

A NEW PERMEAMETER.

By K. V. Karantha.

Magnetic testing has grown in importance during recent years. Though the subject is old, a thoroughly reliable method for measuring the magnetic properties of a sample, involving little labour in preparing the sample for test and easy manipulation during the test, has not yet been evolved.

Of the various means now available the ballistic method employing an anchor-ring still remains the simplest and the most accurate. For routine work, however, it is very unsuitable since it is usually laborious to make the special shape of the sample. Rapid tests can no doubt be satisfactorily made with small stamped ring specimens (T. Spooner, *Electrical World*, 1919, 74, 4) in cases where annealing after stamping is not an objection; but this is not permissible in many other cases where the magnetic properties of a sample may change during the process. Another serious drawback of the anchor-ring method is the necessity for hand-winding each sample with the accessory magnetizing and search coils, requiring much labour and time.

Many attempts have therefore been made to modify the ring method so as to avoid these difficulties and use the material for test in a form easy to machine; but in none has it been possible to retain the features leading to simplicity of operation and the accuracy associated with the ring method. These features are (1) the whole path of the magnetic circuit is completely confined to the material under test and hence no free poles are produced; (2) the whole path of the flux can be regarded as homogeneous in structure. All the modifications are compromises between this ideal and the other extreme of a magnetic circuit composed only partly of the sample under test and partly of a material as vastly different from it in permeability as air. In these instruments or permeameters the sample has the easily machinable shape of a straight rod which can be slipped inside tubes over which the magnetizing and search coil turns have already been wound. To make the rest of the magnetic circuit approach as closely as possible the sample under test, iron yokes are clamped to the ends of the specimen. The joints are made as magnetically tight as practicable, but it has not been found possible to make them perfect. Hence there is always some leakage of flux and consequent production of free poles. Moreover, there is an uncertainty of contacts and a change in the permeability of the material at the joint due to the clamping strains. The exact determination of the value of the magnetizing force from the constants of the instrument then becomes difficult, while the correction for the reluctance of the joints is uncertain and laborious. The effect of the joints has therefore been sought to be compensated or eliminated altogether by introducing separately excited supplementary coils at the joints. This naturally sacrifices simplicity, and the process becomes rather laborious when a high degree of accuracy is required.

Having regard to the fact that any attempt at modification of the ring method by the introduction of a break in the simple magnetic circuit

diminishes accuracy or simplicity, attempts have been made in other directions. The present paper deals with a permeameter which seems to possess some advantages over methods now in use, though it also has its own limitations.

The principle underlying the present permeameter is simple. Let AB (Fig. 1) be part of a straight conductor of infinite length carrying a magnetizing current of I amperes. Considering a point C at a distance of R cm. from the axis of the conductor the value of the magnetomotive force H is given by the relation

$$H = \frac{2 I}{10 R} \text{ C.G.S. lines.}$$

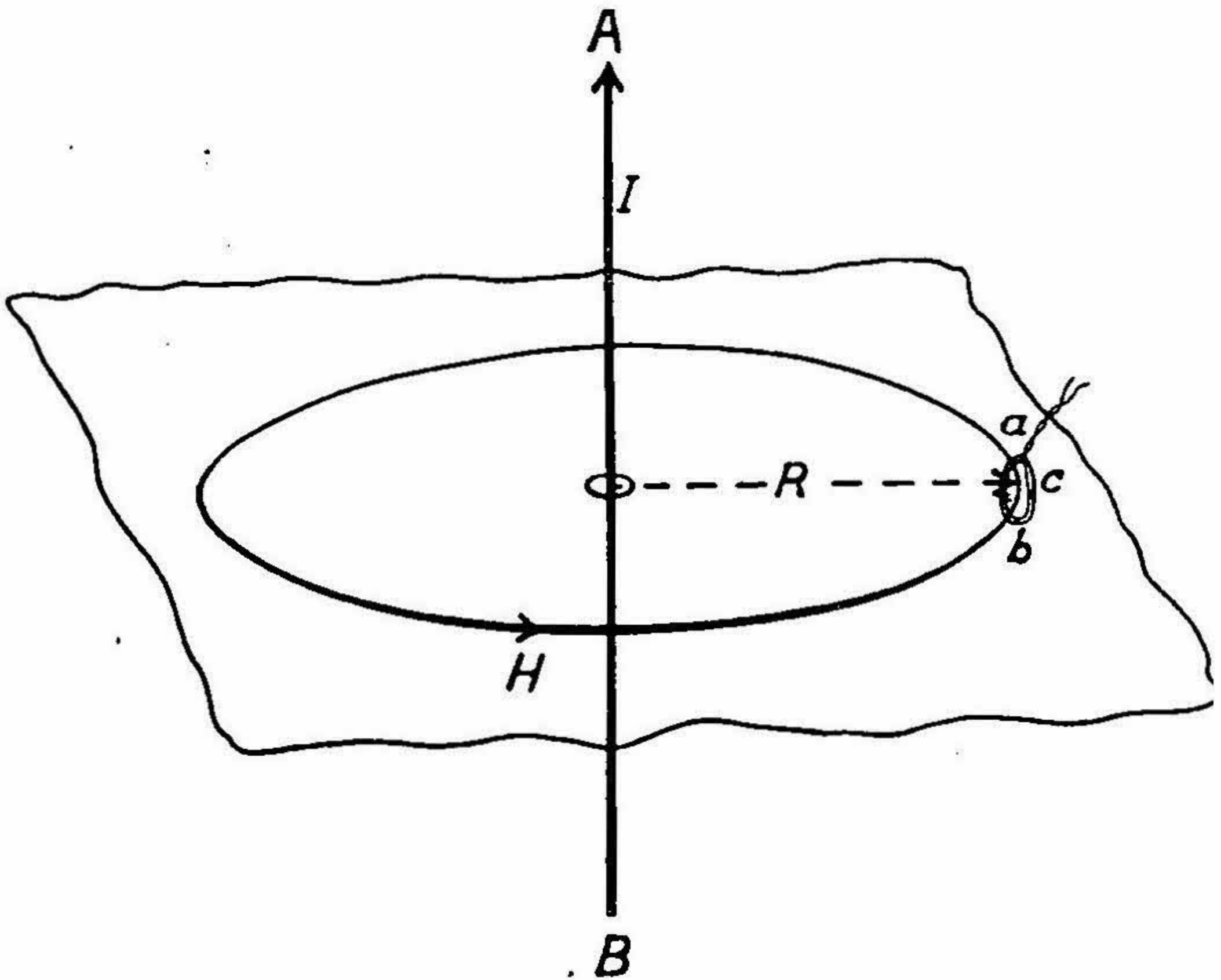


Fig. 1

Considering a sheet of the magnetic material of infinite dimensions and placed normally to the plane of the conductor, the magnetic induction in the sheet would take the form of concentric rings and a very narrow search coil ab placed at right angles to the flux path in two infinitely narrow holes drilled close to each other in the material could be used for measuring the value of induction at the point C .

In practice, quite a short length of the straight magnetizing conductor is found to be sufficient for obtaining a fairly high degree of accuracy in the calculation of H . Also, if the magnetic sheet were large, the shape of its boundary would not materially affect the distribution of flux in the neighbourhood of the conductor. If circular and homogeneous it could be quite

small without the flux distribution being affected. In preparing such a sample the material must be strained at the circular edge, but provided the strain is uniform along the circumference and does not reach the search coil the accuracy would not be affected. The samples actually tested have been square, octagonal and circular, $\frac{1}{2}$ " and $\frac{3}{8}$ " thick and with sides or diameters from $3\frac{1}{2}$ " to 12". A $\frac{7}{8}$ " hole is drilled in the centre of the sample for the magnetizing conductor. The search coil holes were of about 2 mm. diameter and the coil width about 2 cm. The short magnetizing conductor, the appreciable size of the search coil holes, the comparatively large width of search coil, the non-uniformity in the strains at the outer and inner edges of the material, have necessarily reduced the accuracy attainable by this method. A further limitation is imposed by the magnitude of the magnetizing current that can be conveniently used. By introducing suitable modifications in the simple arrangement described above, it was possible to reach 750 amperes in the magnetizing conductor, corresponding to a field strength of 50 C.G.S. lines per sq. cm. at a distance of 3 cm. from the axis, which was the distance from the centre of the conductor to the centre of the search coil used in most of the tests. With further modifications it might be possible to reach somewhat higher values for H.

Regarding the degree of accuracy attainable in the present permeameter, I have adopted the usual method of comparing the B-H curves obtained by this instrument with those given by the ballistic ring method. The extent of divergence between the curves can be expressed either in terms of the induction values for given values of the magnetizing force, or the magnetizing force values for given values of induction. R. L. Sanford of the Bureau of Standards, after examining a considerable number of curves for materials of widely different magnetic characteristics, states (*Bur. Stand. J. of Research*, 1930, 4, 177) that it appears to be most satisfactory to define the accuracy of magnetic data by recording that the value of induction corresponding to a given value of magnetizing force is accurate within a given percentage. I have adopted this form of statement throughout the paper.

The present permeameter was evolved for purposes of commercial magnetic testing. A high degree of accuracy is not necessary in such cases (Charles W. Burrows and R. L. Sanford, *Bur. Standards Bull.*, 1918-19, 14, 267; R. L. Sanford, *loc. cit.*) as commercial magnetic materials are not very homogeneous. In many samples the permeability at different points differs by quite large amounts and in a single transformer sheet the differences may be as high as 20 per cent. Rods which have been specially prepared with a view to uniform permeability along their length often show variations of 5 per cent. or more. For commercial testing an accuracy within 5 per cent. has been found reasonably sufficient (R. L. Sanford, *loc. cit.*, Burrows and Sanford, *loc. cit.*), and the present permeameter was designed to give results within that limit.

The actual shape of the instrument can be inferred from Figs. 2, 3 and 4. It consists of a large, vertically mounted, rectangular coil of wire ABCD with a joint at R for receiving the sample, a part EF of which runs through a brass tube threading the centre hole of the sample under test. At the lower end of this

tube the wires within it open out (Fig. 3) and dip into mercury cups arranged in a circle. The wires forming the rectangular part of coil come up from below and likewise dip into these cups. The connections are so arranged that a current entering the coil at one of its terminals T_1 , would flow through each of the turns before passing out at the terminal T_2 , as shown in Fig. 5 for a five-turn coil. To make the instrument portable a joint has also been introduced at G by means of tube connectors.

