V. "On the Influence of Temperature upon the Magnetisation of Iron and other Magnetic Substances." By HENRY WILDE, F.R.S. Received May 8, 1891.

In my paper on the "Unsymmetrical Distribution of Terrestrial Magnetism,"* it was shown that by heating small surfaces of the thin sheet iron entirely covering the ocean areas of the mapped globe strong magnetic polarity was induced at the heated parts, just as when the magnetic continuity of the iron was interrupted by cutting through the same parts of the iron in an equatorial direction. Although this experiment appeared to me to demonstrate conclusively that the magnetic power of iron was reduced by heating at comparatively low temperatures, and with small magnetising forces, yet, from the contradictory results which have been obtained by other experimenters on the magnetisation of heated iron, directly opposite conclusions as to the magnetic intensities of the land and ocean areas respectively might, with some reason, be drawn from those which I had arrived at.

Barlow, in an interesting paper on the magnetic behaviour of heated iron,† refers to the discordant opinions which prevailed on this subject among natural philosophers from the 17th century to his time, and assigned the cause of these discordances to the observations being made with iron at different degrees of heat.

Barlow found that the magnetic power of the bars of iron which he experimented upon, as measured by the deflections of a compass needle, *increased* with the temperature up to a dull red heat, at which it was the strongest; but, at a bright red heat, all magnetic action of the iron suddenly disappeared. Scoresby,‡ Christie,§ and others had also noted a similar increase in the magnetic power of iron with increase of temperature, when measured by the same means.

Faraday, on the other hand, has described experiments to show that the magnetic power of iron *diminishes* with increase of temperature.|| He also found that iron at a bright red heat was not entirely insensible to the action of large magnetising forces.

More recently, Rowland,¶ Baur,** and Hopkinson,†† by the employment of electro-dynamic methods, have also found an increase in

* 'Roy. Soc. Proc.,' January 22, 1891.
† 'Phil. Trans.,' 1822, p. 117, &c.
‡ 'Edinburgh Roy. Soc. Trans.,' vol. 9, Part I.
§ Christie on Effects of Temperature, &c., 'Phil. Trans.,' 1825, p. 62, &c.
|| 'Phil. Mag.,' 1836, vol. 8, p. 177; 'Phil. Trans.,' 1846, p. 41.
¶ 'Phil. Mag.,' 1874, vol. 48, p. 321.
** 'Wiedemann, Annalen,' vol. 11, 1880, p. 403.
†† 'Phil. Trans.,' A, 1889, vol. 180, p. 443.

the magnetic power of iron with increase of temperature. These experimenters were, however, the first to recognise that the apparent increase of the magnetic power of iron, up to the dull red heat, only held good for small magnetising forces, and, further, that the power diminished for large magnetising forces with ascending temperatures.

Rowland extended his observations to the magnetisation of nickel and cobalt, and found that the magnetic behaviour of these metals with increase of temperature was the same as that observed in iron.

Experiments have also recently been made by Professor Rücker* on the effects of temperature on the natural magnet (*magnetite*), and he has found, by means of an extremely sensitive instrument, that the magnetic power of this mineral increases as the temperature rises, as in the case of iron.

The important bearing which the influence of temperature has upon the phenomena of terrestrial magnetism induced me to undertake an investigation into the causes of the conflicting results obtained by those physicists who have preceded me in this research, with the hope also that I might be able to extend still further our knowledge of magnetic substances, especially in their relation to terrestrial physics.

The apparatus used in the investigation consisted of a bar electromagnet, formed of a cylinder of iron 24 inches in length and 3·5 inches in diameter. The electro-magnet was placed in a vertical position, with its lower end screwed firmly into a massive base of cast iron. The upper end of the core was furnished with a short cylinder of iron, of the same diameter as the core, and having a conoidal termination, which constituted the pole of the magnet.

The magnetometer was a plain cylindrical needle, 4 inches long and 0·13 inch in diameter, suspended from a single fibre of untwisted silk. The needle received a charge of magnetism sufficient to support fourteen times its own weight from either pole, and was thickly covered with spun silk to prevent the weakening of its magnetism by close proximity to the heated substances under examination.

