



## XXVII. On the distribution of magnetic induction in a long iron bar

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silvered quartz fibre, which, in addition to its great simplicity, has the merit of exhibiting the phenomena in a remarkably evident manner.

In conclusion, it may be noticed that the attraction of dissimilar metals, besides being observable experimentally with comparative ease, furnishes a new method for the determination of the electromotive force of contact. This method, which can be performed fairly quickly in all cases, is also capable of considerable precision when suitably arranged, since it is a null method.

XXVII. *On the Distribution of Magnetic Induction in a Long Iron Bar.* By C. G. LAMB, M.A., B.Sc.\*

THE following investigation was undertaken to determine the distribution of induction in a long cylindrical iron rod when it was subjected to various magnetizing forces. It was felt that the great variation of induction which must necessarily occur in a cylindrical bar would vitiate to some extent the ordinary assumptions made when employing rods for magnetic measurements.

In order to get a sufficiently clear notion of the induction distribution, and how it is produced, it is desirable to determine the following data:—

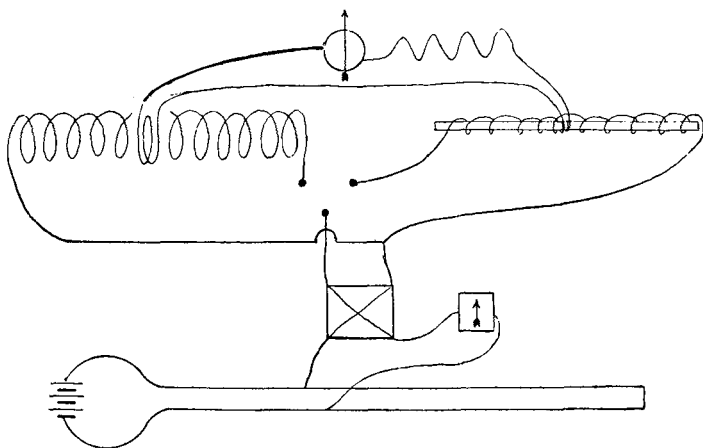
- (P) A curve of magnetization of the bar as determined by means of a search-coil at its centre.
- (Q) A series of curves at various fixed magnetizing forces showing the distribution of induction in each case.
- (R) A magnetization-curve of the bar when made into a ring, so that the induction is the same at every cross-section

The bar used in the present case was a circular bar of Low Moor iron; it was 0·485 cm. in mean diameter, and 123·4 cm. (48 inches) long, and before experiment was very carefully annealed. The magnetizing-coil was wound on a brass tube, somewhat longer than the specimen and of larger diameter; the specimen was fixed centrally inside this by ebonite rings near the centre and at one end. The search-coil was made as small as possible, and was wound on an ebonite bobbin attached to the end of another brass tube of such a size as just to slide over the rod, while the search-coil could just slide inside the tube covering the magnetizing-coil; on the inner tube marks were made showing when the search-

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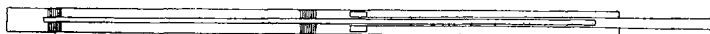
coil was at the centre of the bar, and at other definite positions up to the end. For the determination of curve A it was kept at the centre. The larger magnetizing-currents were read on Weston standard ammeters calibrated by comparison with a Crompton potentiometer; the small currents and those on the steep parts of the magnetization-curves were read directly by means of the potentiometer. The currents were adjusted by ordinary resistances for the larger values, or by a simple circular potential-slide as shown developed in fig. 1 for the smaller ones.

Fig. 1.



The ballistic galvanometer used was a Crompton "Midget" D'Arsonval, and was tested for proportionality by means of a standard field of known mutual-induction coefficient; it was found to be practically quite accurate. The standard field was also used throughout the experiment to calibrate the ballistic galvanometer, the connexions being shown in fig. 1. Fig. 2 shows the arrangement of the search-coil and specimen rod.

Fig. 2.