The following are the details of the instrument used in the tests. The width of the coil was 3 feet, its height $4\frac{1}{2}$ feet, and there were ten turns of No. 12 S.W.G.—D.C.C. wire within the tube and No. 10 S.W.G. better insulated conductor for the rest of the circuit. The wires in the tube were 24 inches long and the tube EF was 21 inches long. At the centre of the tube was a metal rod of $\frac{1}{4}$ inch diameter wound over with two layers of empire cloth tape. The ten conductors were symmetrically arranged around it and the whole taped over tightly, shellac-varnished and slipped into the brass-tube which was $\frac{5}{8}$ inch in diameter. The bundle fitted somewhat tightly inside the tube and there was no lateral play. This arrangement ensured the wires being symmetrically arranged around the central axis of the tube; they were opened out at either end and the insulation at the ends removed. The top ends were then passed through ten holes in a 3-inch diameter ebonite disc and connected by means of tube-connectors to the upper ends of the rectangular part of the coil. The lower ends were bent over a short ebonite cylinder with ten grooves on its sides. These ends thus formed a cage of slightly less than $\frac{7}{8}$ inch diameter and could be easily slipped into the mercury cups below. These cups were formed by drilling holes in an ebonite rod $1\frac{1}{2}$ inch in diameter and $1\frac{1}{2}$ inch long. The holes were 1 inch deep and had the shape shown in Fig. 4. The wooden rings Q and R through which the ends of the wires passed were 3 inches in diameter and served to keep the wires in position. The coil was suspended from the top and clamped at the bottom. For introducing a sample, the rod EF was raised and the test sheet inserted from below. After the sample was raised to the level of the centre of EF it was supported on a wooden plank resting on pins projecting from the edge of the work-table. The lower end of the rod EF was then re-inserted into the mercury cups. A pin K in the frame R served to prevent the ebonite cup from being pushed down during the operation. Once the ends of the wires were properly arranged, no difficulty was experienced in inserting or removing the samples, and the operation took very little time.

The most suitable shape for the sample is circular and about 10 cm. in diameter. The exact size is immaterial provided the outer edge is not too near the outer hole of the search coil. A 5 or 6 inch octagonal sample gives values only about 1 per cent. higher than a circular sample, while even a square gives satisfactory results for still larger sizes. For materials having a maximum permeability of over 1,500 the search coil holes had to be drilled with No. 48 twist drill of 0.076 inch diameter. For materials of smaller permeability No. 42 drill holes (0.093 inch diameter) were found to be sufficient. One of the holes was drilled 2 cm. from the centre of the plate or about 1 cm.

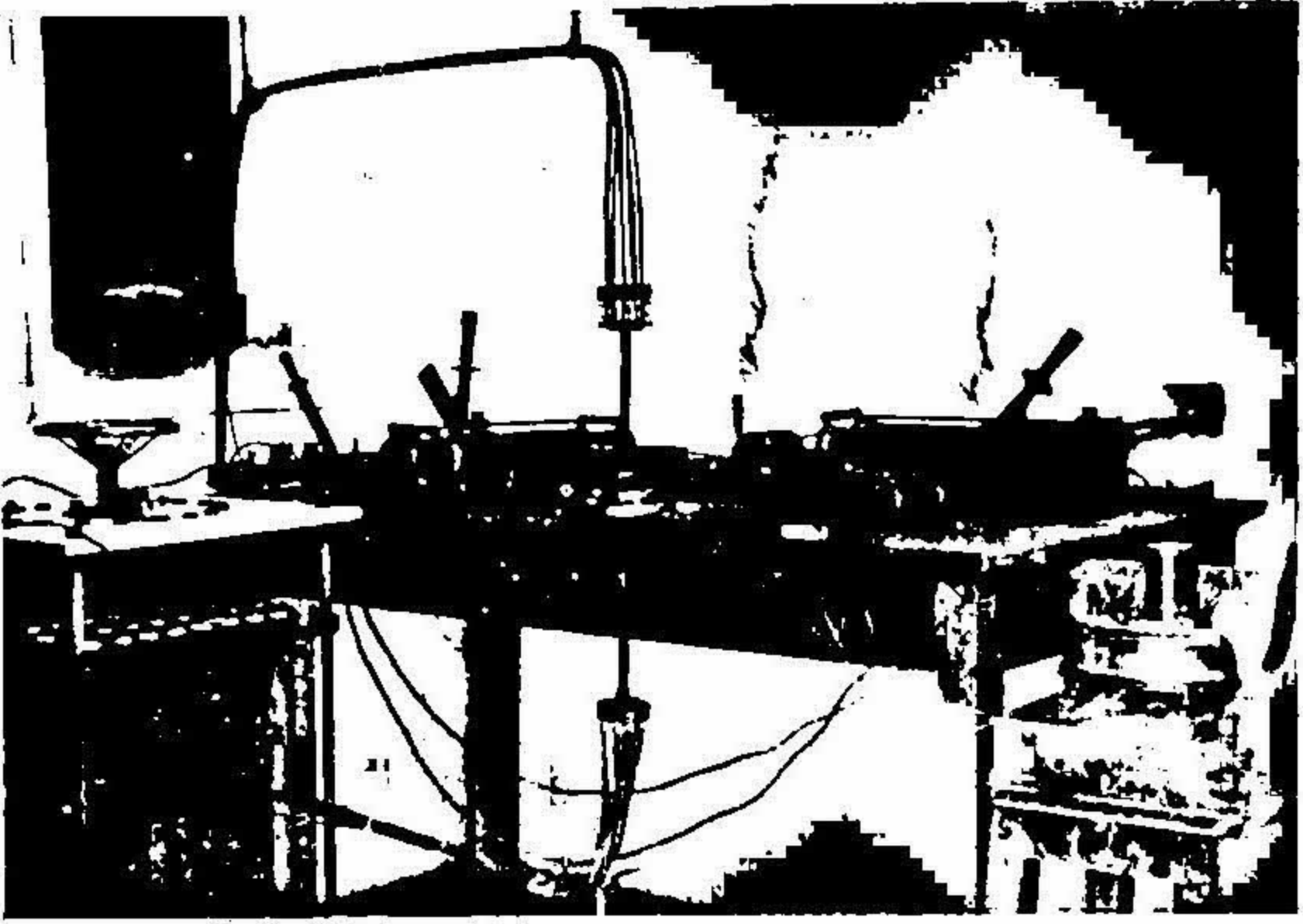


Fig. 6. The Permeameter used in the following tests.
Two circular samples are shown arranged for test.

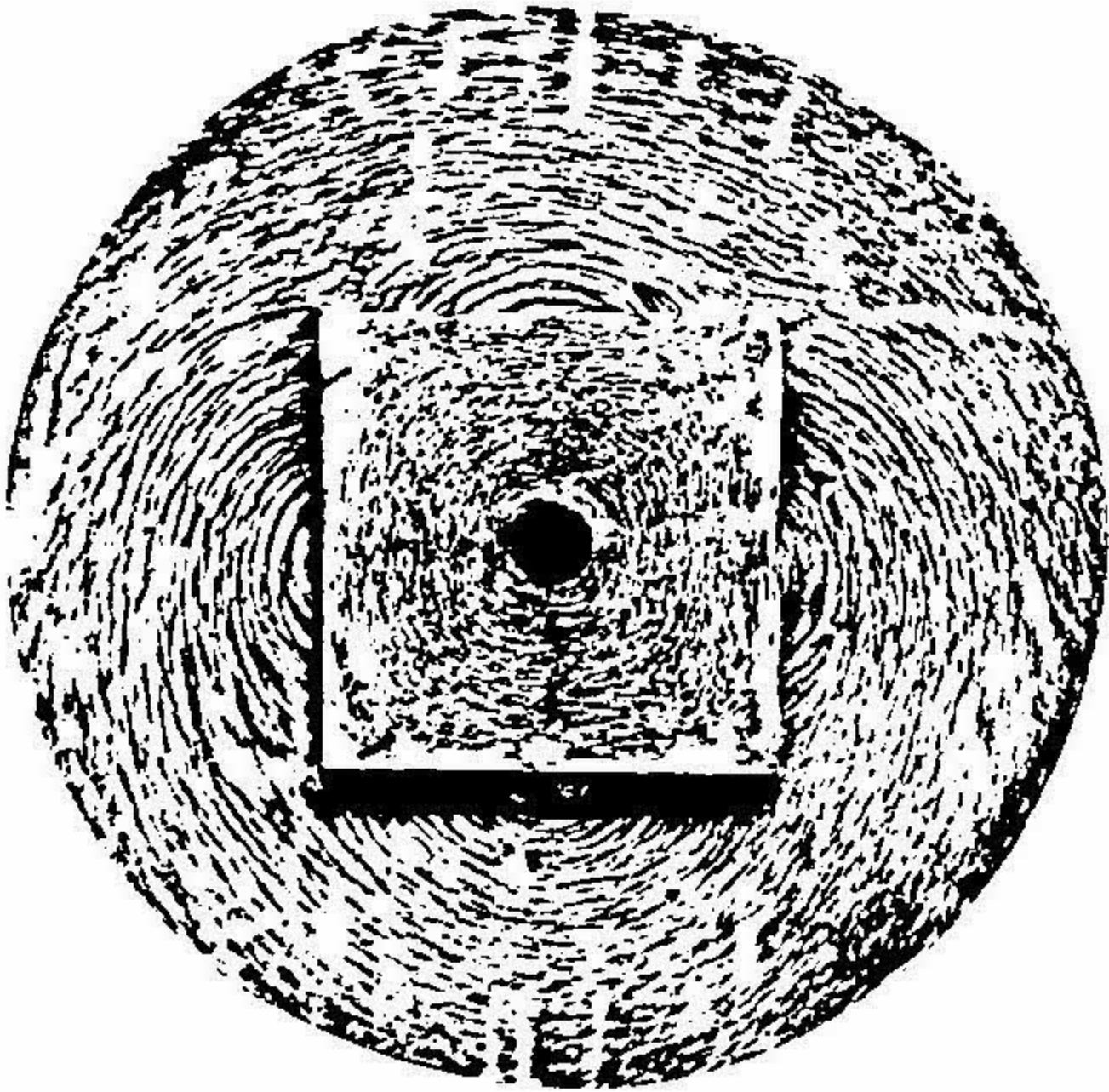


Fig. 7. Distribution of Magnetic Flux in and around a square plate
with a current passing through its centre.

from the inner edge of the sample. The second hole was drilled 4 cm. from the centre. The mean distance between their centres gives the effective width of the search coil. A search coil was wound through these holes using No. 36 S.W.G. double cotton-covered copper wire. No extra insulation was necessary, and 5 or 6 turns were found to be sufficient. It therefore takes very little time to wind the search coil.

In the following tests the change of flux through the search coil was measured by connecting this directly to a central zero flux-meter having 100 divisions on either side of the zero point. A deflection of one division was found to correspond to a change in flux linkage of 985 C.G.S. lines with no extra resistance in the search coil circuit. The resistance of the search coil itself was about 1.5 ohms and that of the flux-meter coil about 21 ohms. Using a $\frac{1}{2}$ inch thick wrought iron plate, 6 turns in the search coil and a field strength of 30 C.G.S. lines per sq. cm., a deflection of about 46 to 48 divisions was obtained. This could be read with ease. The accuracy of the reading was therefore quite high except at the lowest values of flux density.

The value of the magnetomotive force was calculated from the formula already given and was subject to three sources of error due to (1) Assuming that the magnetizing force value at the search coil centre is identical with the mean value of H over the width of the search coil: (2) The effect of asymmetry in the arrangement of conductors within the tube EF, or of the displacement of the axis of the tube with respect to the centre line of the central hole in the sample, as a result of which the actual axis of the magnetizing current may be different from the geometrical centre of the sample: (3) The effect of the portions AB, AD and DC of the coil which the formula does not take into account.

