent.; in the second the maximum decrease (between 15° C. and 90° C.) is about 2·5 per cent. and the minimum is less than 0·5 per cent.

This decrease of permeability is of importance, whatever its interpretation may be, since it is peculiar to the meteoric iron. No similar phenomenon is shown, to my knowledge, in any of the permeability curves of nickel-iron alloys for weak fields published hitherto; but there is no doubt of its existence here since, as will be seen from the data, it was observed repeatedly.

Now, just as the data already cited indicate that the taenite contains a nickel-poor constituent which disappears or becomes magnetically undetectable under thermal treatment, so those just mentioned point to the presence of a nickel-rich constituent which behaves in the same way.

§ 7. By inspection of the curves drawn from OSMOND's data (with which the less complete results published by HOPKINSON and by DUMONT are in accord) it will be seen that an alloy containing more than 30 per cent. of nickel loses during heating, and regains during cooling, the greater part of its magnetic proporties at a temperature above 15° C., which is higher in proportion as the nickel content (below 70 per cent.) is greater. When the magnetic change (now approximately reversible) takes place at 300° C., the alloy contains about 37 per cent. of nickel (DUMONT, 'Comptes Rendus,' vol. 126, p. 742, 1898, gives 300° C. as the temperature of disappearance in a particular alloy containing 39·4 per cent. Ni).

Suppose that the taenite is originally a *comparatively* coarse mixture of alloys containing approximately 40 and 6 per cent. of nickel which exist together in such proportions that the taenite as a whole contains roughly 27 per cent. of nickel. The effect upon such a mixture of repeated heating to a high temperature and cooling under ordinary conditions will be to produce eventually the artificial alloy containing 27 per cent. of nickel in which the structure is comparatively fine (see below, Section VIII., § 2, p. 104, and § 11, p. 108).

During the first heating of the meteorite, after the original crystallisation, the permeability of the 6 per cent. alloy in the taenite will rise continuously to 650° C. That of the 40 per cent. alloy will rise at first, but will subsequently reach a maximum and afterwards practically disappear at about 350° C. (This was not observed—the material having been heated to dull redness, as already explained, before any observations were taken.) Above 750° C. the taenite will consist of two non-magnetic substances containing different percentages of nickel. During the first heating to 800° C. and the subsequent cooling there would be appreciable interdiffusion of these constituents.

In subsequent heatings (the material being raised to a high temperature between each) there would, on this hypothesis, be 6 per cent. and 40 per cent. alloys and also all intermediate artificial alloys in varying proportions. Gradually, however, the material as a whole would approach the condition of the artificial alloy of the same composition. Comparatively few heatings would be sufficient to convert the more intimately mixed portions of the 6 per cent. and 40 per cent. alloys into the artificial 27 per cent. alloy.

The early evidence of the presence of this alloy (shown in fig. 9) proves that much of the mixture is intimate.

When all the taenite had been converted into the artificial 27 per cent. alloy, the behaviour of the material as a whole would be as follows:—The permeability would rise continuously during heating at first, would reach a maximum in the neighbourhood of 400° C., would then fall comparatively rapidly until the rate of increase of permeability due to increase in temperature of the 6 per cent. alloy (of which the meteorite is mainly composed) over-balanced the rate of loss due to increase in temperature of the 27 per cent. alloy. The magnetism of the latter would finally disappear at about 490° C., and, if the heating were then discontinued, the permeability would remain lower than at the corresponding temperature during heating until, towards the temperature of the air, the permeability would become subject to a comparatively rapid increase.

§ 8. Inspection of fig. 14 (2nd winding) shows that this is almost exactly what is observed after the material has been heated a large number of times. The only essential difference is that there is still at first a small decrease in permeability, which ceases below 100° C., and which would be accounted for if there were still in the taenite small quantities of alloys containing slightly more than 27 per cent. of nickel.

On the other hand, when the material has been heated only a few times, the variation is different, as shown in the curves for the 1st winding. Here there is a pronounced decrease of permeability between 400° C. and 450° C. as before—pointing to the presence of a considerable amount of 27 per cent. alloy; but there is also another pronounced decrease during the first stages of the heating from 15° C. This is obviously what would occur if, besides the artificial 27 per cent. alloy, there were still appreciable quantities of alloys containing amounts of nickel intermediate between 27 and 40 per cent.

In the lower curve (*cf.* Experiments, *a*, *b*, *c*, Section IV., § 3, p. 42) the decrease continues approximately to 300° C., and hence in these early observations there is detectable the alloy containing at least 37 per cent. of nickel (see fig. 23).

§ 9. Of special significance is the peculiarity, above referred to, of these earlier and of the later curves, namely, that the percentage decrease of permeability at lower temperatures during heating is much greater when the permeability follows the upper curve than when it follows the lower.

This peculiarity will be seen by comparison of the experiments *a* and *b*, 33 and 34, 1st winding, with the experiments 1 and 2, 39 and 40, and also of the experiments 111 and 112, 2nd winding, with 119 and 122.

These results are in complete accord with the interpretation of the magnetic phenomena which is advocated. In the lower curves the permeability is relatively small, because (see § 11, below, p. 100) most of the irreversible 27 per cent. alloy has not undergone the transformation into the magnetic state. There are, in consequence, gaps in the magnetic circuit at 15° C. which are absent when the 27 per cent. alloy is magnetic—as it is when the upper curve is obtained. Consequently, during heating in the first case, the loss of magnetism by the reversible alloys merely causes increase of size in gaps already present, while in the second case the gaps are absent initially and are produced by the loss of magnetism of these reversible alloys.

Now the effect upon the induction through a circuit of the formation of a small transverse gap is very much greater when no gap is present initially than when the gap formed merely increases the size of one already in existence. Thus the induction B (in a given field), when there is a transverse gap equal to the fraction θ of the circumference in a ring of permeability μ, is

$$B = B_0/\{1+\theta(\mu-1)\},$$

where B_0 is the induction when the gap is absent. And since, from the above expression,

$$dB/d\theta = -B(\mu-1)/\{1+\theta(\mu-1)\},$$

it is seen that the effect of a small increase, $d\theta$, in the gap is greatest when $\theta = 0$, and, assuming $\mu-1 = 100$ (which is approximately the case in the present experiments), the percentage variation of B with θ is twice as great when $\theta = 0$ as when $\theta = 1/100$.

The above expressions apply only when the permeability of the material which loses its magnetism is assumed to be the same as that of the rest of the material. If the permeability of the former is less than that of the latter, the effect is of the same character, but less pronounced in proportion as the difference between the permeabilities increases; but the above computation is sufficiently accurate for the present purpose. It shows, when compared with the numerical data in the tables, that the effects observed are of the order of magnitude theoretically deducible, and confirms the view that they are due to the formation of breaks in the magnetic circuit in the way described.