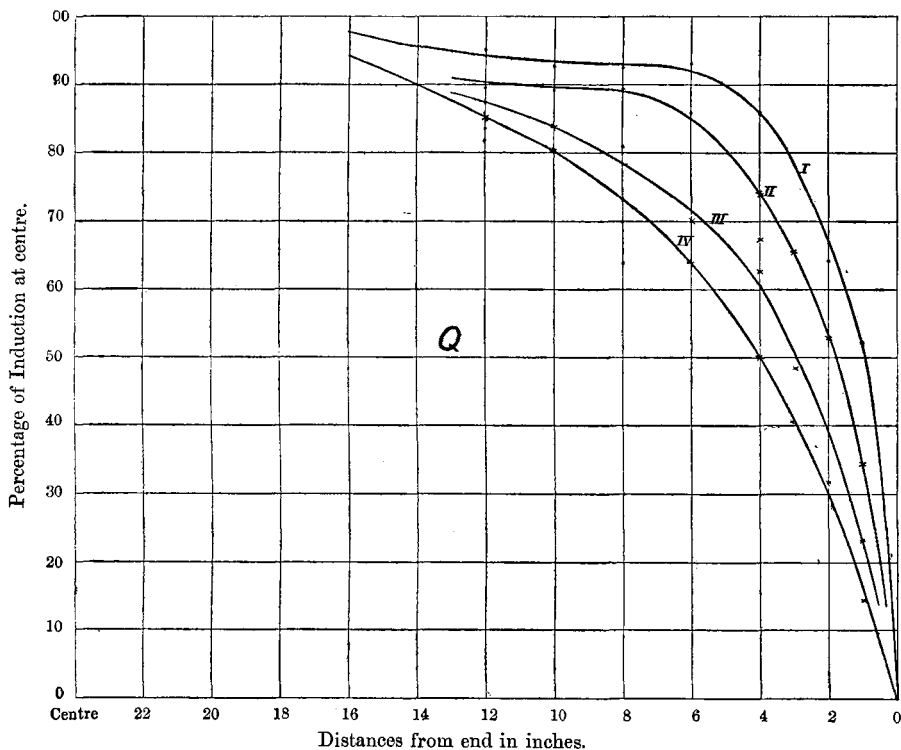


The results on reduction were carefully plotted to a large scale, and fig. 5 is a reduced copy of this curve; it connects

the applied magnetizing force and the induction at the centre of the bar; we will refer to these as  $H_a$  and  $B_c$ .

The next step was to determine the curves of induction in the bar; these are called set Q (figs. 3 and 4), and nine were taken (numbered I. to IX.) at values of the magnetizing-current giving values of  $H_a$  shown in Table II. The points selected at which to measure the induction were: as near the end as possible, 1, 2, 3, 4, 6, 8, 10, 12, 14, 16, 18, 20 inches from that end, and at the centre (24 inches from end). A preliminary