The error due to (1) has been calculated in the appendix and amounts to nearly 4 per cent. in the case of the samples tested. This could be eliminated by the use of a correction factor, 3.97 per cent. in the case of the tests referred to herein.

Error due to asymmetry in the arrangement of the conductors was reduced to a minimum by arranging conductors as already described. The tube itself was maintained in the exact centre of the hole in the specimen by inserting two semi-circular ebonite channels cut from a tube 8 cm. long and having an external diameter of $\frac{7}{8}$ inch and an internal diameter only very slightly larger than that of the tube.

A practical test was also applied to detect any asymmetry due to faulty workmanship. A sample was placed in position and after magnetizing it in the usual manner for a test, readings were taken for the induction with the plate rotated each time by 45° . If the axis of the total current in the tube and the axis of the sample were not coincident, the search coil would be nearer the current axis in some positions than in others, and the value of the magnetizing force in, and therefore of the magnetic induction through, the coil would be different for the different positions. The actual readings obtained were however very consistent, differing from each other by less than 1 per cent. The error due to asymmetry is therefore negligible.

The error due to the effect of the rectangular portion of the coil can be calculated and was found to be negligible. This was further verified by a direct test which also served to indicate absence of short-circuits in the magnetizing coil. An iron ring whose B-H curve was determined by the usual method was slipped over the tube EF and placed symmetrically around it. It was provided with a search coil with a few turns which was then connected to a flux-meter. The ring was magnetized to different values by suitable currents through the permeameter and the corresponding values of induction measured. The B-H curve obtained by this method was found to agree very closely with that obtained by the standard method.

The procedure adopted in testing a sample in the permeameter was exactly the same as that in the ring method; the details are therefore not given here. After a sample was tested in the permeameter it was reduced to the form of a ring and wound with magnetizing and search coils for the determination of the correct values. It was thus very easy to check the accuracy of the instrument. This is not possible with most other permeameters. Wrought iron, both annealed and unannealed, was used for the following tests as this material has a very high permeability and is affected most by strains introduced when preparing the sample for test (C. W. Smith and George W. Sherman, *Phys. Rev.*, 1914, 267). It is believed that the accuracy obtained with this kind of iron would also be obtained with other grades where even higher accuracies may be expected.

Plate 1 shows the results of tests on a $\frac{3}{8}$ -inch unannealed wrought iron plate initially 12 inches square and having a maximum permeability of 1580. Curve I gives the true B-H curve for the material as obtained by the anchor ring method. Curve III gives the values obtained with the present permeameter with the 12-inch square sample; Curve IV gives the values when it was reduced to 6-inch square. The values obtained with the sample in the form of a 5-inch circular disc are given in Curve II which shows that the maximum error, except at very low values of induction, does not exceed 1 per cent. Even in the case of the 12-inch square plate the error over the corresponding range does not exceed 2 per cent.

Plate 2 gives the results of test with a $\frac{1}{2}$ -inch unannealed wrought iron plate. The maximum permeability for the sample was 2000. Except at very low values of induction the error is nowhere greater than 3.5 per cent. for either the circular or the square plate. With the circular plate, however, the percentage error decreases with induction, while with the square plate it remains practically constant.

Plate 3 gives the results with a $\frac{1}{2}$ -inch annealed wrought iron plate having a maximum permeability of 4150. Except at the lower values of induction the error does not exceed 1 per cent. for circular and 3 per cent. for square plates.

Plate 4 shows the effect of reducing the diameter of the plate used in the above test to $3\frac{1}{2}$ inches (9.2 cm.). In this case the search coil holes were made with No. 42 drill and the outer edge of the specimen was only 5 mm. from the outer hole of the search coil. The error in this case is found to be

very large at the lower values of induction but to decrease to a very small value at higher values of induction.

Effect of space outside the search coil.

A study of curves II and III in Plate 4 indicates that for the lower values of H the induction in the case of a 3½ inches diameter plate is lower than for the 6 inches diameter plate, while for higher values of H it is greater. This may be explained as follows. It is well known that the effect of strain is to reduce the permeability at low values of induction and that this effect is negligible at high values (Smith and Sherman, *loc. cit.*). At higher values of induction the effect of the crowding within the search coil section of the flux which would normally pass outside the area of the coil becomes more pronounced.

A minimum width of space outside the search coil therefore seems necessary. Three circular samples of annealed wrought iron each about 10 cm. in diameter were tested using No. 48 drill for the search coil holes. The B-H curves for two of these agreed very closely with the correct B-H curves obtained by the ring method. The curve for the third sample together with the correct B-H curve in Plate 5 shows a close agreement. This indicates that widths exceeding 1 cm. outside the search coil are not necessary.

Effect of relation between the search coil width and its distance from the axis.

When the ratio of the width of the search coil to its distance from the axis is large, a high degree of accuracy is not to be expected at low values of induction due to the great difference in values of permeability at different points on the search coil section. Table I shows that with annealed wrought iron the permeability at the edges of a search coil 2 cm. wide, whose mean distance from the magnetizing axis is 3 cm., may be nearly 100 per cent higher or lower than its mean value at the centre. These values of permeability were derived from a true B-H curve of the material obtained by the ring method.

TABLE I.

Variation of permeability at different sections through a search coil 2 cm. wide and 3 cm. from the centre.

Centre of search coil			Inner edge of search coil				Outer edge of search coil				Percentage variation in permeability
H	B	μ	H _i	B _i	μ_i	$\frac{\mu_i}{\mu}$ %	H _o	B _o	μ_o	$\frac{\mu_o}{\mu}$ %	
0.4	300	750	0.6	800	1330	177	0.3	120	400	52.5	116
0.8	1800	2250	1.2	4900	4080	181	0.6	800	1330	59.1	120
1.2	4900	4080	1.8	7000	3890	95.4	0.9	2800	3110	76.2	85.5
1.6	6400	4000	2.4	8400	3500	87.6	1.2	4900	4830	121.0	104
2.0	7760	3880	3.0	10000	3330	85.5	1.5	6100	4070	105.0	95.3

Hughes (*J. Inst. Elec. Eng.*, 1927, 65, 932) has shown that for a ring in which the ratio of the radial thickness to the mean diameter is 0.3 as in the case of all the above tests, the error due to variations in permeability over the section can be very large at low inductions in materials of higher maximum permeability like annealed wrought iron, but is only about 1 per cent. at higher values of induction. Table II taken from his paper gives the values for the correction factor K by which the observed results have to be multiplied to obtain the correct values.

TABLE II.

Values of K for ratio of radial width to mean diameter=0.3.

$\frac{\xi}{a}$	0.2	0.4	0.6	0.8	1.0	1.5	2	4	7	10
K	—	0.7705	0.9103	0.9513	0.9693	0.9865	0.9925	0.9981	0.9994	0.9997

In the above table ξ is the magnetic reluctivity at mean diameter = $\frac{\text{magnetizing force at mean diameter}}{\text{actual flux density at mean diameter}}$ and a is the intercept on the axis of a tangent to the ξ - H curve.

The ξ - H curve has been drawn (Plate 6) for annealed wrought iron and it will be seen that beyond the bend of the ξ - H curve ξ/a has a value larger than 2 giving an error of less than 1 per cent. as seen from the table. At lower values of ξ/a the error would be large unless the search coil was placed farther away from the centre.

Effect of the centre hole.

As already mentioned, the effect of strain is to reduce permeability. The material at the inner edge is strained due to the drilling of the large centre hole. Plate 7 gives curves obtained with search coils between the inner edge of the specimen and the inner hole for the search coil. It will be seen that values of induction in these curves are much lower than those obtained with search coils placed with their inner side 1 cm. from the inner edge of the sample.

It is improbable that the strains due to the drilling of the centre hole extend as far as 1 cm. from the edge of the hole, but it is not advisable to drill the search coil hole nearer than this distance, as otherwise part of the flux of this region might be diverted, particularly at higher values of H , into the search coil area on account of saturation.

Effect of non-uniformity of material.

It has been found that the permeability in the direction of rolling is generally different from that at right angles to it (L. W. Chubb and T. Spooner, *Elec. Jour.*, 1916, 393; G. H. Cole, *ibid.*, 1924, 55). This difference can be shown in the new permeameter by using two separate coils in these two directions, and the difference was found to be greatest in large square samples and smaller in large circular samples. In small circular samples the two sets of readings agree very closely as expected. Therefore when a single search

coil is used the sample must be circular and small, about 10 cm. in diameter. With square samples it was found better to use a pair of search coils at right-angles and connect them in series. This gives more accurate average values than a single coil along a diagonal.

If the material is decidedly non-uniform, a single search coil would give higher or lower values of induction according as the material enclosed by the coil is more highly or less highly permeable than the average; but, although about fifty samples have been tested, the error due to this cause has not been serious, and with 10 cm. circular samples it is found to be very small, especially if the average of two coils is taken.

Effect of the shape of the sample.

The shape of the sample affects the shape of the flux path. Assuming infinite permeability, it can be shown that the tubes of induction close to the inner and outer edges will have the same shape as the edges. Hence in circular samples of homogeneous material all the tubes of induction will be circular and the best results will be obtained. With square samples the innermost tube of induction is circular and the outermost nearly square. The intermediate ones, *e.g.*, those passing through the search coil, will approximate more to the circle or the square according as they are nearer the inner-circular, or the outer square edge. With large samples, therefore, the distribution of flux in the region where the search coil is placed can still be regarded as approximately circular. Fig. 7 shows the distribution of flux within and around a square iron plate magnetized by a current passing through its centre, and was obtained by using iron filings. The plate was only 5 inches square and therefore the distortion is fairly large even in the region near the inner edge. It will be noted that the effect of the corners is to widen out the section of a tube of induction along the diagonals. If, therefore, search coils are placed along diagonals the values of induction obtained would be too low. Along a section parallel to the sides and passing through the centre, the flux would be somewhat more crowded than in circular plates. The error due to placing the search coils parallel to the sides is found, however, to be smaller than when placing them along the diagonals. The ratio of the value of B obtained by measuring it in these positions is some measure of the distortion of the tubes of induction from the circular shape.

Plate 8 gives results of tests on square plates having two search coils, one placed parallel to the edge and the other diagonally. Plates 9 and 10 give B - H curves with progressively decreasing size of samples. It will be seen that the error rapidly decreases as the size of the specimen increases. A 12-inch square specimen gives results practically as good as a circular one (Plate 1, curves II and III). The effect of the corners is greatest in materials of high maximum permeability.

Effect of search coil holes.

The effect of using various sizes of drills was studied with certain samples. Plate 11 gives the results of tests on an annealed wrought iron plate. It will be noted that two of the curves cross each other and this has been observed in other similar tests where a number of search coils are used in the

same plate. This is probably due to non-homogeneity of the material. In all cases, however, it was observed that at high values of induction the smaller drills always give better results than the larger. No. 48 has been chosen as being the most suitable for ease of drilling.

Effect of search coil width.