§ 10. The thermo-magnetic data seem thus to point to the correctness of the view that the taenite is composite, that it is transformed by successive heatings into a relatively more homogeneous alloy (containing between 25 to 30 per cent. of Ni) and that the transformation takes place by the gradual interdiffusion of its richer and weaker constituents (containing probably not less than 6 per cent. of Ni in the one case and probably not more than 40 per cent. of Ni in the other).

Fig. 25 summarises the evidences for these conclusions. The full curves indicate the condition of the meteoric iron after it had been heated four times above 800° C. They have been plotted from the numbers given in the table on pp. 42, 43, using the constants of the 1st winding given on p. 39. The dotted curves indicate the state of the material after it had been heated about twenty times above 800° C., including once above 900° C. They were plotted from the data on pp. 43 to 45, using the constants

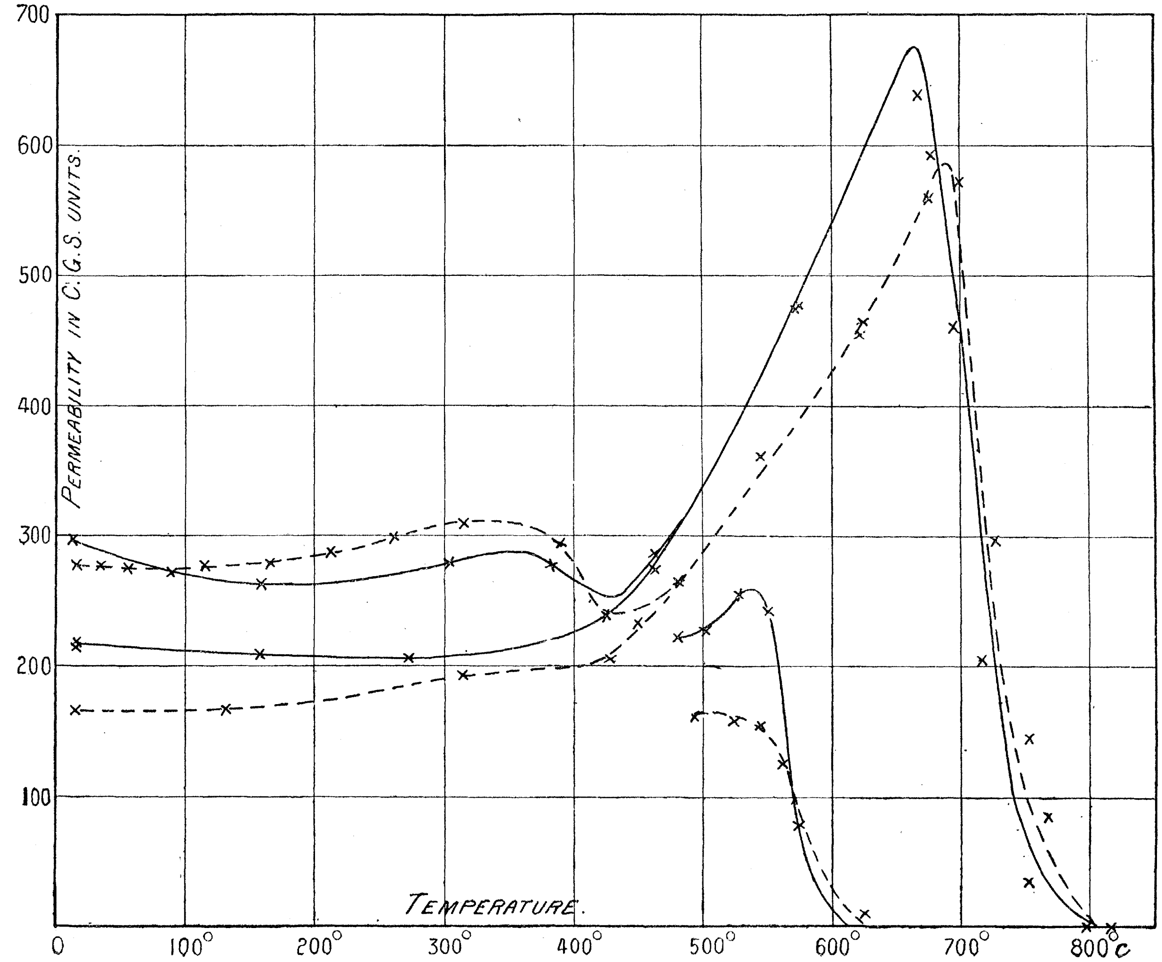


Fig. 28. Meteoric iron.

Permeability changes produced by repeated heating.

of the 2nd winding stated on p. 39. The greater distance of the lower dotted curve below the lower full curve at the air temperature than at temperatures above 350° C.; the greater permeability at temperatures above 100° C. on the upper dotted curve than on the upper full curve, and the greater permeability above 500° C. on the full curve than on the dotted curve, are all in accord with the interpretation given of the gradual change of the taenite produced by repeated heating.

§ 11. There is only one further point with respect to the curves for the meteoric iron that remains to be discussed, viz., the cause of the fact that the 27 per cent. irreversible alloy does not become magnetic at the normal temperature, for such an alloy, during the first cooling from 800° C.

It is probable (Section VI., § 5, p. 86) that an irreversible alloy containing only 6 per cent. of Ni is not completely transformed into the magnetic state during cooling until its temperature is near that of the air. The transformation is accompanied by considerable increase in volume. Hence, since the later stages take place at a low temperature, when the rigidity of the material is comparatively great, a considerable amount of internal strain may arise. It is in the already strained material that the transformation of the 27 per cent. alloy has to begin.

But if the material is subsequently heated to a temperature not high enough to cause the 6 per cent. alloy to begin to undergo the magnetic transformation in the reverse direction, the internal strain in this alloy will be diminished. The effect of such heating will be to make more homogeneous the distribution of iron and nickel throughout the material (Section VI., § 12, p. 92). A sufficient number of heatings would convert it from a heterogeneous mixture of alloys containing different percentages of Ni losing and gaining their magnetic properties at different temperatures into a homogeneous alloy magnetic at all temperatures between 15° C. and 600° C.

When the temperature is reached, during cooling, at which the 27 per cent. alloy (imbedded in the now more homogeneous alloy) tends normally to become magnetic, its transformation—retarded at first, perhaps in a way analogous to the depression of the freezing-point of water by pressure—may become possible. Indeed, when it is remembered (*cf.* HOPKINSON and GUILLAUME) that an irreversible alloy rich in nickel increases by about 2 per cent. in volume as it changes from the non-magnetic to the magnetic condition, it is clear that an appreciable part, at least, of the observed retardation must be due to an effect of the kind just mentioned.

§ 12. The views expressed in the above and in the preceding paragraphs were confirmed by some experiments on the effect of thermal treatment upon the density of the meteoric iron, in which it was found that changes in density corresponding with the changes of permeability produced by heating to different temperatures, as above described, could be observed; but these experiments are omitted for the present from considerations of space.

It may be mentioned, however, as showing the advantages of the thermomagnetic method of analysis, that a change in the taenite which produces an alteration of over 50 per cent. in the permeability of the meteorite is not enough to produce a change of more than 0·1 per cent. in the density.