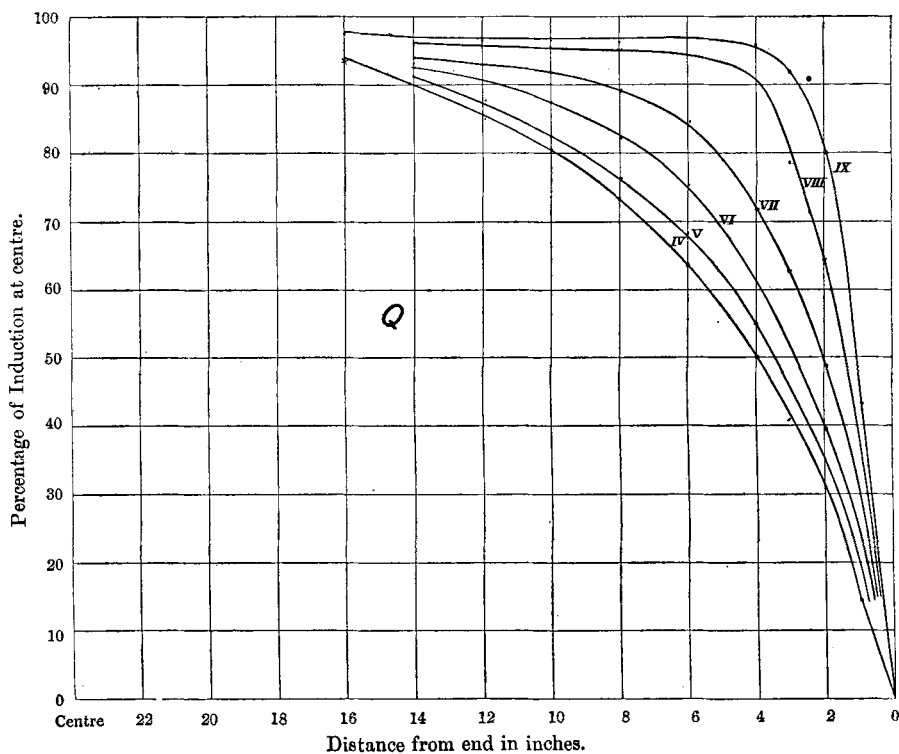
Fig. 3.



experiment showed that either half of the bar gave closely agreeing results at one definite value of  $H_a$ . Several observations were taken at each point, and from the mean of these the induction at each of the specified points was calculated as a percentage of that which occurred at the centre: these

values are given in Table I. Curves were carefully plotted to a large scale; those marked Q are given to show the mode of variation along the bar, the points near the centre are not shown as it will be noted from Table I. that some of the curves cross there owing to slight local differences in the iron; these points are omitted to avoid confusion. The curves subsequently referred to as "Curves Q" must be taken as being drawn carefully through all the points, not those given here.

Fig. 4.



The bar was then very carefully welded and re-annealed, wound with a secondary coil and then a magnetizing-coil, and a reversal-curve again taken as for the bar. B, H curves were drawn to suitable scales for high and low inductions so as to

TABLE I.

No. of Curve Q.	Inches from end.												
	Centre.	20.	18.	16.	14.	12.	10.	8.	6.	4.	3.	2.	1.
I. ...	100	.....	99	96	94	95	93	93	93	86	78	64	52
II. ...	100	.....	99	95	91	89.5	89.5	89.5	86	74	60	53	34
III. ...	100	.....	100	97	92	87.5	83.5	78	70	67.5	48	37	23
IV. ...	100	.....	99	94.1	90.5	85	80.2	73.3	63.7	50	40.5	31.8	14.8
V. ...	100	99.4	96.2	93	90.3	87.2	82.6	76.4	68	53.8	45	34	21.4
VI. ...	100	98.8	96.2	93.6	91.8	90.1	87.2	82.4	75	61	51.5	39.5	24.5
VII. ...	100	98.5	96	94	93.5	93	92	89	84.5	71.5	62	48.5	31
VIII. ...	100	99.0	99	96.5	96.2	96	95.5	95	94.5	92	78.5	64	41.5
IX. ...	100	99.8	98.5	97.5	97.5	96.5	96.5	96	97	96	92	80	43