The iron experimented upon was a cylindrical bar of good malleable iron, 6 inches long and 0·7 inch in diameter. One end of the iron bar was drilled through its diameter to receive a strong iron pin, which projected crosswise on each side of the bar for the purpose of dropping it readily, when heated, into a stirrup placed over the electro-magnet. Several of these bars were prepared from the same rod of iron, to replace those which were reduced in thickness by fusion and oxidation, as well as for other experiments.

* 'Roy. Soc. Proc.,' 1890, vol. 48, p. 522.

The iron bar, with its stirrup, was pendent from the end of a balanced lever placed over the pole of the electro-magnet, while the arm of the lever, on the other side of the fulcrum, was weighted with a sliding weight, or with variable weights, to balance the attractive force of the iron when in contact with the electro-magnet.

For the measurement of smaller magnetic forces, a special balance was constructed which, besides balancing forces up to 15 lbs., would turn with a weight of less than half a grain.

Prëliminary experiments were made upon the bar by placing it, when cold, in the direction of the dip, with one of its ends at a definite distance from the magnetometer, and in the same horizontal plane. When in this position, the magnetic force of the iron bar, augmented by the earth's magnetism, produced a deflection of the needle from the magnetic meridian of 20°.

The bar was then heated to bright redness, and replaced in the same position as before, when all the phenomena described by Barlow were reproduced. The heated bar had no perceptible action on the magnetometer, but on cooling down to a less red heat the magnetic action of the iron began to manifest itself, gradually at first, and then very rapidly, till the deflection of the needle, which was 20° with the cold iron, now advanced to 43°, thereby showing an increase of the magnetic power of the iron at this temperature. On the further cooling of the bar, the magnetic action of the iron gradually diminished, till the same deflection of the needle was obtained as at the commencement of the experiments.

The increase in the magnetism of the bar, as shown by this experiment, although greatly augmented by the earth's magnetism, was, however, very feeble; for when the bar was placed horizontally at the same distance from the needle the deflection was only increased 5° by heating it to the temperature most favourable to its magnetisation; and no increase of magnetism could be perceived when a small electro-magnet, however feebly excited, was brought into direct contact with the heated iron.

The bar was again heated to incipient whiteness, and placed over the pole of the electro-magnet. As the cooling proceeded, observations were taken of the intervals of time required before the magnetic force was sufficient to cause the bar to adhere to the pole of the electro-magnet for each definite increase of weight on the lever.

The colour, and several shades of colour, of the heated iron above visible redness, progressing towards the orange and yellow, are expressed in wave-lengths of well-known spectral lines of the alkaline and alkaline earth metals in the arc spectrum, as observed through a direct-vision spectroscope of five prisms. Below these temperatures, I have selected the melting points of zinc (442° C.) and tin (230° C.), small fragments of which metals could be dropped

into a cavity formed in the upper end of the bar. These temperatures were afterwards verified, and similar results obtained, when the bar was plunged into crucibles of the melted metals. The temperature of 100° C. was determined by plunging the bar into boiling water during the period of cooling. For temperatures below zero, a bath of solid carbonic acid and ether was employed, into which the bar was placed until it was cooled down to −76° C. The refrigerating arrangement was so effective, from the large supply of solid carbonic acid at my disposal, that a globule of mercury placed in the cavity at the upper end of the bar remained solid several minutes after the completion of the experiment.

All the experiments detailed in the following table were made with descending temperatures, as strictly concordant results were not obtained with definite increments of heat, especially for the lower ranges.

The electro-magnet was excited by a constant current of 20 ampères.

Table I.

Temperatures of bar.	Tractive force.	Times of cooling.	
λ	lbs.	m.	s.
Yellow, Na 5895	0·002	0	00
Orange, Ba 6141	0·008	0	13
Red, Ba 6496	1·0	0	20
,,	6·0	0	11
,, Li 6705	12·0	0	8
,,	18·0	0	14
,, Ka 6946	24·0	0	22
,,	30·0	0	29
,, Rb 7800	36·0	0	49
+442° C.	42·0	1	25
+230° C.	47·0	6	44
+100° C.	50·0	8	20
+ 13° C.	52·0	No observation.	
− 76° C.	53·6	,,	
Time of cooling from λ 5895 to 100° C.		19	15

The principal result shown by these experiments is the continued diminution of the magnetic power of the iron, from the lowest to the highest temperature to which the bar was subjected.