§ 13. If the conclusions already given are correct, it is possible to discuss with some confidence the conditions under which the characteristic structure of meteoric (octahedral) iron has arisen.

Suppose that the alloy is comparatively poor in nickel, *i.e.*, that it contains only a little more than the minimum amount necessary for the existence of Widmanstätten figures, and suppose further that the structure is acquired during cooling of the alloy from a comparatively high temperature.

The material will be a homogeneous solid solution of iron and nickel at temperatures above 700° C. Below this temperature the solution is metastable, but spontaneous crystallisation (see Section VI., § 1, p. 78) cannot occur until a temperature of about 600° C. is reached. The solution then becomes labile, and spontaneous generation of nuclei can take place. If the subsequent rate of cooling is extremely slow the crystallisation will proceed (see p. 79) around the first nuclei.

Suppose that these original nuclei are arranged in the form of an octahedral network (*cf.*, *e.g.*, the crystals of steel described by TSCHERNOFF, 'Metallographist,' vol. 2, 1899, p. 74) and that the material is of comparatively uniform composition, so that the octahedral lamellæ of crystalline nuclei are at nearly uniform distances apart. These nuclei will contain a relatively small percentage of nickel (see Section V., § 2, p. 67, also fig. 23), and the remaining solid solution will contain a greater percentage of Ni than the meteorite as a whole. If the cooling continues extremely slowly, crystallisation will proceed around the nuclei from the metastable solid solution. The crystals (both the nuclei and the deposits around them), and also the solid solution, will gradually get richer in nickel (*cf.* Section VI., § 3, p. 85).

If the rate of cooling is sufficiently slow, the strength of the solid solution (in the spaces between the octahedrally arranged bands forming round the first growth of nuclei) may continue to increase, so that its temperature remains always above that at which it passes into the labile condition. Under these circumstances there will be no further spontaneous generation of nuclei (above the eutectic temperature) after that which occurs at 600° C.

The "crystallisation" (*i.e.*, regular structural re-arrangement of the material) will proceed outwards from each of the octahedral planes along which the spontaneous re-arrangement began. The layers of solid solution (material not yet structurally re-arranged) will become gradually narrower. At the same time the layers of "crystallised" material will become wider. Throughout the whole process there will be a continual re-adjustment of the percentages of iron and nickel in the crystals and in the solid solution.

The final state of the material below the air temperature will be such that it contains layers of homogeneous nickel-poor alloy and thin intervening layers of eutectic. The actual width of each layer of nickel-poor alloy will depend upon the distance apart of the first lamellæ formed when the material reached the temperature of lability; but the ratio of the widths of the nickel-rich and nickel-poor layers (taenite and kamacite) will be nearly constant if the original distribution of lamellæ is symmetrical.

§ 14. A perceptible change in the process of crystallisation will occur if the rate of fall of temperature is more rapid than that above contemplated, so that, after the first deposition of nuclei during cooling, the solid solution does not always remain above its temperature of lability. Then the growth of crystals may be insensible between the time of deposition of one set of nuclei and the next. At each deposition crystals slightly richer in nickel than those last deposited will be formed, and a solution richer in nickel will be left. The latter will remain metastable while the temperature falls a little; then it will become labile and there will be a fresh deposition of nuclei. The crystallisation will thus proceed by spontaneous generation of successive sets of nuclei from a solid solution which gets continuously richer in nickel as the temperature falls. The strongest solution will contain about 27 per cent. of nickel, and, becoming labile at about the air temperature, will begin to crystallise then as a mixture of nickel-rich and nickel-poor alloys. At any temperature above this there will be always some solid solution, which, after partial crystallisation in the condition of lability, leaves a stronger solution which is metastable until the temperature falls.

During cooling the solid solution will never become so rich in nickel that it contains more than 27 per cent., for any solid solution containing less than this percentage can begin to crystallise by becoming labile before the eutectic temperature (about 0° C.) is reached, and when the latter temperature is attained the solid solution remaining will crystallise as a mixture of the nickel-rich and nickel-poor alloys.

In its final state the material will be roughly homogeneous, for practically the same process of crystallisation will have occurred in every small element of the mass. There will be mixed crystals containing every proportion of nickel from 2 or 3 per cent. to about 6·5 per cent. (as well as the richer crystals of the second type formed at the eutectic temperature), for the cooling will have proceeded so rapidly that the continual redistribution of nickel necessary to produce uniformity in composition of the mixed crystals (of the nickel-poor type) will not have had time to occur.

§ 15. On such a view of the process of crystallisation during cooling as is above indicated, it will be seen that a structure identical in form with that observed in the Widmanstätten figures and similar in composition to that shown by the magnetic properties is explicable. The fact that the breadth of the layers of kamacite sometimes varies from one part of a meteorite to another would be explained by difference in the rate of cooling, or in the manner of deposition of nuclei in different parts of the material. The fact that the average thickness of the kamacite bands decreases as the total percentage of nickel in the material increases can be explained in the same way. Thus, for example, in a meteorite containing a relatively high percentage of nickel, *e.g.*, 12 per cent., the whole material will exist "uncrystallised" until a temperature in the neighbourhood of 300° C. is reached. When this temperature—the temperature of lability of the metastable solid solution—is attained, crystallisation will begin; but the rate of growth round the original nuclei will be so slow (on account of the lowness of temperature) that, unless the rate of cooling is excessively slow, there will be a succession of returns to the state of lability during cooling. If we assume that the successive growths of nuclei take place in parallel octahedral layers, the final result, after the eutectic temperature is passed, will be comparatively narrow bands of kamacite with intervening thin bands of taenite.

When the percentage of nickel is higher than 15 or 20 per cent., the temperature at which the crystallisation begins will be so low that, as in the case of comparatively rapid cooling considered above, the crystallised material may appear to be homogeneous (*cf.* Section V., §§ 8 and 9, p. 71).

§ 16. It seems clear that if meteoric iron were kept for an indefinite period at a high temperature (below its melting-point), the structure which distinguishes it from artificial nickel iron, of the same percentage composition, at the air temperature should disappear. For the material should thereby be converted into a uniform solid solution which, on cooling, under ordinary conditions would undergo the same changes as take place in the artificial alloys. The disappearance of the meteoric structure would take place by interdiffusion between the taenite and the kamacite by which the original taenite layers would become eventually much poorer in nickel and the kamacite layers a little richer. This process would apparently be very slow, however, unless the temperature were raised much above the highest used in the present experiments in which very little interdiffusion of these two constituents seems to have occurred. I have attempted to show, however, from the thermomagnetic curves, that the temperature conditions permitted an analogous process, on a very minute scale, to take place within the taenite itself in the time over which the experiments extended. The taenite, initially a relatively coarse mixture in which, owing to the slowness and uniformity of the original cooling, comparatively large crystals of the two components of the eutectic were present, became gradually converted into a fine-grained mixture of the same constituents possessing appreciably different thermomagnetic properties.

SECTION VIII.—FURTHER DATA FROM ARTIFICIAL ALLOYS.