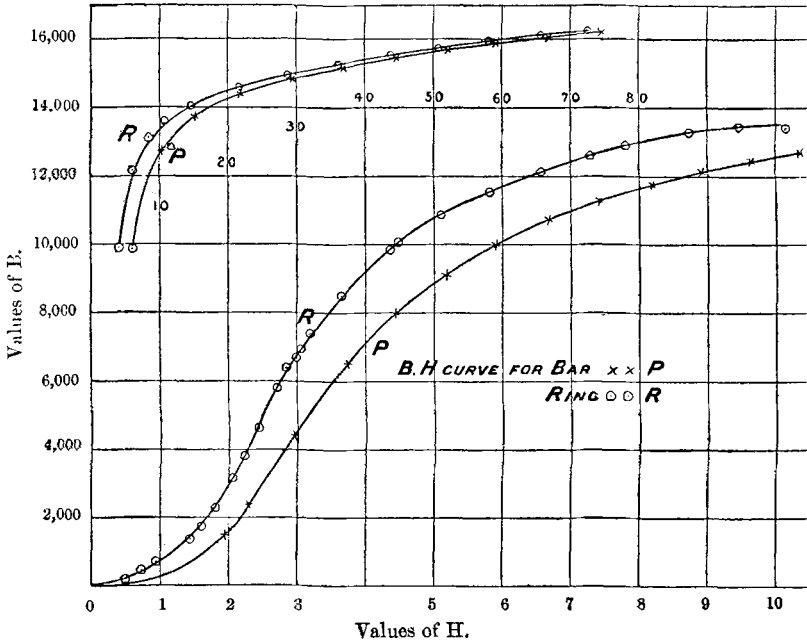
TABLE II.

Curve Q.	H <sub>a</sub> .	H <sub>m</sub> .	B <sub>c</sub> .	B <sub>m</sub> .	B <sub>h</sub> .	$\frac{H_m}{H_a}$ .	$\frac{B_m}{B_c}$ .	$\frac{B_h}{B_m}$ .	Equiv. length as fraction.	D in inches.
I. ...	0.74	.....	162	146	... ..	.....	.....	.....	.90	2.4
II. ...	1.49	1.18	572	477	468	.79	.84	.98	.835	4.0
III. ...	2.23	1.81	2,350	1,880	1,790	.81	.80	.96	.80	4.8
IV. ...	3.35	2.30	5,500	4,070	4,080	.69	.74	1.02	.74	6.3
V. ...	4.47	2.84	8,000	6,160	6,200	.64	.77	1.00	.77	5.4
VI. ...	6.70	3.84	10,700	8,680	8,800	.57	.81	1.01	.81	4.6
VII. ...	11.6	6.04	13,500	11,900	11,740	.52	.88	.99	.88	2.9
VIII. ...	20.0	11.50	14,300	12,900	13,600	.58	.90	1.04	.90	2.3
IX. ...	35.0	22.10	15,200	14,100	14,600	.63	.92	1.04	.92	1.9

permit accurate reading of the quantities; the curve connecting B and  $\mu$  was deduced and likewise plotted. Reduced copies of these curves are shown at R (figs. 5 and 6). References after must be taken to apply to the large-scale curves as before.

From curves Q we can easily deduce the mean induction by taking the area and base of the curves; this is given in Table II. under the heading  $B_m$ . The equivalent length of

Fig. 5.



the bar will be the same proportion of its actual length that  $B_m$  is of  $B_c$ ; this is also shown in the table. Half the difference between the true and the equivalent lengths will give the distance of the resultant pole from the end; this is tabulated under the heading D.

From Table I. and the curve P the actual inductions can be derived for the various points of the bar at any definite value of  $H_a$ ; if we can assume the annealing to have been good enough to permit us to take the bar as being the same under the two conditions (which is borne out by the close approximation of the curves towards the maximum induction), it is possible to deduce the distribution of  $H$  in the bar by cross reading from curve R the value of the  $H$  for each value of  $B$  at each point. Curves showing the distribution of  $H$  are given in set S (fig. 7). From these the value of the mean  $H$  was found as above described for  $B$ , and is tabulated under  $H_m$  in Table II. The induction this would have produced in the bar

Fig. 6.