Plate 12 gives results of tests to find the effect of search coil width using unannealed wrought iron. A coil more than 2 cm. wide was not considered suitable since for the same ratio of coil width to its mean distance from the central axis, the value of H would be lower than with smaller widths. From Plate 12 and curve II in Plates 1 and 2 it will be seen that a 2 cm. search coil gives values slightly higher than the correct values for unannealed wrought iron. For annealed wrought iron it will be seen from curve II, Plates 3 and 5 that the values obtained with circular plates are slightly lower than the correct values. A test with 1.5 cm. search coil gave still lower values; 2 cm. therefore appears to be the most suitable coil width.

Hysteresis Loop.

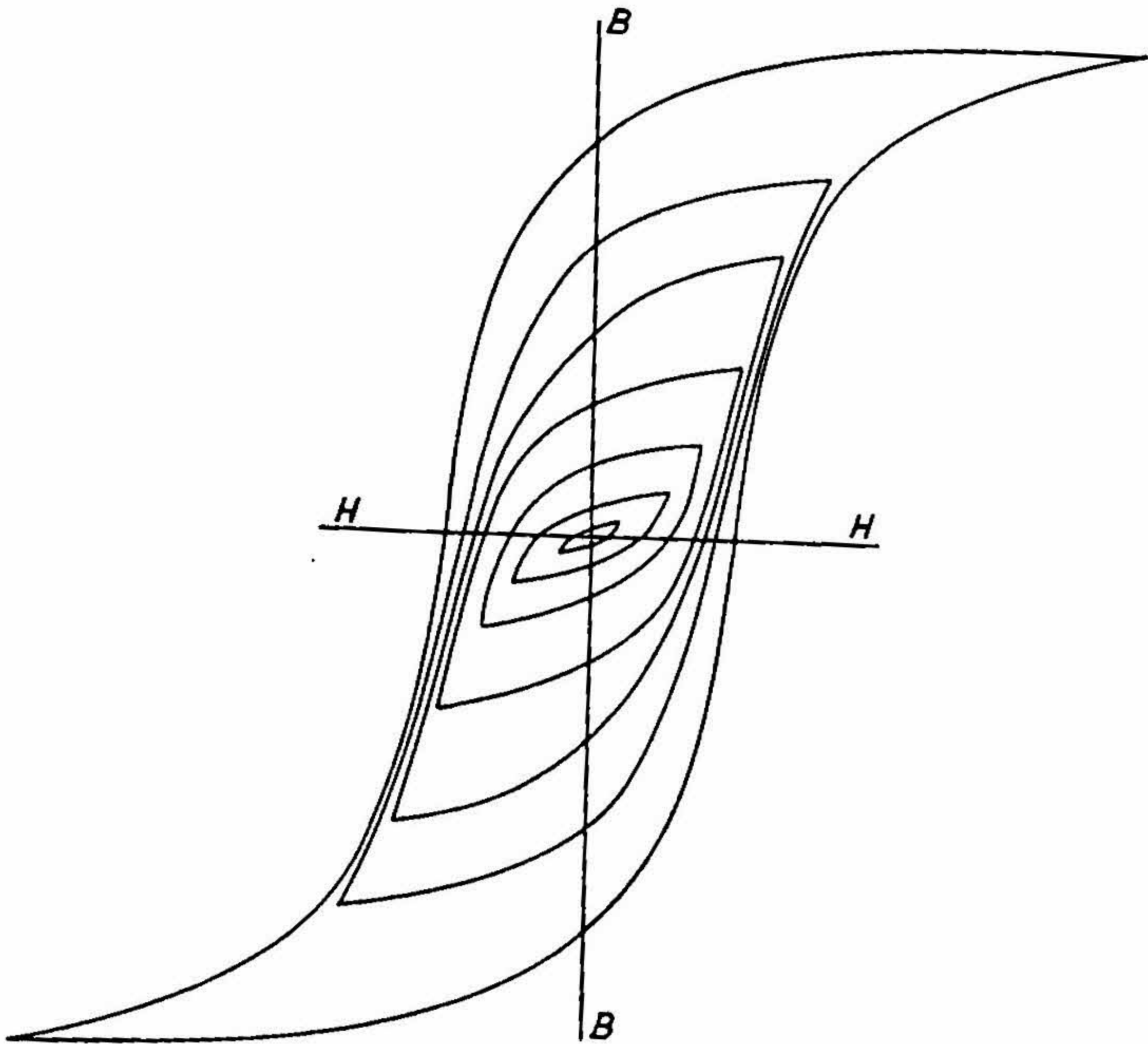
The permeameter was used for measuring remanance and coercive force in the 9.8 cm. circular plate whose B-H curve is given in Plate 5. Inductions of 10,000, 12,500 and 15,000 lines per sq. cm. were used. The data for the hysteresis loop were also obtained for an induction of 10,000 lines per sq. cm. Similarly 15 cm. square and circular plates were tested at induction of 12,500 lines per sq. cm. In the above samples the material was wrought iron. The results obtained were checked by the ring method, and a comparative statement is given in Table III.

TABLE III.

Comparative Values of Coercive force, Remanance and Hysteresis Loss as obtained by (a) Ring method, and (b) The new Permeameter.

Specimen	Max. Induction B C.G.S. Lines per sq. cm.	Max. Magnetizing Force H			Remanance			Coercive Force			Percentage error in area of Hysteresis Loop*
		Plate	Ring	% Error	Plate	Ring	% Error	Plate	Ring	% Error	
Circular 9.8 cm. diameter	10,000	3.59	3.57	0.53	7170	7030	2.0	1.18	1.17	0.9	
	12,500	6.30	6.18	1.95	8500	8210	3.5	1.23	1.15	7	+4.98
	15,000	17.20	16.00	7.5	12900	11700	10.2	1.33	1.184	12.3	
Circular 15 cm. diameter	12,500	6.54	6.47	1.04	8400	7850	7	1.19	1.12	6.2	+11.2
Square 15 cm. side	12,500	6.54	6.47	1.04	8720	7850	11	1.26	1.12	12.5	+17.9

* Derived from Plates 13 and 14. Plus values indicate higher values with plates.



Graded Cyclic Magnetisations

Fig. 8

By this method a higher value of the coercive force is to be expected for the following reasons. At low values of induction (Fig. 8) the ratio of the coercive force to the maximum induction is greater than at higher values (J. A. Ewing, *Magnetic Induction in Iron and other Metals*, 3rd Edn., 106 and 109). Hence when a coercive force is applied just sufficient to wipe out the flux within the search coil section, the corresponding value of H in the material between the search coil and the centre hole is larger than necessary to wipe out the flux there, and hence a small negative flux is induced in that region. In the region outside the search coil, the value of H is not sufficient to wipe out the flux; hence some positive flux remains. If this portion is wider than the inner portion, there will be a positive resultant flux which will readjust itself within the body of the sample. This explains the larger error in the area of the hysteresis loop with 15 cm. circular and square plates than with a 9.5 cm. plate.

Conclusion.

The permeameter possesses the following advantages. The method is an absolute one and no shearing curves or standard samples are necessary. It gives a high degree of accuracy when working on the positive side of the ξ -H curve. The results can be accurately reproduced for the same sample and hence alterations in permeability due to strains, etc., can be easily investigated. The effect of strains due to machining is negligible, except in materials of very high permeability. A number of samples can be tested at a time. The operation of testing for the determination of permeability as well as the hysteresis loop is very simple, and can be easily adjusted for tests at any given values of H up to its maximum ; but the principal advantage of the instrument is simplicity. Very little labour is involved in preparing a sample for test.

These are to some extent diminished by the following disadvantages. The instrument is not capable of giving accurate values of remanance, coercive force and hysteresis loss ; but the greatest drawback is the limited range of H, equal to only a quarter of that attainable in other permeameters. This can be increased by 50 per cent. by the following modification. Instead of the $\frac{5}{8}$ inch diameter tube a $\frac{3}{4}$ inch tube can be used. The extra space thus made available and the space at the centre now occupied by a rod can also be utilised for copper. Instead of using ten conductors of circular section, fifteen wedge-shaped copper strips arranged commutatorwise may be used.

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APPENDIX.

Ratio of average magnetizing force to the magnetizing force at the centre of section in circular samples.—In Fig. 9 let ABCD represent the search coil portion of the specimen, its centre being at a distance R from the axis of the magnetizing rod. Let $2a$ be the radial width and b the depth of the metal enclosed in the search coil.

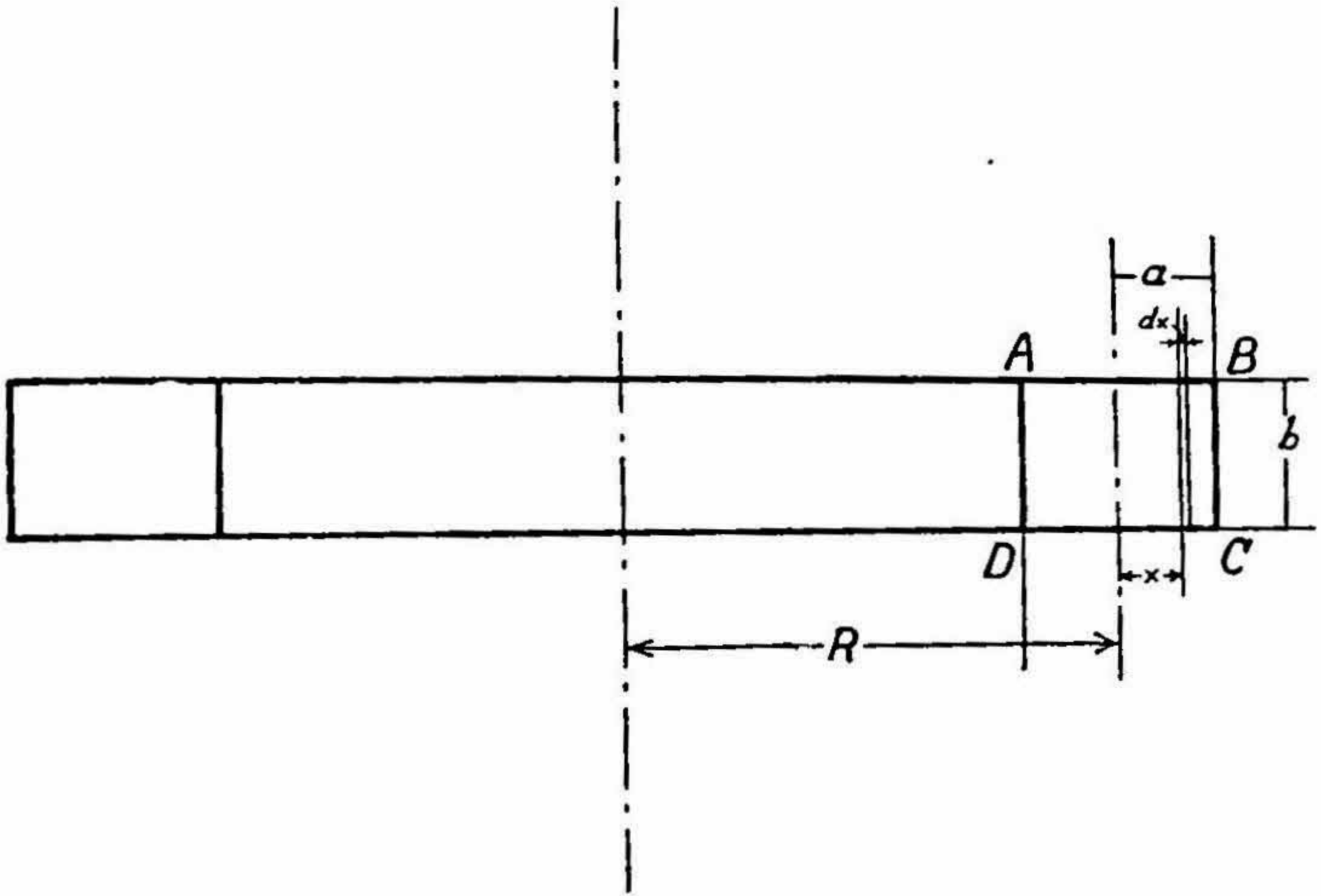


Fig. 9

When a current I flows in the magnetizing rod, the total magnetizing flux in an elementary ring of thickness dx is

$$dX = \frac{2I}{R+x} b dx = \frac{2I b dx}{R+x}$$

The total magnetizing force in the section is

$$X = 2I b \int_{-a}^{+a} \frac{dx}{R+x} = 2b I \log \frac{R+a}{R-a}$$

$$= 2b I \log \frac{1+p}{1-p} \text{ where } p = \frac{a}{R}$$

The average magnetizing force is

$$H_0 = \frac{X}{2ab} = \frac{I}{a} \log \frac{1+p}{1-p}$$

The magnetizing force at the centre of the section is

$$H_r = \frac{2 I}{R}$$

$$\text{and } \frac{H}{H_r} = \frac{1}{2p} \log \frac{1+p}{1-p}$$

For the size of search coils used in these tests $a=1$ cm. and $R=3$ cm.