As it was of importance to determine whether iron entirely loses its magnetic power by heating, the temperature of one of the bars was raised to incipient fusion; but when the bar was carefully balanced there still remained in it a measurable amount of magnetic force when the electro-magnet was brought into action.

The results also show a rapid increase of the magnetic power of the bar from λ 6496 to λ 6705. This increase was attributed, in the first instance, to an error of observation, but on repeating the experiment similar results were obtained. The rapid increment of magnetic force in the interval of cooling between these spectral lines may, therefore, be regarded as a real phenomenon.

In all the experiments which have hitherto been made, where an increase of the magnetic power of iron with increase of temperature has been observed, it does not appear to have been suspected that the *mass* of the iron, in relation to the magnetising forces employed, might be an important factor in the results obtained, and that small magnetising forces might only penetrate to a small depth below the surface of the iron, when cold, till the more central portions of the mass were brought into action by increase of temperature. Several magnetic properties of iron and steel, however, point to the probability of this action of weak magnetising forces. Coulomb found that the magnetism of similar steel bars did not increase in the ratio of their number when laid together, from which it was inferred that the magnetism diminished from the surface to the centre of the bars. Joule has shown that a hollow electro-magnet has greater attractive force than a solid one of the same sectional area, with a small magnetising current.* It is also well known that the distribution of magnetism on the polar surfaces of electro-magnets is much greater at the circumference than it is at the centre.

That small magnetising forces penetrate but a small depth into a mass of iron was shown by heating one of the bars to redness, and sprinkling over its surface ferrocyanide of potassium, in powder, before plunging the heated bar into cold water. The conversion of the surface of the iron into steel by this well known process was sufficient to reduce the deflection of the needle from 20° to 15°, when the bar was placed in the direction of the dip.

In addition to the evidence adduced of the surface action of small magnetising forces on a mass of iron, it further appeared to me that as the time and limit of magnetisation of iron vary with the mass, for constant magnetising currents, or that the time and limit of magnetisation are constant when the magnetising current and mass vary in proportion, so it also appeared to me that, when the mass of iron and magnetising force were proportional, the diminution of the magnetic power of iron with increase of temperature would be constant for small, as well as for large, magnetising forces.

That the increase of the magnetic power of the heated bar, as shown by the magnetometer, was caused by the large mass of the iron in relation to the magnetising force of the needle was shown by the following experiments :—

* 'Annals of Electricity,' 1840, vol. 4, p. 60.

(*a*.) A small cylinder of iron wire, 0·2 inch long and 0·5 inch in diameter, was mounted in a twisted loop formed at the end of a piece of thin copper wire. The copper wire was fixed to an arm moving horizontally, in such manner that, when the cylinder of iron was brought into close proximity to one pole of the needle, the iron drew the needle from the magnetic meridian to a point where equilibrium was established between the attractive force of the iron and the earth's magnetism. The needle was then blocked a small fraction of an inch in advance and also behind this position; so that any increase or diminution of the magnetic power of the iron would limit the range of the needle to a fraction of an inch in either direction.

When a small gas-flame, or a lighted taper, was brought under the cylinder of iron wire till it became visibly red hot, the needle receded from the iron towards the magnetic meridian, thereby indicating a diminution of the magnetic power of the iron by the magnetometer which had previously shown an increase in the magnetic action of the large bar. On removing the source of heat from the iron, the needle again advanced towards it. On reheating the iron, the needle again receded, and the operation could be repeated at pleasure.

[That the recession of the needle from the heated iron was not due to the temperature being sufficiently high to render the iron virtually non-magnetic was shown by the needle again advancing towards the heated iron when brought into closer proximity to it without change of temperature, but no increase was observable in the magnetic power of the iron with any increase of temperature above 13° C.—*June* 3, 1891.]

(*b*.) A small cylinder of steel was prepared from the same piece as that from which the magnetometer needle was cut, and of the same dimensions as the one used in the previous experiment. All trace of permanent magnetism was removed from the steel by heating it to bright redness in a blowpipe flame, so that either end of the cylinder when cold was attracted indifferently by the same pole of the needle. When the steel was submitted to the process of heating and cooling in proximity to the magnetometer, as in experiment (*a*), its magnetic behaviour was the same as that observed with the iron.