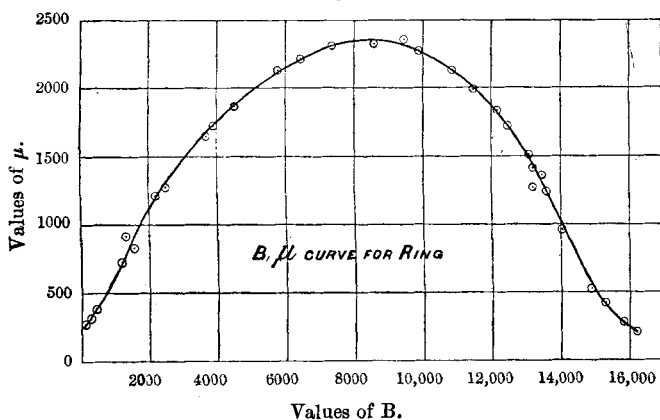
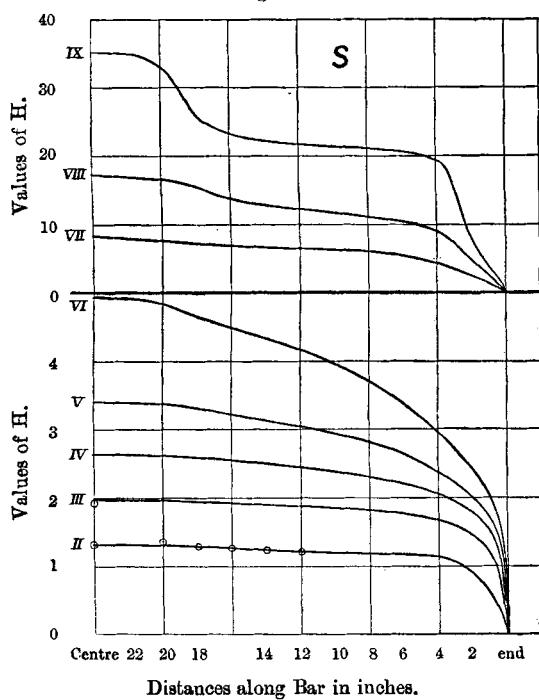


Fig. 7.

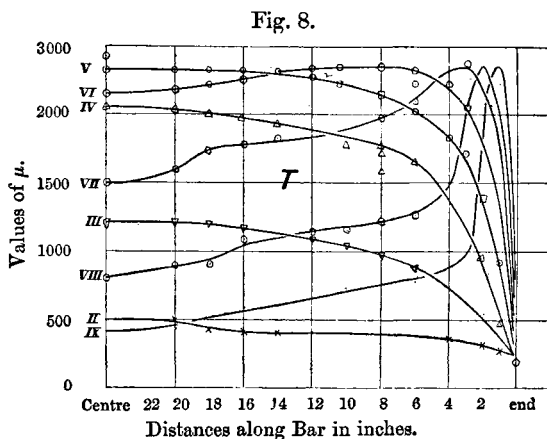




was likewise read off curve R, and is given in Table II. under  $B_h$ ; it is the induction that would have been produced by the mean value of  $H$  had the induction been uniform all along the bar.

The values of  $\mu$  at successive points were likewise read off from curve, and these are shown in curves T (fig. 8).

Table II. contains also the ratios of some of the more important quantities.



On comparing P and R (fig. 5) it will be noticed that the differences in the abscissæ (giving the "demagnetizing force" at the centre) are far from proportional to  $B$ , until we get to regions where the induction through the bar is so high as to be practically constant all along (as shown in Q. IX., fig. 4); below such values the demagnetizing force is considerably *larger* than the amount that is usually taken for the length-ratio of 250 to 1 that was used here. Possibly some of this difference is due to imperfect annealing; but great care was taken, and curves P and R agree very well in those parts where from Q. IX. we see the induction is nearly constant along the bar. Furthermore, we should expect that with the great variations shown in set Q the leakage-paths would demand very varying proportions of the impressed magnetomotive force, instead of a constant portion, as is the usual assumption. In fact, we cannot possibly tell what value of  $B$  to take in the equation  $H = \lambda B$  for demagnetizing force, since in the cylindrical bar (unlike the ellipsoidal) the leakage-flux is not independent of the induction. The ratio of  $H_m$  to  $H_a$  attains a minimum

value near the point of greatest demagnetizing force, *i. e.* about 13,000; but stress cannot be laid on this owing to the reading-off from one curve to the other. It would seem, however, that the assumption of a constant demagnetizing factor is not quite satisfactory; consequently the magnetometric method with cylindrical rods, although extremely useful for comparative work, must be used with much caution in determinations of an absolute character.