$$\therefore p = \frac{1}{3}$$

$$\text{In that case } \frac{H_o}{H_r} = 1.0397.$$

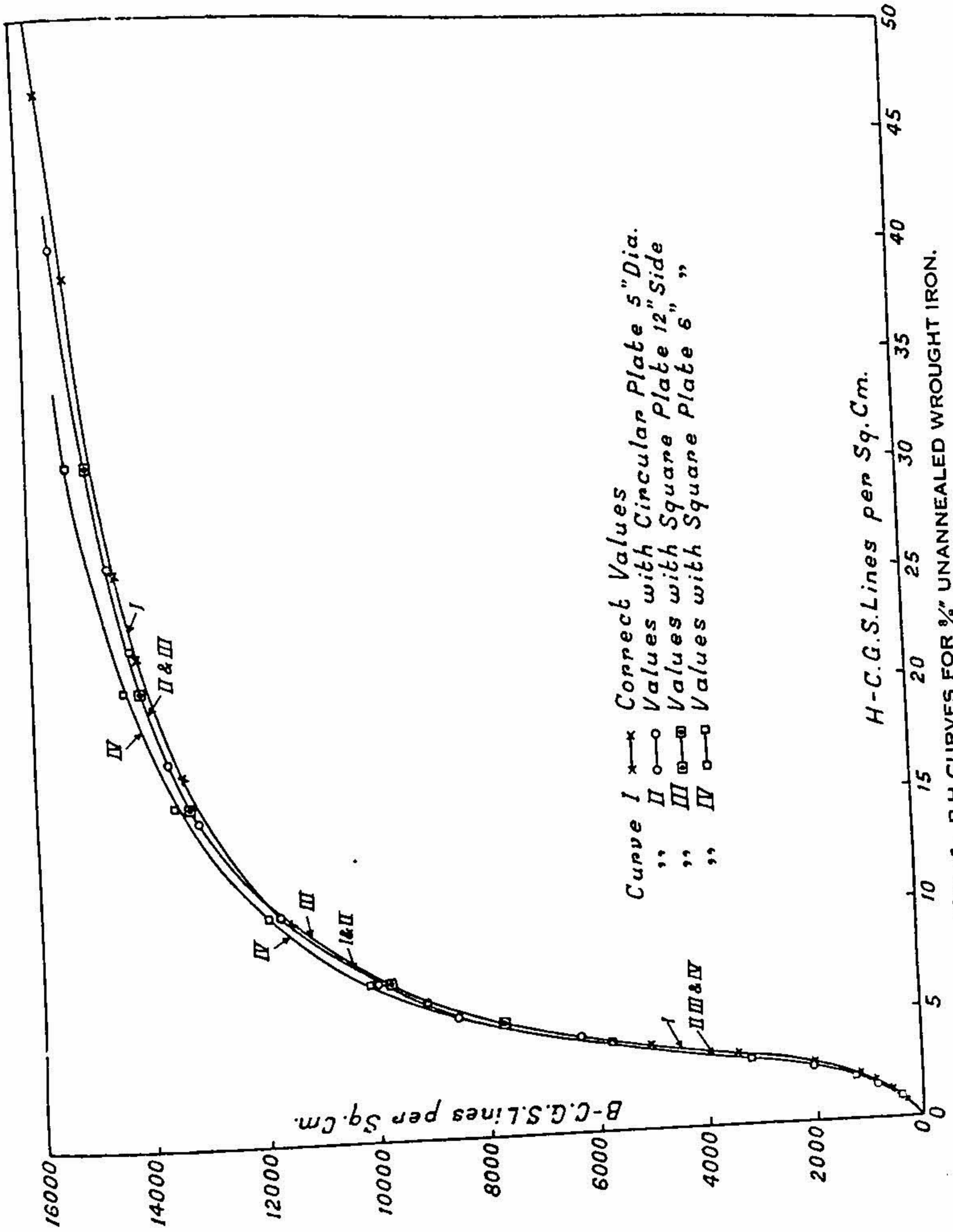


Plate 1. B-H CURVES FOR $\frac{3}{8}$ " UNANNEALED WROUGHT IRON.

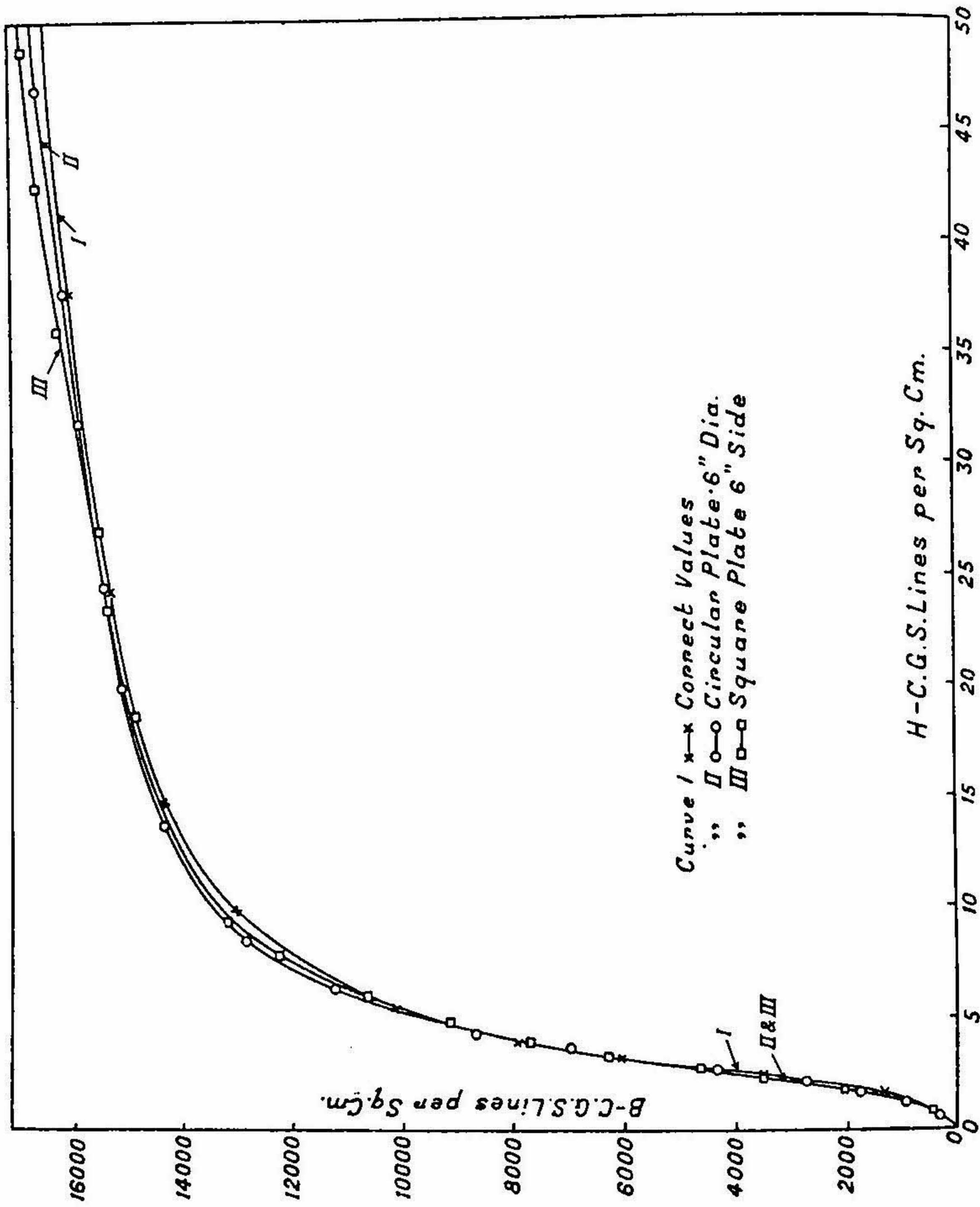


Plate 2. B-H CURVES FOR 1/2" UNANNEALED WROUGHT IRON.