§ 1. In the preceding section an attempt has been made to establish quantitatively, from thermomagnetic data, the truth of the hypothesis, due originally to ROOZEBOOM, that nickel-iron alloys are examples of a system giving rise to a series of mixed crystals of two types and possessing a eutectic, or transition point.

The evidence is based mainly upon a study of meteoric nickel iron and, if the conclusions are correctly drawn, it follows that:—

(*a*) If the cooling alloy contains less than about 27 per cent. of nickel, the crystals which form first are of the nickel-poor type and contain, when stable equilibrium is reached, not more than 7 per cent. of nickel.

(*b*) If the cooling alloy contains more than 27 per cent. of nickel, the crystals which first form are of the nickel-rich type and contain not less than 37 per cent. of nickel.

(*c*) If the cooling alloy contains (approximately) 27 per cent. of nickel, there are formed simultaneously mixed crystals of two types, one containing not more than 7 per cent. and the other not less than 37 per cent. Ni. The transition begins (*cf.* Section VII., § 11) in this alloy at about the ordinary temperature of the air. The beginning of the transition in any other alloy occurs at a higher temperature.

§ 2. Although the existence of the eutectic is to be expected below 0° C. in any alloy containing more than 7 per cent. or less than 37 per cent. of nickel, it has not yet been identified micrographically in artificial alloys.

I have attempted to show, however, that it can be identified in meteoric iron in which the rate of cooling has probably been slow and uniform, and which has probably remained for a very long time at or below the eutectic temperature. In such alloys the segregation of the two constituents of the eutectic has proceeded to an extent that is magnetically discernible.

If the above conclusions are correct it would seem that the eutectic cannot be definitely detected microscopically in artificial alloys only because of the absence of sufficient segregation, but it is still possible that the thermomagnetic method (of which the advantages have been pointed out) may reveal its presence.

§ 3. The thermomagnetic data, for various artificial alloys, have already been discussed, but there is a further series of experiments to which reference should be made (*cf.* HONDA and SHIMIZU, 'Phil. Mag.,' 1905, pp. 548 and 642). Messrs. HONDA and SHIMIZU have not, to my knowledge, given any interpretation of their results, but they have determined the thermomagnetic properties for temperatures between about $-186°$ C. and 800° C., and fields up to about 400 C.G.S. units, in the case of eleven nickel-iron alloys.

For the present purpose the most important data are those for a 36 per cent. alloy, and for a set of six alloys containing percentages of nickel ranging from 29·24 to 24·04. Unfortunately there are no similar data for alloys containing lower percentages of nickel.

According to the views stated above, the 36 per cent. alloy will give rise on cooling to mixed crystals almost wholly of the nickel-rich type.

Of the others, the $29\frac{1}{4}$ per cent. alloy, containing a little more than the eutectic percentage of nickel, will give first mixed crystals of the nickel-rich type, but, subsequently, when the eutectic temperature is reached, a eutectic mixture of nickel-rich and nickel-poor crystals. The 24 per cent. alloy, on the other hand, containing a little less than the eutectic percentage of nickel, will give first mixed crystals of the nickel-poor type, and, subsequently, at a lower temperature, the eutectic mixture.

§ 4. In seeking for the interpretation of the results obtained, it is necessary to consider the extent to which nickel-rich and nickel-poor crystals are likely to be thermomagnetically distinguishable.

A study of the permeability curves for nickel-iron alloys, at the air temperature after cooling from a high temperature, shows that these alloys can be divided magnetically into two classes.

When the percentage of nickel is 35 or more the alloy is magnetically soft. The "second stage" in the magnetisation curve is soon attained and the maximum permeability occurs when the field intensity reaches 2 or 3 C.G.S. units.

When the percentage of nickel is 25, or less, the alloy is magnetically hard. The hardness decreases as the nickel content is reduced. When the percentage of Ni is 25 the maximum permeability is not attained until H = about 50 C.G.S units, but even when the percentage is as low as 5, a field intensity of, roughly, 10 C.G.S. is required.

It is clear, therefore, that mixed crystals containing about 7 per cent. Ni and forming at or near the temperature of the air must, although their exact properties are not deducible *a priori*, be distinguishable magnetically from mixed crystals containing not less than 37 per cent. of nickel.

Further, the effects of temperature change upon the BH curves will be very different in the two cases.

In the nickel-rich crystals, on account of their magnetic softness, increase of temperature (below the critical temperature) will not be accompanied by increase of induction (for a given field) unless the field intensity is small. In the nickel-poor crystals, however,

$$(dB/d\theta),\ \text{H constant},$$

will not become negative until H is relatively large.

Thus, while in each case the $\mu\theta$ curve will be convex to the axis of temperature when the field is very small, it will become concave to the axis of temperature in the nickel-rich alloy under a field for which the $\mu\theta$ curve of the nickel-poor alloy is still convex.

These relations are shown in HOPKINSON'S curves ('Roy. Soc. Proc.,' 1890; *cf.* also WILLS, 'Phil. Mag.,' 1900).

§ 5. The significance of the results obtained by HONDA and SHIMIZU may now be briefly considered.

In the 36 per cent. alloy, for a field of 50 C.G.S., the permeability decreases continuously from the temperature of liquid air to that at which magnetism practically disappears (about 250° C.). The decrease is most rapid at the end, nearly half of the original magnetisability being lost between 150° C. and 200° C.

Further, there is very little thermal hysteresis during cooling and, in sharp contrast with the behaviour of the alloys containing less than 30 per cent. of Ni, the magnetic properties at 15° C. are practically unchanged by cooling to $-186°$ C. This is clearly in agreement with the theory already given when it is remembered that 36 per cent. is approximately the nickel content of the least concentrated of the nickel-rich mixed crystals.

§ 6. In the alloys containing between 30 and 28 per cent. Ni the permeability decreases as the temperature rises from $-186°$ C. until a temperature of about 150° C. is reached. Beyond this the permeability rises for $H = 50$, and diminishes slowly for $H = 400$, to a temperature of about 300° C. After this the permeability falls at first gradually and then very rapidly in both fields as the temperature approaches 500° C.

These data are clearly explicable if we assume that, at $-186°$ C., each alloy is a mixture of the magnetically soft 36 per cent. nickel-iron and of a magnetically harder alloy for which the permeability increases with rise of temperature, even when $H = 50$, and disappears at a higher temperature than that of the soft alloy.

The character of the magnetism which first appears during cooling is significant.

If the IH curves be plotted from the data given, it will be seen that the initial small amount of magnetism at the temperature of the air is that of a magnetically soft material, and that each of the curves closely resembles that, at the same temperature, of the 36 per cent. alloy already referred to.

Further, as the temperature is reduced below 0° C., the magnetisability gradually increases; but at the same time the IH curve becomes more and more clearly that of a mixture of magnetically hard and magnetically soft materials.

§ 7. In the alloy containing 26·7 per cent. Ni the relative amount of the magnetically hard material, at −186° C., has so far increased that the initial fall of permeability during heating has practically disappeared.