The increase of magnetic power in the iron and steel, during the period of cooling, appeared to come on gradually, in the same manner as the magnetic power of the bar in relation to the large electro-magnet; and both experiments show decisively that the magnetic power of iron diminishes with increase of temperature for small, as well as for large, magnetising forces.

(*c*.) A fragment of the natural magnet (*magnetite*), weighing 2 grains, was detached from a compact and well crystallised mass of this mineral. The magnetite was heated to bright redness to remove all

trace of polarity, and care was taken to prevent new polarities being given to it by accidental contact with the needle. On heating the magnetite in the wire loop, as in experiment (*a*), the influence of temperature was more marked than with the iron, as the needle receded towards the magnetic meridian before the magnetite was visibly red-hot, and advanced again very readily when the source of heat was removed.

(*d.*) A small rectangular prism of nickel, 0·2 inch long and 0·05 inch across the sides, was submitted to the magnetometer as in the previous experiments, when the increase of temperature in diminishing the magnetic power of the nickel was most pronounced at the temperature of melted tin, and the metal became quite insensible to the needle at a point much below the red heat.

(*e.*) A rectangular prism of pure cobalt, of the same dimensions as that used in the previous experiment, was submitted to the action of the magnetometer, when, contrary to expectation, the needle advanced towards the cobalt before it became visibly red-hot, and remained stationary when the temperature was raised to redness; thereby showing an increase of magnetic power of the cobalt with increase of temperature.

The magnetic behaviour of the cobalt was so remarkable as to induce me to make further experiments upon the metal with more powerful magnetising forces.

A cube of pure cobalt from the Chemical Museum of the Owens College was kindly placed at my disposal for these experiments by Professor H. B. Dixon, F.R.S. The cube was 0·3 inch across the sides, and a short piece of platinum was screwed into the centre of one of its faces for suspension from the balance over the large electro-magnet. The temperature of the cube, below the red heat, was determined by the fusion of small fragments of zinc and tin, placed in a conical recess drilled into the upper face of the cube.

Similar cubes of nickel and malleable iron were prepared for comparison with the results obtained with the cobalt.

The method of experimenting was as follows:—The cube of magnetic metal was suspended over the electro-magnet, excited by a current of 20 ampères, and while in this position was heated by an oxyhydrogen flame until the requisite temperature was attained. The cube was then quickly brought into contact with the pole of the electro-magnet, without any intermission of the heating blast, and the magnetic force was measured by the weight required to detach the cube from the electro-magnet. The cube was reduced to the temperature of $-76°$ C. by immersing it in a bath of solid carbonic acid and ether, whilst suspended over the electro-magnet.

The results of these experiments with the magnetic metals are given below:—

Table II.

Temperatures.	Tractive force in lbs.		
	Iron.	Nickel.	Cobalt.
Orange, Ba 6141	0·0005	0·0002	0·02
Red, Ba 6496	0·02	0·0003	5·00
„ Rb 7800	9·50	0·001	6·31
+442° C.	11·00	0·024	7·25
+230° C.	12·50	2·000	6·75
+ 13° C.	12·75	3·125	6·31
− 76° C.	12·87	3·312	6·12

The principal feature of interest in the table is the same inversion of the magnetic power of the heated cube of cobalt, in relation to iron and nickel, as was obtained by the minute force of the magnetometer needle acting upon the small prism of the same metal. The increase of the magnetic power of the heated cube was, however, much greater relatively with smaller magnetising forces; for, while the ratio of increase with 20 ampères of current was as 1 : 1·15 between 13° C. and 442° C., the ratio with 3 ampères was as 1 : 1·6 between the same temperatures.

The abruptness of the change in the magnetic condition of iron, nickel, and cobalt, observed by Faraday,* at what is now aptly termed the critical temperature, is also well seen in the table.

Following up the results of the experiments which showed that the apparent increase in the magnetic power of heated iron was dependent upon the mass in relation to the magnetising force, it appeared to me that heated cobalt might show a diminution of magnetic power, as in the case of iron and nickel, if a sufficiently large magnetising force were brought to bear upon a minute quantity of the metal, notwithstanding that it had so far shown an increase of power for large, as well as for small, magnetising forces.