On looking at curves Q we note that the induction drops most quickly somewhere in the neighbourhood of *maximum* permeability, that is, the induction leaks out more when the bar is the better conductor. This at first seems peculiar; but on referring to set T, one sees that in the cases where the permeability is increasing as we go along the bar, the induction keeps in the bar, and the quicker the permeability diminishes the more the induction leaks out. In fact, the leakage at any place depends on the average permeability of the part nearer the end of the bar, and not on the value at that particular place.

An interesting relationship is brought out in Table II. It will be noticed that the ratio of  $B_m$  and  $B_a$  ranges from about 2 per cent. less than unity to about 4 per cent. more. This is not a great variation from unity considering the number of operations to be gone through before arriving at the figures. It would thus appear that the induction in the iron and that in the air so arrange themselves as to give a mean induction in the bar equal to that which the mean H would have produced had it been applied to the bar and no leakages taken place.

A very striking point is the great alteration in equivalent length of the bar; on the ellipsoidal assumption it is  $\frac{2}{3}$  the length, and Kohlrausch's number for a cylinder is  $\frac{5}{8}$ . We see that, far from this being a constant number, it varies from .9 to .74; so that any determination depending on constancy of this quantity will be somewhat vitiated. A direct experiment was made to test the amount of displacement of the poles as follows:—A piece of iron wire was inserted in the magnetizing-solenoid used above, and a brass wire was attached so that it could be slid up or down, always inside the solenoid. It was first adjusted so as to be exactly opposite the needle of a magnetometer. Various magnetizing-currents were then sent round the solenoid, and the wire was moved along inside until the maximum deflection was produced: the following numbers were obtained:—

Current.	Distance Wire was moved.
1.45 . . . . .	1.5 cm.
1.04 . . . . .	2.2
0.80 . . . . .	4.2
.57 . . . . .	6.5
.45 . . . . .	8.0
.38 . . . . .	12.0
.12 . . . . .	10.5

These results are of course quite rough, but the same general result is obtained as in the first experiments. The direct comparison of a ballistic and a magnetometric curve for the same bar would show that they approximately agree, since the factors causing variation of the equivalent length will affect both delimitations in the same way; preliminary experiments have confirmed this. It is hoped to examine bars bent into incomplete rings and other forms.

The kind assistance of Mr. L. G. Walter, B.A., in the earlier experiments is gratefully acknowledged.

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XXVIII. *On the Magnetic Hysteresis of Cobalt.* By J. A. FLEMING, M.A., D.Sc., F.R.S., Professor of Electrical Engineering in University College, London, A. W. ASHTON, B.Sc., 1851 Exhibition Scholar, and H. J. TOMLINSON, Salomons Scholar, University College, London\*.

[Plates VII. & VIII.]

ALTHOUGH determinations have been made of the magnetic constants of cobalt by other observers, we have not been able to find any very complete set of observations on the magnetic hysteresis values of cobalt of known chemical composition corresponding to various cyclical magnetic forces of known range or maximum value. Having in our possession a cobalt ring of supposed fairly pure commercial cobalt, a series of magnetic experiments were undertaken with it, the results of which are embodied in the following tables and diagrams (see Plates VII. & VIII.).

A rectangular sectioned circular ring of the metal was cast for us by Messrs. H. Wiggin & Co. of Birmingham, and turned up true in the lathe. The dimensions of the ring were then carefully measured and the mean values were found to be as follow :—

\* Communicated by the Physical Society : read June 23, 1899.