The decrease of permeability of the soft material during rise of temperature is almost exactly counterbalanced by the corresponding increase of that of the hard material.

Thus over a considerable range of temperature we have a material of practically constant magnetic properties. We have, in fact, a magnetic analogue of the alloy of practically negligible thermal coefficient discovered by GUILLAUME.

The 26·7 per cent. Ni alloy is a *magnetic invar*. Its BH curves are nearly identical for values of H between 25 and 400 over a temperature range of more than 300° C. (from −186° C. to at least +120° C.).

§ 8. In the 24·4 and 24·04 per cent. Ni alloys the permeability increases as the temperature rises from −186° C., even in the strongest fields. A study of the data shows that the effect of a magnetically hard material now preponderates. The presence of the nickel-poor material is shown clearly, in the curves for the 24 per cent. alloy, by the marked increase of permeability (for $H = 50$) beyond 200° C., *i.e.*, after the opposing influence of the nickel-rich material has disappeared.

If the IH curves be plotted from the data given, it will be seen that the initial small amount of magnetism at the temperature of the air shown by the alloys containing less than 27 per cent. of nickel is that of a magnetically hard material and that, as the temperature falls, the hardness no longer increases rapidly with increase in the amount of magnetic material.

§ 9. All the data above, together with others from the same paper which might be cited, admit of simple interpretation if it be assumed that alloys containing between 24 and 30 per cent. of nickel consist mainly of a mixture of two materials, one nickel-rich and the other nickel-poor, forming a eutectic, and that the richer alloys contain a small excess of the nickel-rich material, whilst the poorer alloys contain a small excess of the nickel-poor material.

From these data it appears that the artificial eutectic mixture is one in which the thermal variation of permeability is relatively small over a considerable range.

A further important conclusion with respect to this eutectic is revealed by the behaviour after interrupted heating (*cf.* Section VI. above) of the 24·4 per cent. alloy as described by HONDA and SHIMIZU.

If there were no thermal hysteresis, the eutectic, which appears at about 0° C. during cooling, should disappear at the same temperature during heating. That it does not do so seems due to thermal hysteresis in the nickel-poor constituent. The nickel-rich constituent apparently loses its magnetism, without appreciable hysteresis, at about the temperature corresponding to the percentage of Ni which it contains (*i.e.*, between 250° C. and 300° C.), but that of the nickel-poor constituent persists and does not disappear until about 500° C. Hence at 400° C. the nickel-rich crystals have become converted into a non-magnetic solid solution, but the nickel-poor crystals still remain.

If the heating is continued until the solution of the nickel-poor crystals has begun, but interrupted before it is complete, there will be a partial re-growth of these crystals as the temperature falls. At the air temperature, however, a considerable portion of the nickel-poor alloy will be still in the non-crystalline (non-magnetic) condition (*cf.* Section VI., § 10, p. 88).

But below 300° C. during cooling the nickel-rich component of the eutectic (which, on account of insufficient heating, has not become incorporated with the nickel-poor crystals to form a homogeneous solid solution) will begin to regain its magnetism. Its permeability will increase rapidly as the temperature falls (*cf.* the curves for the 36 per cent. alloy).

At the air temperature the permeability of the material as a whole will be less than before heating began, because some of the nickel-poor alloy is still non-magnetic, but the material will be magnetically softer, because it now contains a relatively greater proportion of nickel-rich alloy. For this last reason also, during subsequent rise of temperature, the permeability will decrease much more rapidly than during the first heating.

Each of these conclusions is in accord with experimental data (*cf.* HONDA and SHIMIZU, *loc. cit.*, pp. 657, 658, and fig. 7, *j*, Plate XII.).

§ 10. A study of the thermomagnetic properties of alloys containing lower percentages of nickel than 24 and higher percentages than 29 will reveal more, and may show that the percentages of nickel to be ascribed to the two constituents of the eutectic are not quite as I have stated them. Meanwhile the evidence already obtained, and indicated above, seems sufficient to establish the coexistence of two constituents (in different proportions) in alloys containing between 24 and 30 per cent. Ni. The general accuracy of the interpretation given seems also assured.

§ 11. In the preceding Section VII., discussing the $\mu\theta$ curves for a meteoric iron under the influence of weak fields, I have attempted to show that the taenite consists originally of (in round numbers) 6 per cent. and 40 per cent. nickel-iron alloys intimately mixed, but sufficiently segregated to be distinguishable thermomagnetically. I have interpreted the curves on the assumption that a succession of heatings to a temperature of about 800° C. converts the material into a more intimate, *i.e.*, finer-grained, mixture possessing the properties of the artificial 27 per cent. alloy. The initial decrease of permeability, observed after treatment described in the paper, between 15° C. and 300° C., has been explained by assuming that it is due to the presence of alloys containing between 40 per cent. and 27 per cent. of nickel in a relatively coarse mixture while the destruction of "meteoric" segregation in the eutectic is still incomplete. I have since confirmed this interpretation by observing the permeability change (under the same field $H = \cdot 43$ C.G.S.) during heating to 100° C. of a ring, not previously heated, cut from the core already described.

In this case there is no initial decrease, but an increase of about 5 per cent. between 15° C. and 100° C.—as would be expected if the material contained only 6 per cent. and 40 per cent. alloys.

It may be mentioned further that the micro-photographs of taenite given in fig. (5*d*), Plate 2, closely resemble those of well-known examples of "sorbitic," or finely-segregated, pearlite (*cf.* OSMOND, 'Microscopic Analysis of Metals,' pp. 88 and 89, 1904). The two fragments of taenite (seen in fig. 5*d*) appear to belong to differently orientated plates; but such structural details as are shown in the original negative are difficult to reproduce, and no quantitative value is claimed for the figure. Better photographs could probably be obtained after a more prolonged search than was made while the apparatus was at my disposal; but even the best microphotographs of fine-grained structures frequently leave room for doubt with respect to their significance. On the other hand, if two constituents of a material have thermomagnetic properties which are sufficiently distinct, their coexistence will be demonstrable without doubt by the magnetic method, however fine grained the microstructure may be.

§ 12. In conclusion, it seems reasonable to hope that the theory advocated will prove to be an adequate basis of correlation of the properties of all alloys of nickel and iron, and that the thermo-magnetic method is capable of further development as a means of observing continuously and of interpreting changes in the internal structure of magnetic alloys.