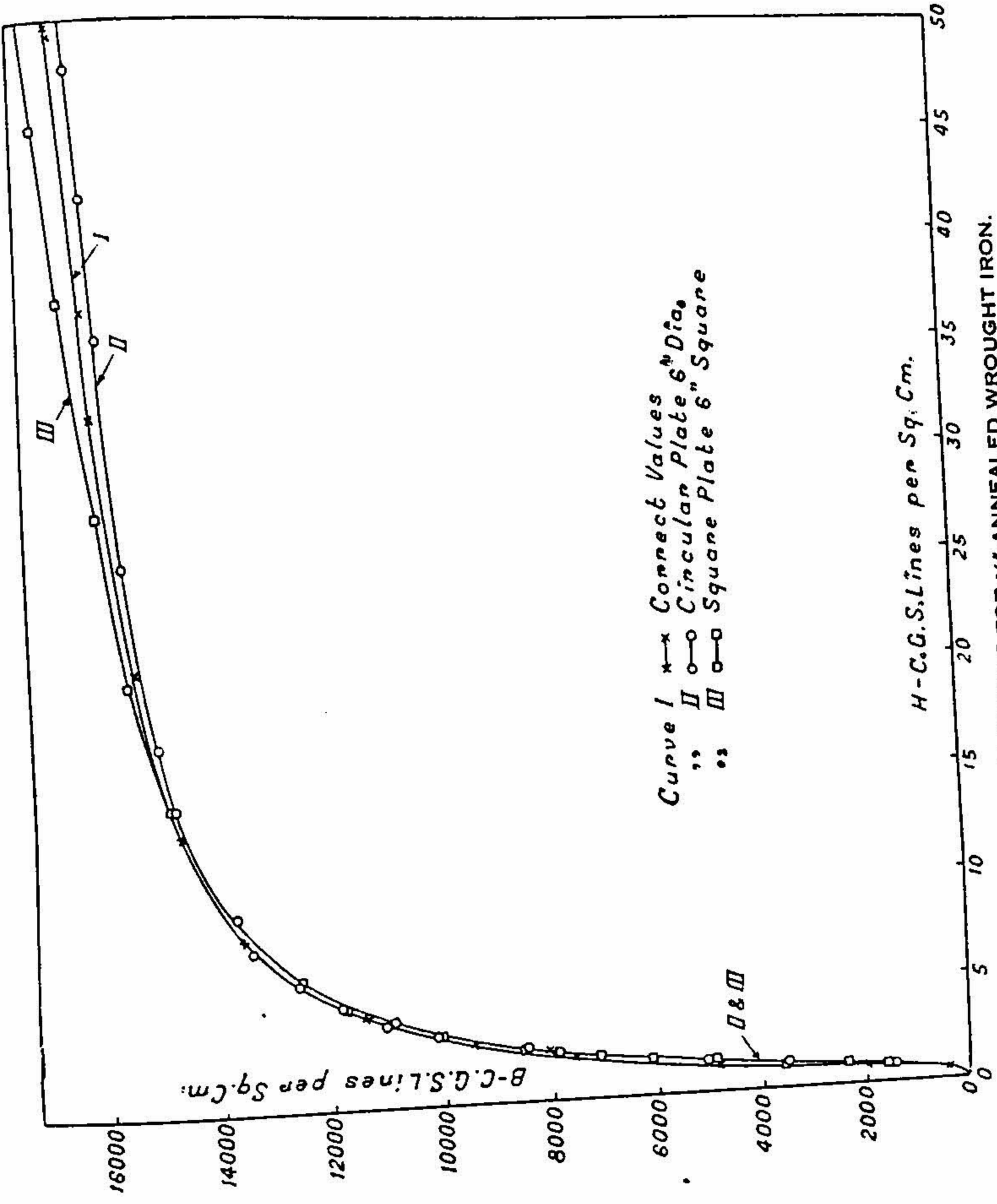


Plate 3. B-H CURVES FOR 1/2" ANNEALED WROUGHT IRON.

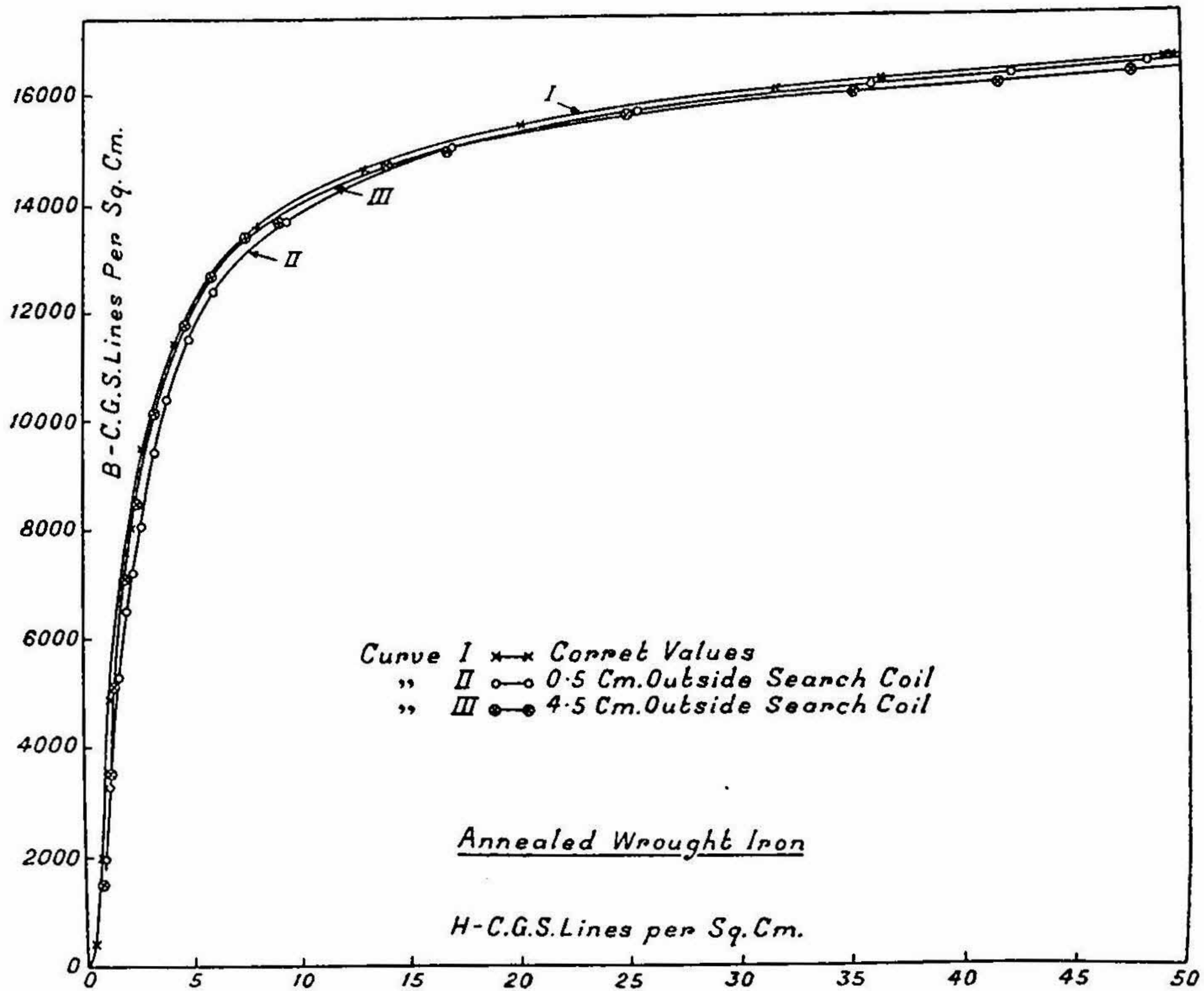
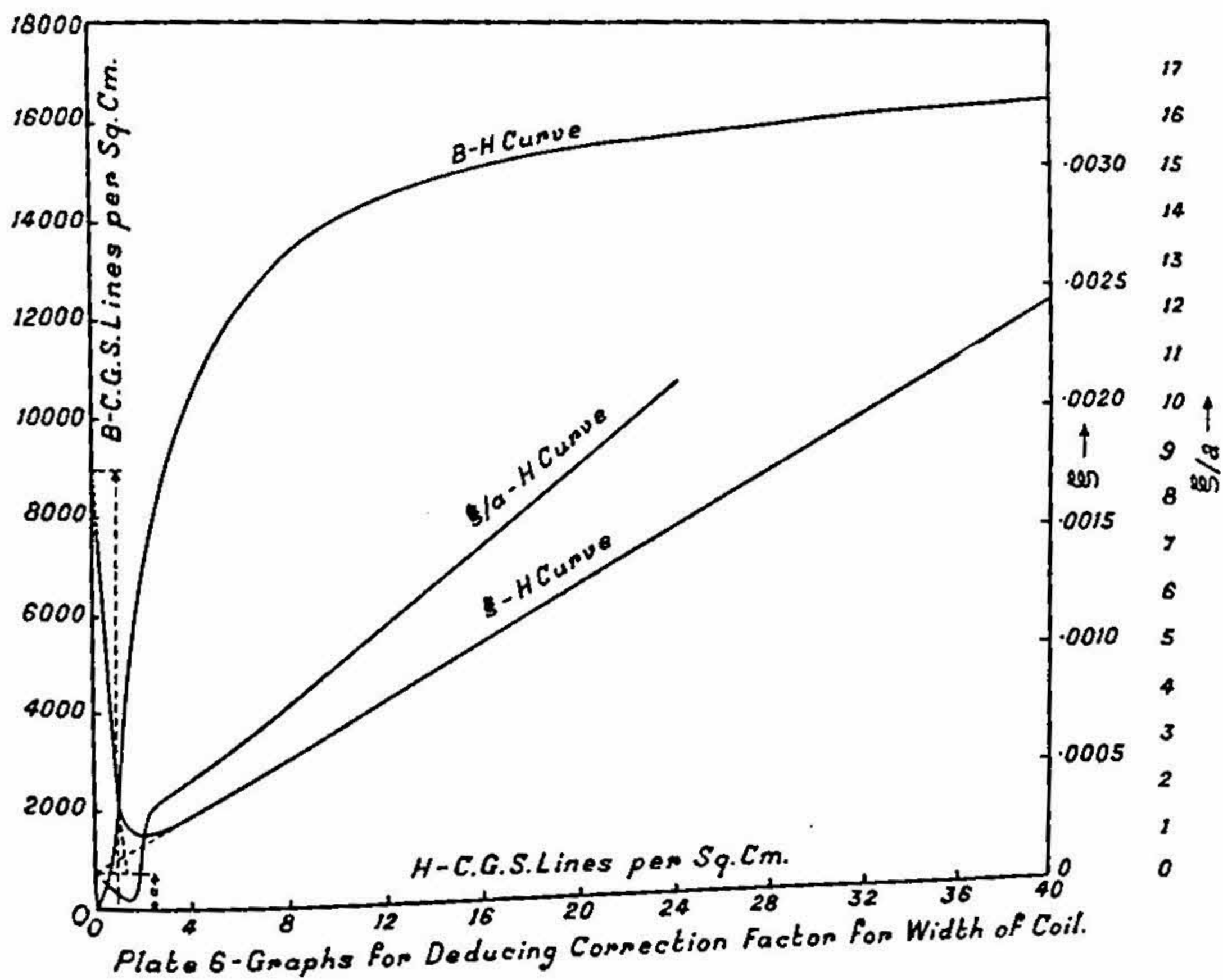
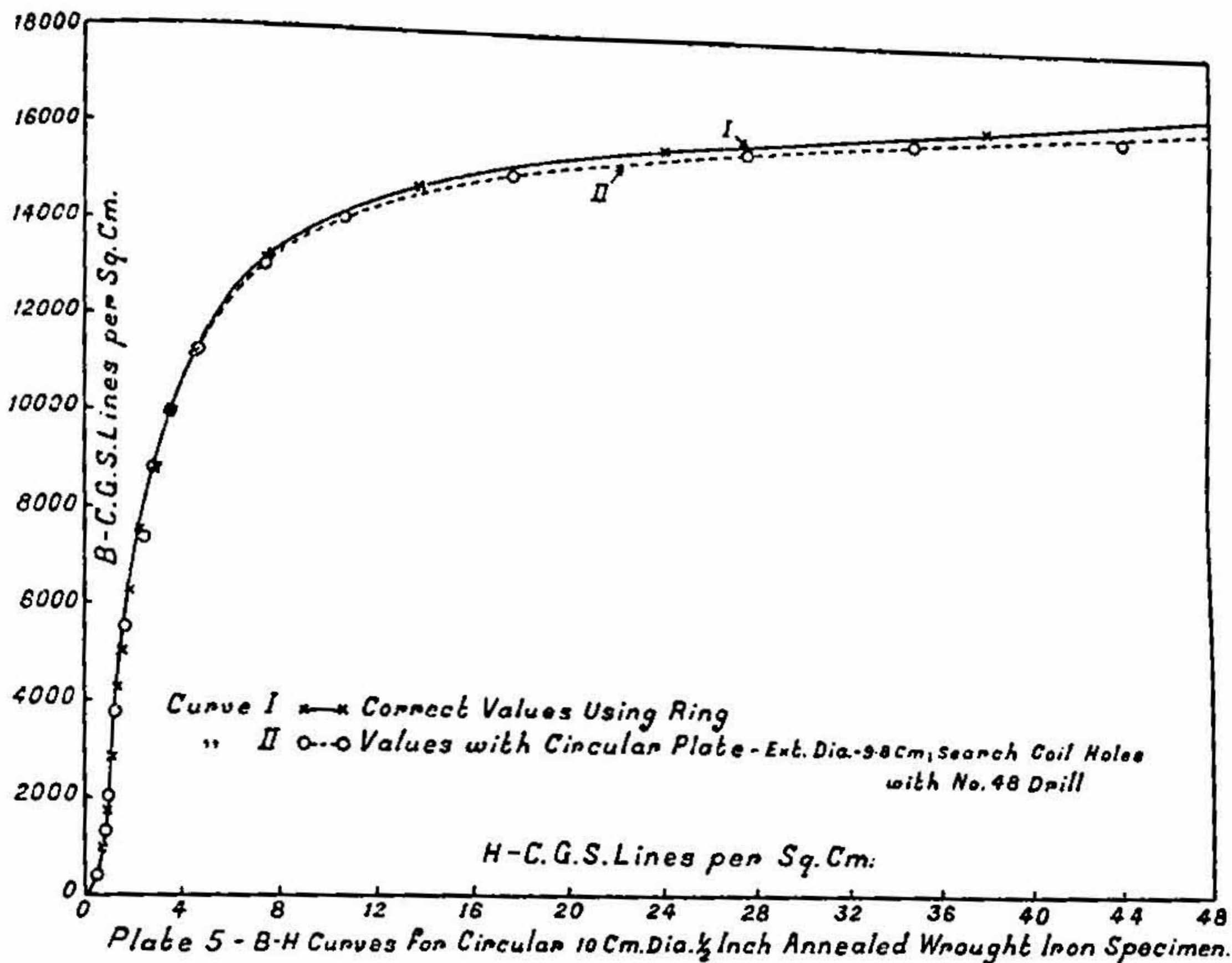