A minute cylinder of cobalt, 0·06 inch long, 0·05 inch in diameter, and $\frac{1}{4}$ grain in weight, was formed from a piece of the same cube of the metal used in the previous experiments. A small hole was drilled up the end of a thick piece of copper wire in the direction of its axis, into which the cylinder of cobalt was driven tightly for nearly the whole of its length. An eye was formed at the other end of the copper wire for suspending the cobalt over the electromagnet.

Similar cylinders of iron and nickel were formed from the cubes

* 'Phil. Mag.,' 1836, vol. 8, p. 177; *ibid.*, 1845, vol. 27, p. 1.

experimented with, and mounted for suspension over the electro-magnet in the same manner as the cylinder of cobalt.

The flat end of the electro-magnet was surmounted by a cone of iron 4 inches high and 3 inches in diameter at the base, with the apex rounded to form a pole 0·1 inch in diameter.

As a test of the magnetic intensity at the pole of the electro-magnet, the little cylinder of iron was suspended from the balance, when the tractive force was 0·601 lb. with 20 ampères of current, which is equal to 305 lbs. per square inch of section, or more than 17,000 times the weight of the iron.

When the cobalt was submitted to the same magnetising force as the iron, the tractive force at 13° C. was 0·304 lb., which is equal to 154 lbs. per square inch of section, or 8000 times the weight of the cylinder of cobalt.

On heating the cobalt, whilst suspended over the electro-magnet, a constant diminution of the magnetic power of the metal was now observed from 13° C., as in the case of iron and nickel, the tractive force diminishing from 0·304 lb. at 13° C. to 0·296 lb. at 442° C.

The results of the experiments with the minute cylinders of the magnetic metals are given below :—

Table III.

Temperatures.	Tractive force with current = 5 ampères.	Tractive force with current = 20 ampères.	Tractive force per sq. in. with current = 20 ampères.	Ratio of tractive force to weight of metals.
	lb.	lb.	lbs.	
Iron—				
442° C.	0·390	0·547		
13° C.	0·437	0·601	305	17000
Nickel—				
442° C.	0·001	0·003		
13° C.	0·064	0·127	64	3300
Cobalt—				
Ba 6496	0·109	0·172		
442° C.	0·156	0·296		
13° C.	0·140	0·304	154	8000

That the property of the anomalous increase of the magnetic power of the heated cobalt was broken down by the intensity of the magnetic force and the diminution of the mass conjointly, as in the case of the small and large bars of iron, was further shown by submitting the little cylinder of cobalt to the action of the electro-magnet excited by 5 ampères of current, when the tractive force of the heated cobalt was increased from 0·140 lb. at 13° C. to 0·156 lb. at 442° C.

On comparing the tractive force of the cobalt with that of iron, each with 5 ampères of current, it will be seen from the table that it was still very high, being no less, for the iron, than 0·437 lb. = 222 lbs. per square inch of section, or more than 12,000 times its own weight. Although this amount of tractive force is greater than any so far recorded for iron, yet the magnetising force was not sufficient to break down the property of the increase of magnetic force of the heated cobalt. It is well, however, that I should point out that the property only pertains in the highest degree to the metal when in a state of purity, as several of the specimens experimented upon, from different sources, only exhibit the property in a feeble manner, the diminution being due to the presence of iron in the cobalt.

As the determination of the limit of the magnetisability of iron by different methods is of some importance to magnetical science, an experiment was made on a cylinder of annealed charcoal iron wire 0·2 inch long, 0·05 inch in diameter, and $\frac{3}{4}$ grain in weight. The cylinder was driven up the end of a thick copper wire for the purpose of suspension as in the previous experiments. The tractive force of this specimen of iron at 13° C., with 40 ampères of current, was 0·75 lb., which is equal to 381 lbs. per square inch of section, or 7000 times the weight of the iron.

That the limit of magnetisability was virtually arrived at in this experiment was shown by reducing the current to 20 ampères, when the tractive force remained at 0·734 lb. = 373 lbs. per square inch of section, or only 8 lbs. less per square inch than the tractive force obtained with 40 ampères of current.

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