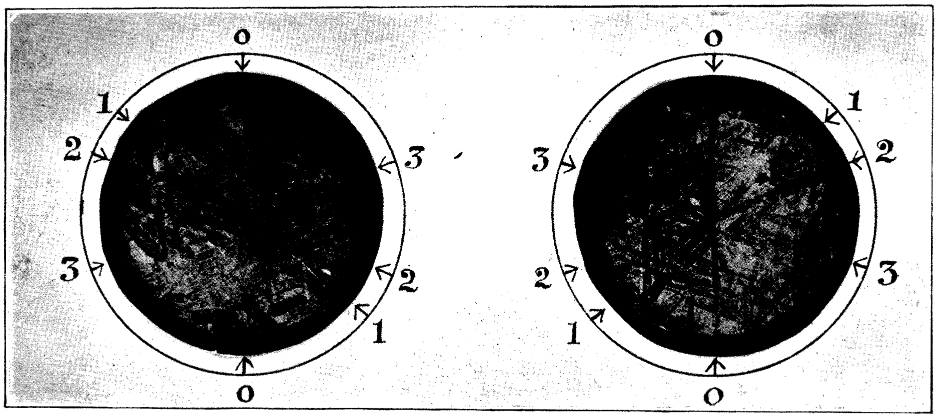


Fig. 2. Fig. 3.

(Natural size.)

Fig. 4.

(Enlargement of the negative of fig. 2.)

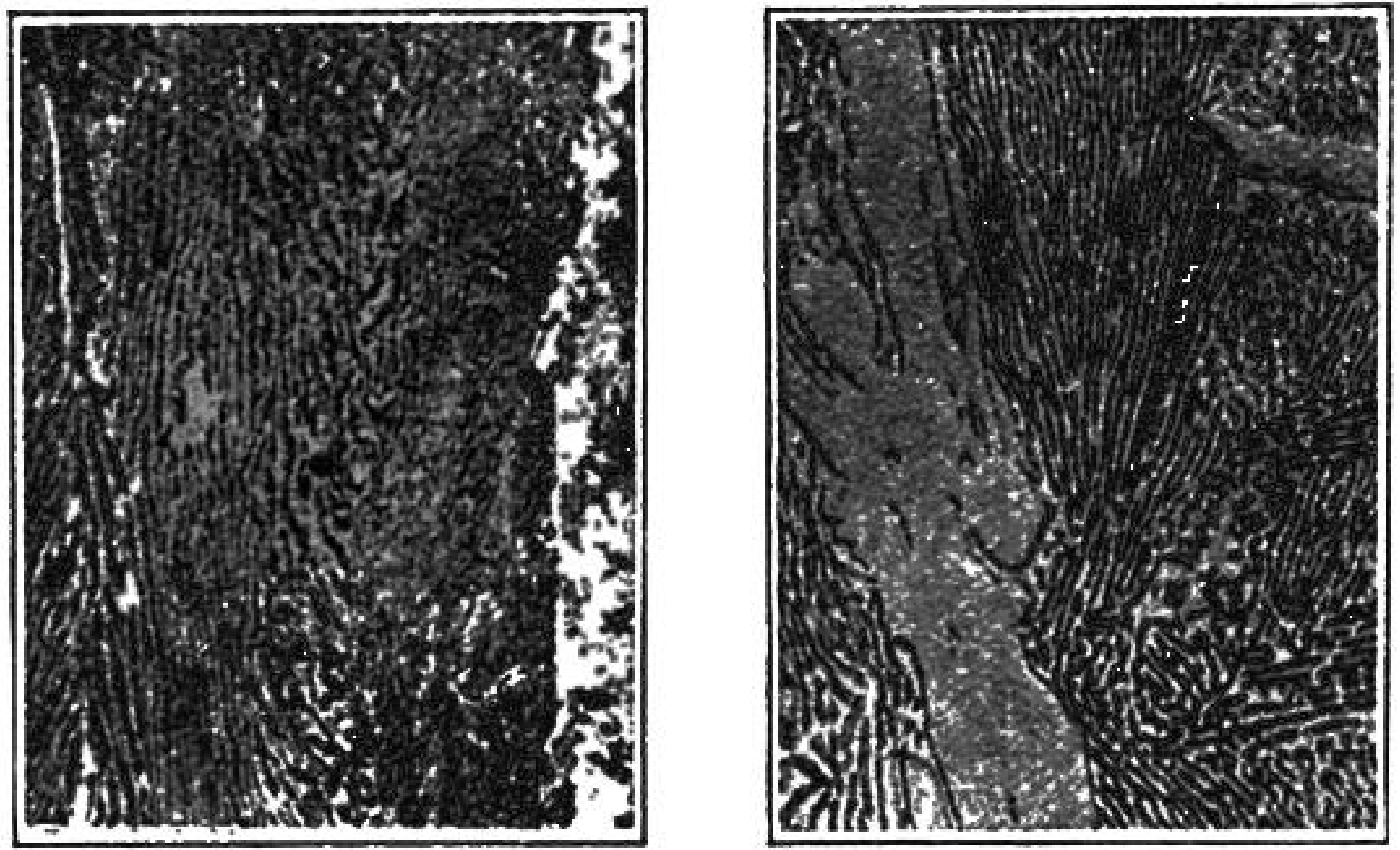
Fig. 5*a*.
× 50 diameters.

Fig. 5*b*.
× 50 diameters.

Fig. 5*c*.
× 80 diameters.

Fig. 5*d*.
× about 500 diameters.

Microphotographs of Sacramento meteorite.



San Cristobal Meteorite.
(Brezina.)
(?) contains eutectic
percentage of nickel.

× 23.

Lamellar Pearlite.
(Osmond.)
Contains the eutectic
percentage of carbon.

× 1000.

Fig. 24.

Cast Steel.
× 22 diameters.

0·4 per cent. Carbon.
Ferrite (light).
Pearlite (dark).

Meteoric Iron.
× 2 diameters.

13 per cent. nickel (approx.).
Kamacite (light).
Taenite (dark).

Fig. 25.