Plate 4. EFFECT OF SPACE OUTSIDE SEARCH COIL.



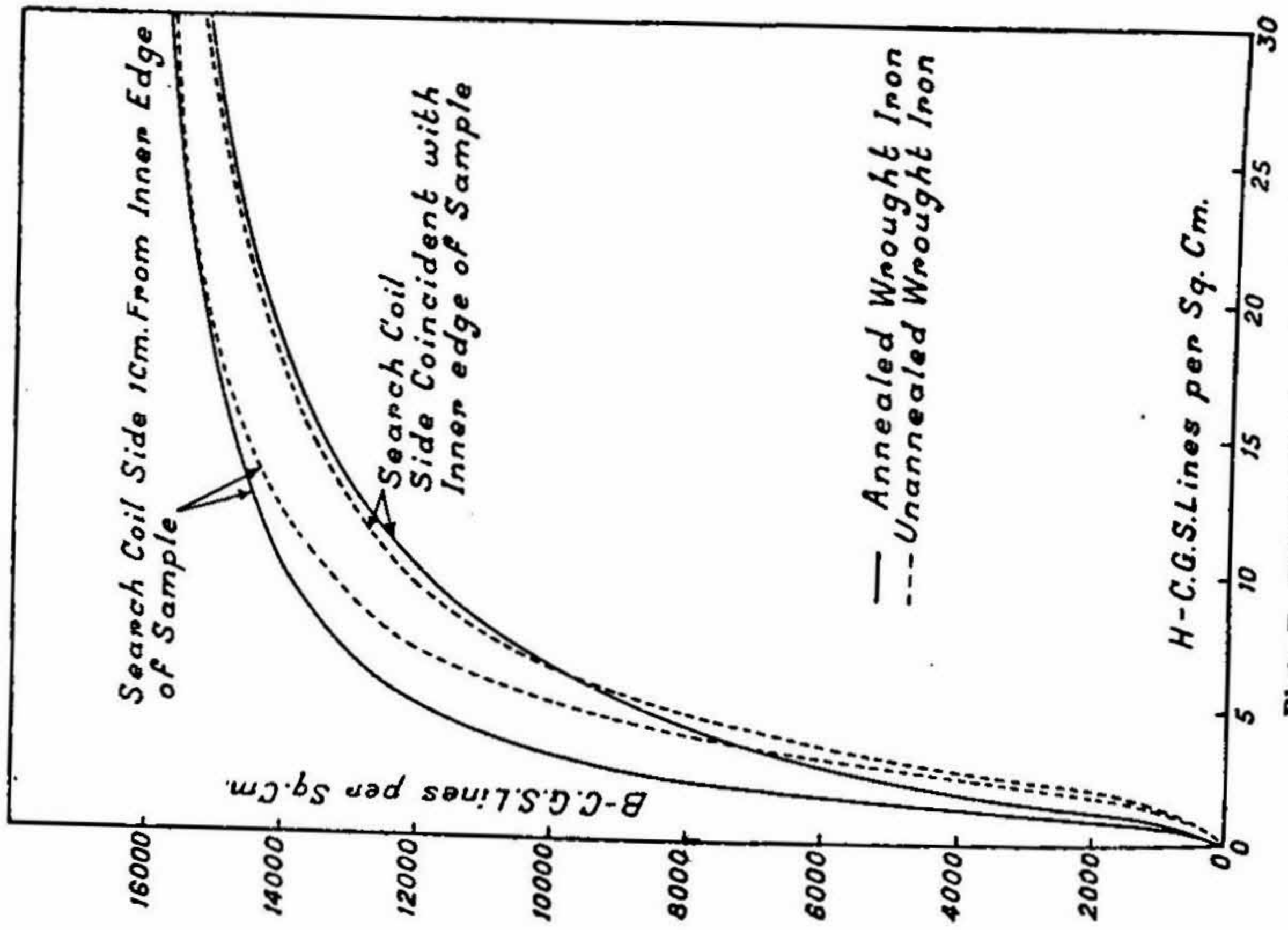


Plate 7. EFFECT OF CENTRE HOLE.

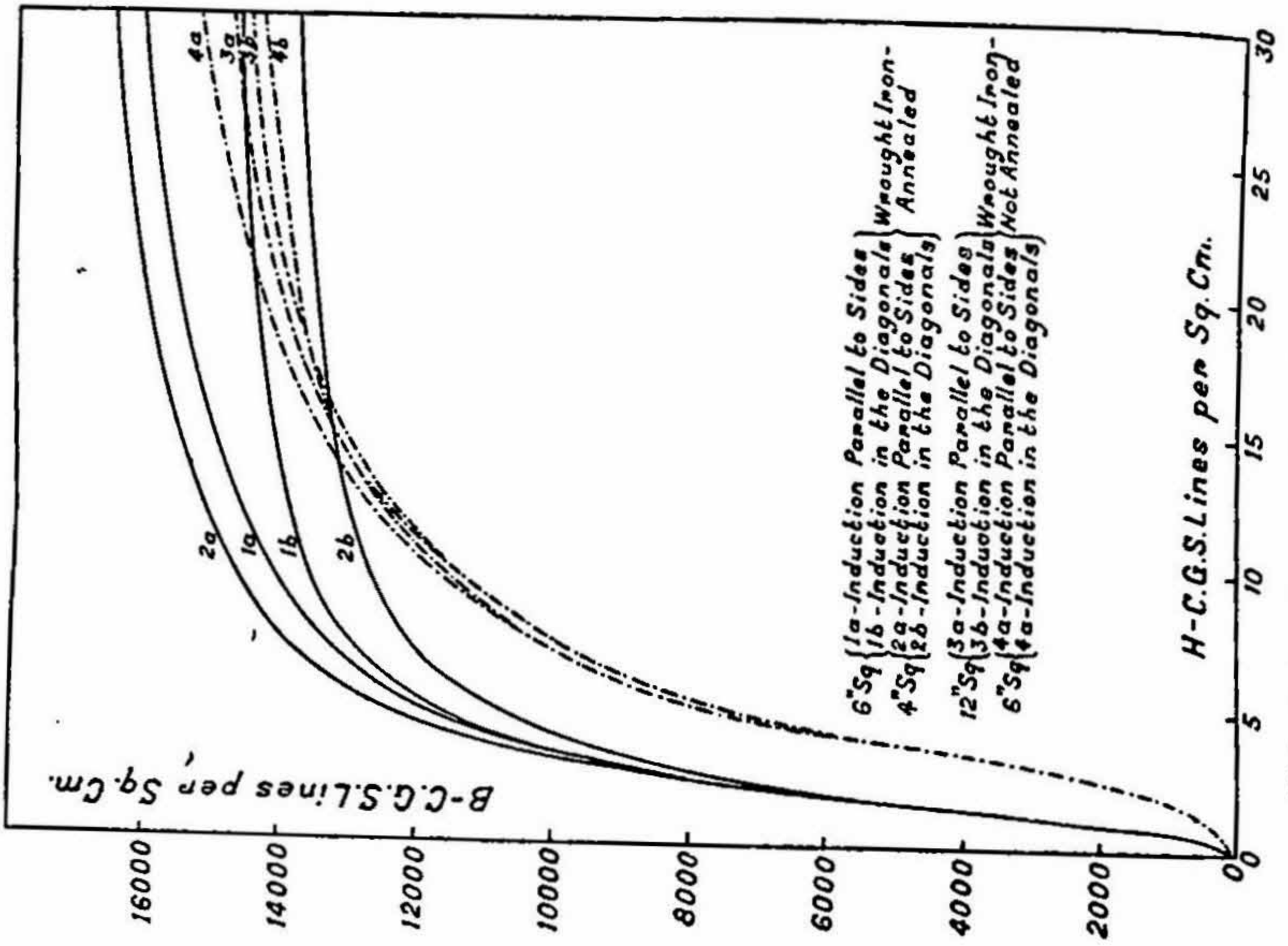


Plate 8. B-H CURVES WITH SQUARE SAMPLES.