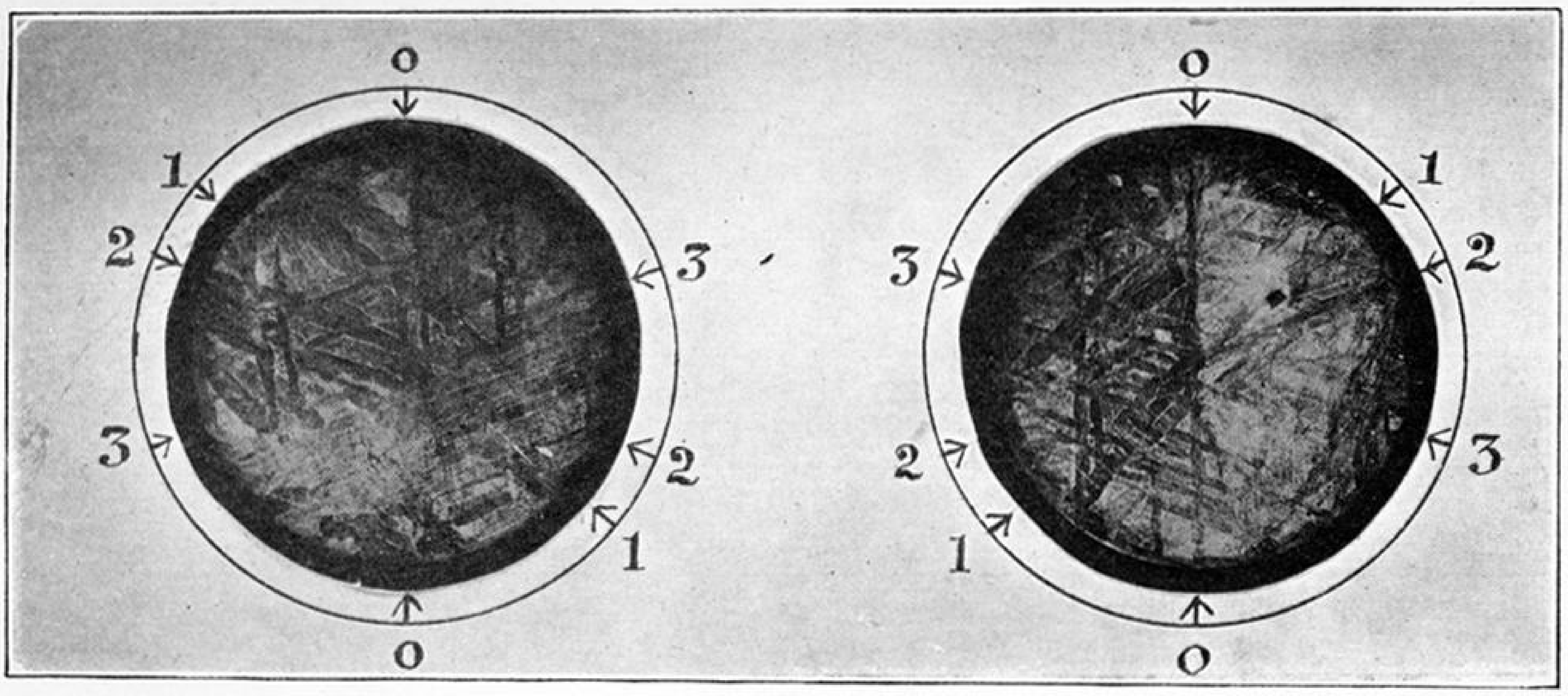


Fig. 2. Fig. 3.

(Natural size.)

Fig. 4.

(Enlargement of the negative of fig. 2.)

Fig. 5*a*.
× 50 diameters.

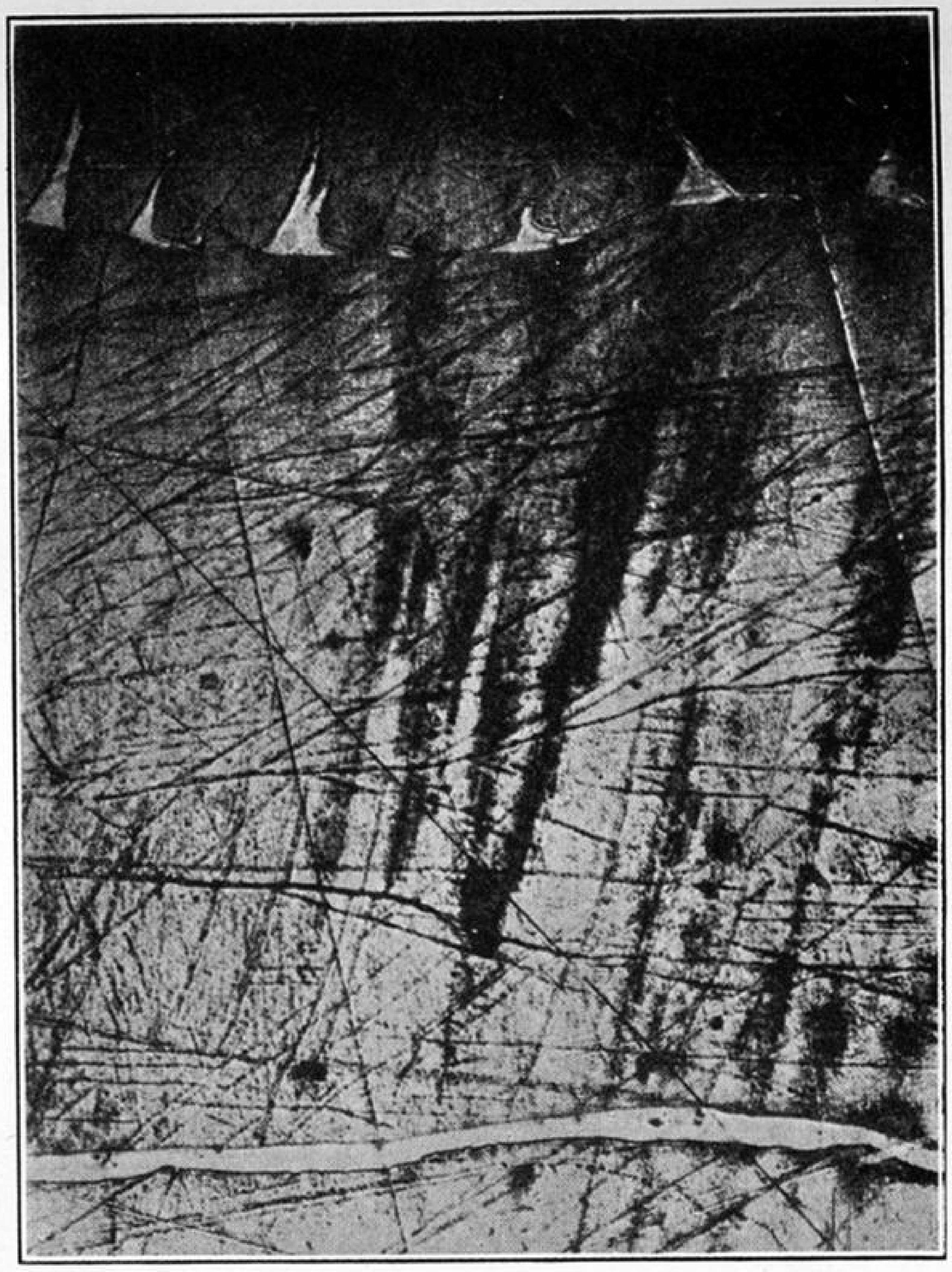


Fig. 5*b*.
× 50 diameters.

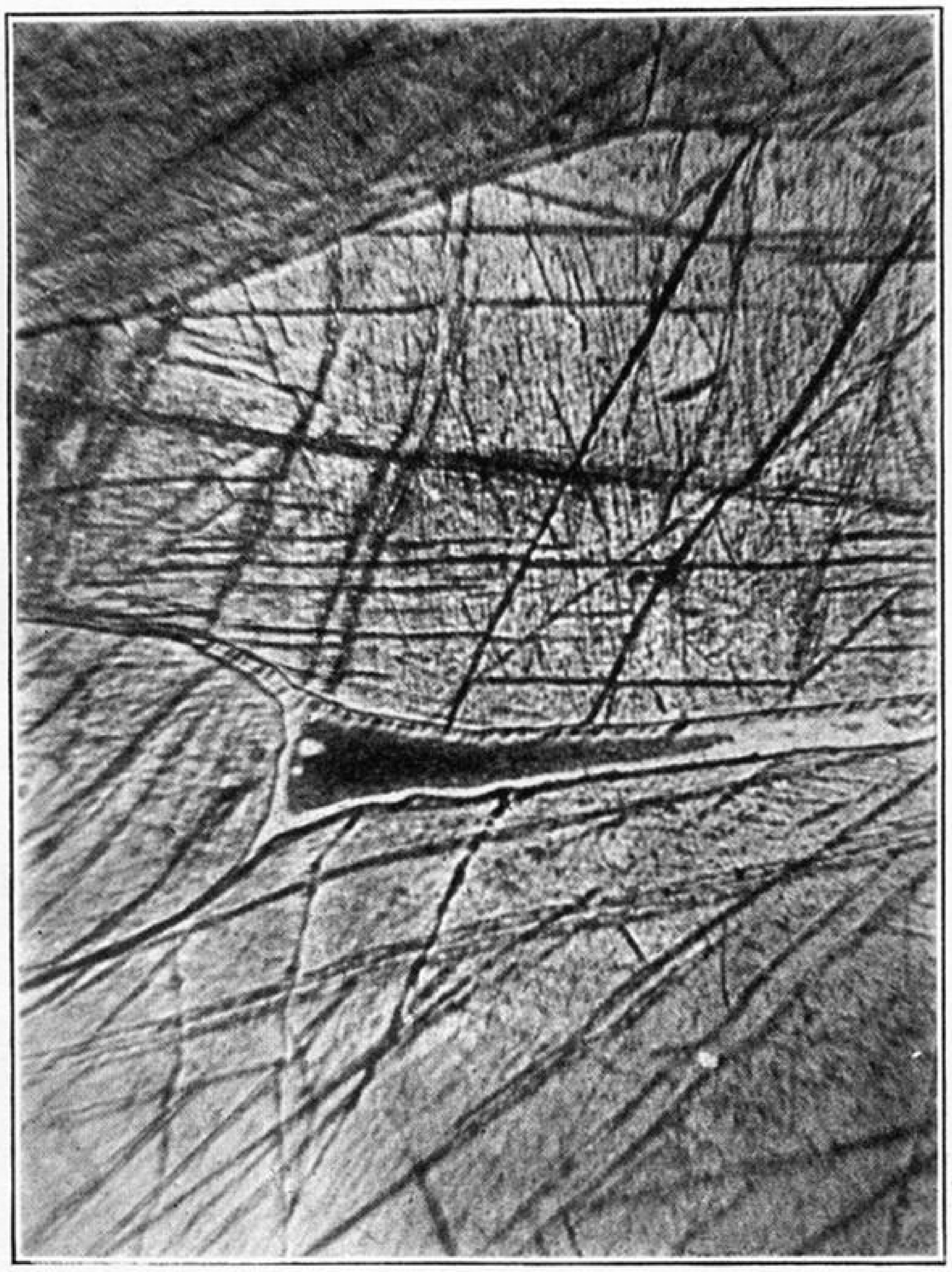


Fig. 5*c*.
× 80 diameters.

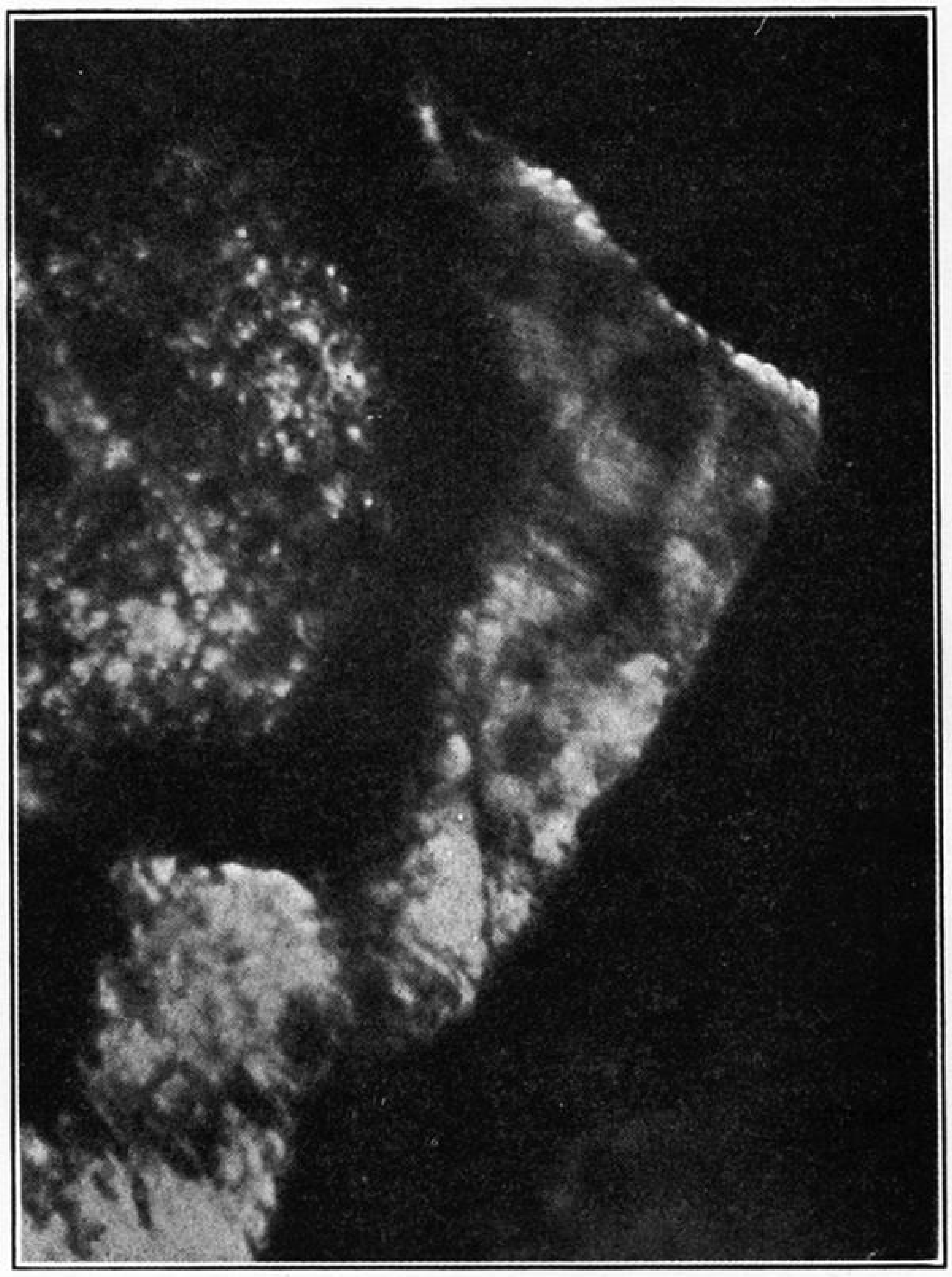


Fig. 5*d*.
× about 500 diameters.

Microphotographs of Sacramento meteorite.