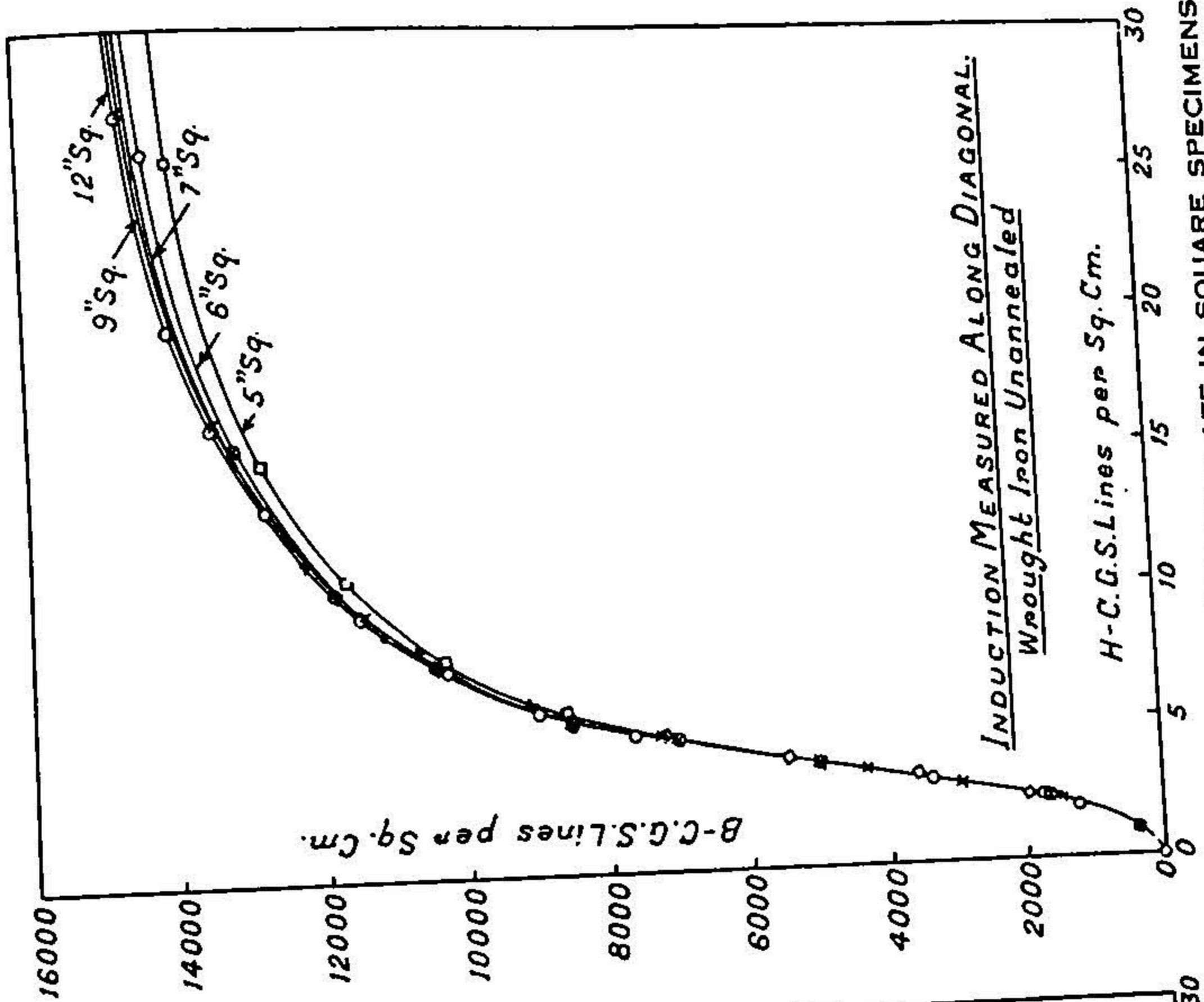


Plate 10. EFFECT OF SIZE OF PLATE IN SQUARE SPECIMENS.

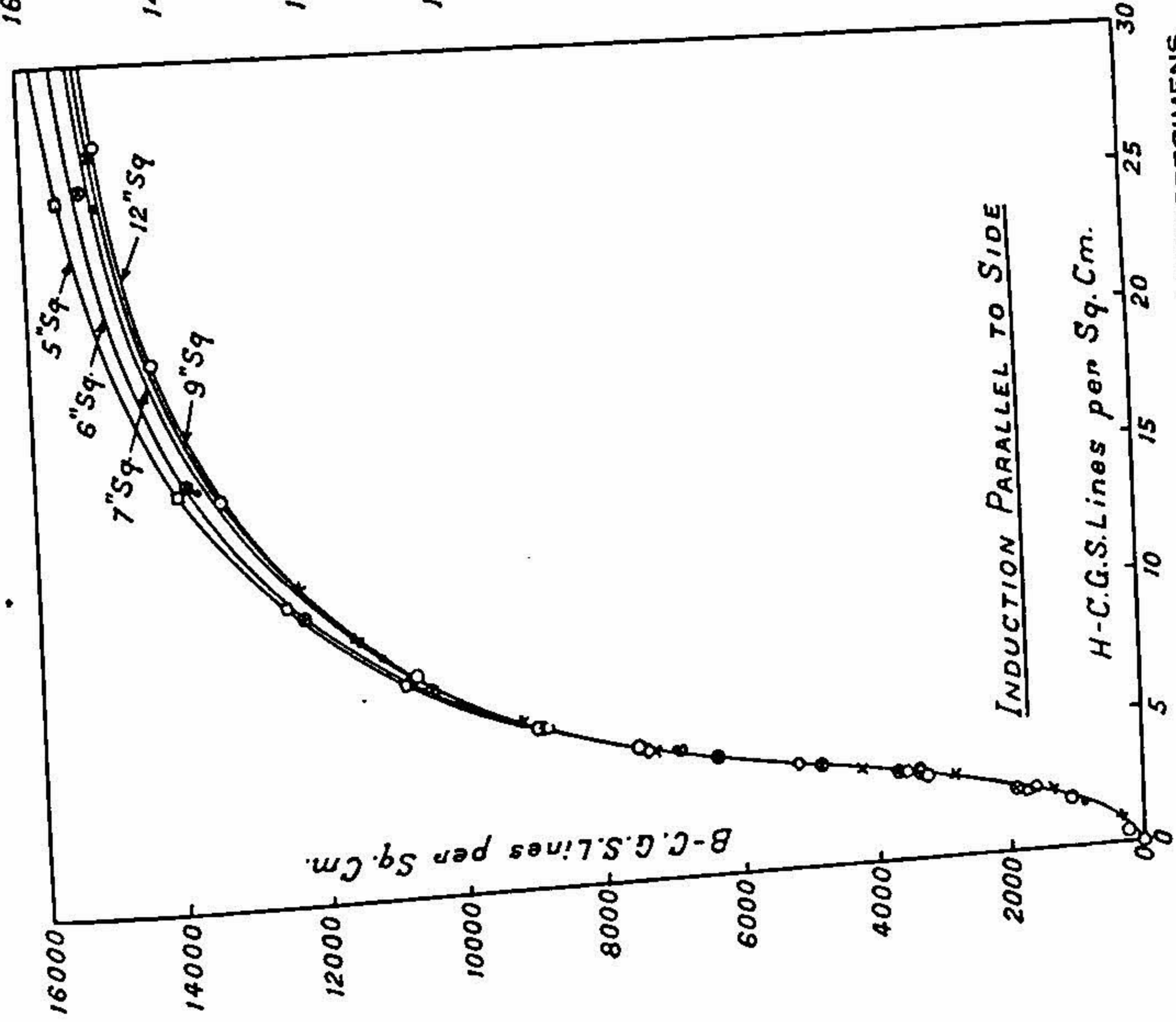


Plate 9. EFFECT OF SIZE OF PLATE IN SQUARE SPECIMENS.

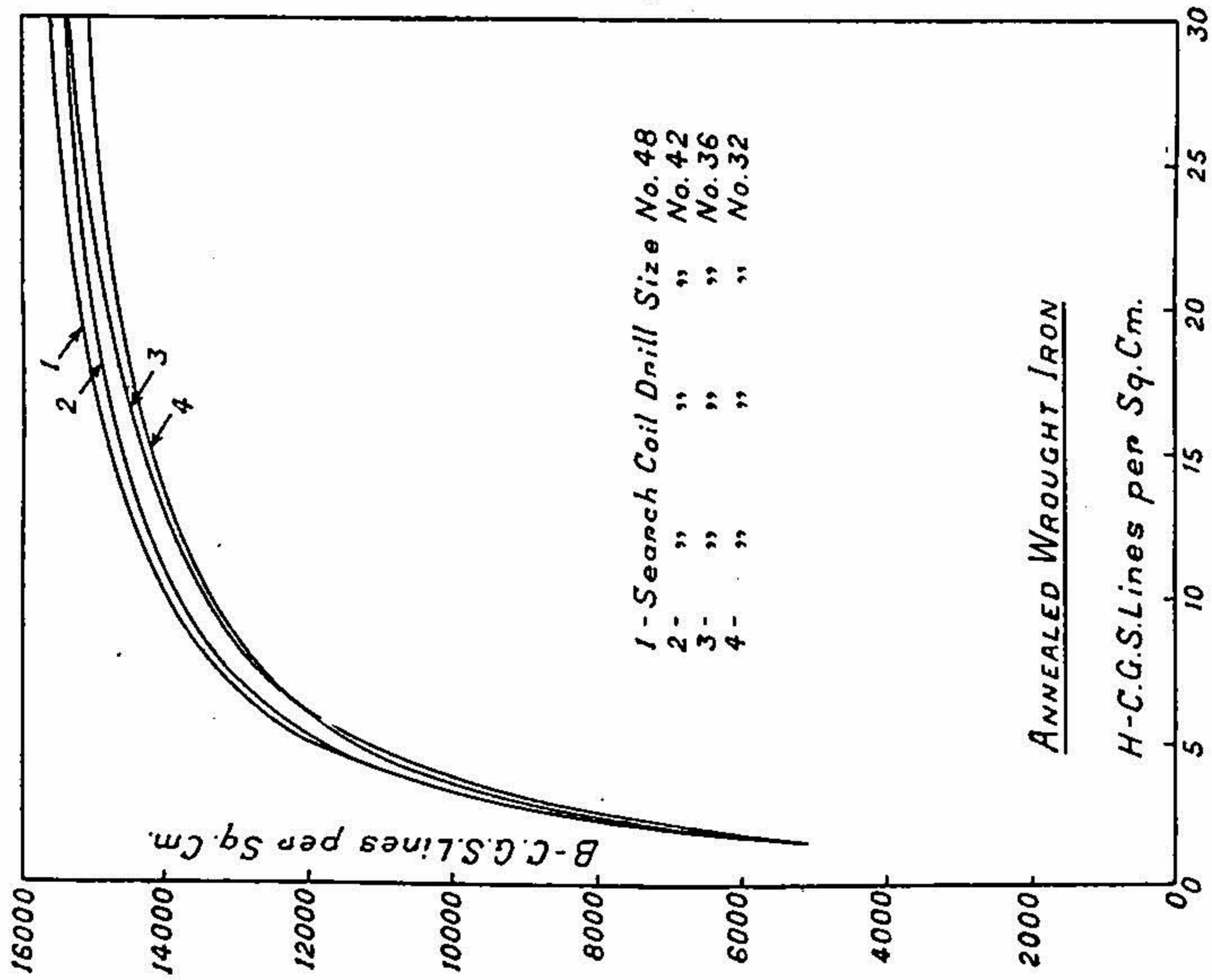


Plate 11. EFFECT OF SEARCH COIL HOLE SIZE.

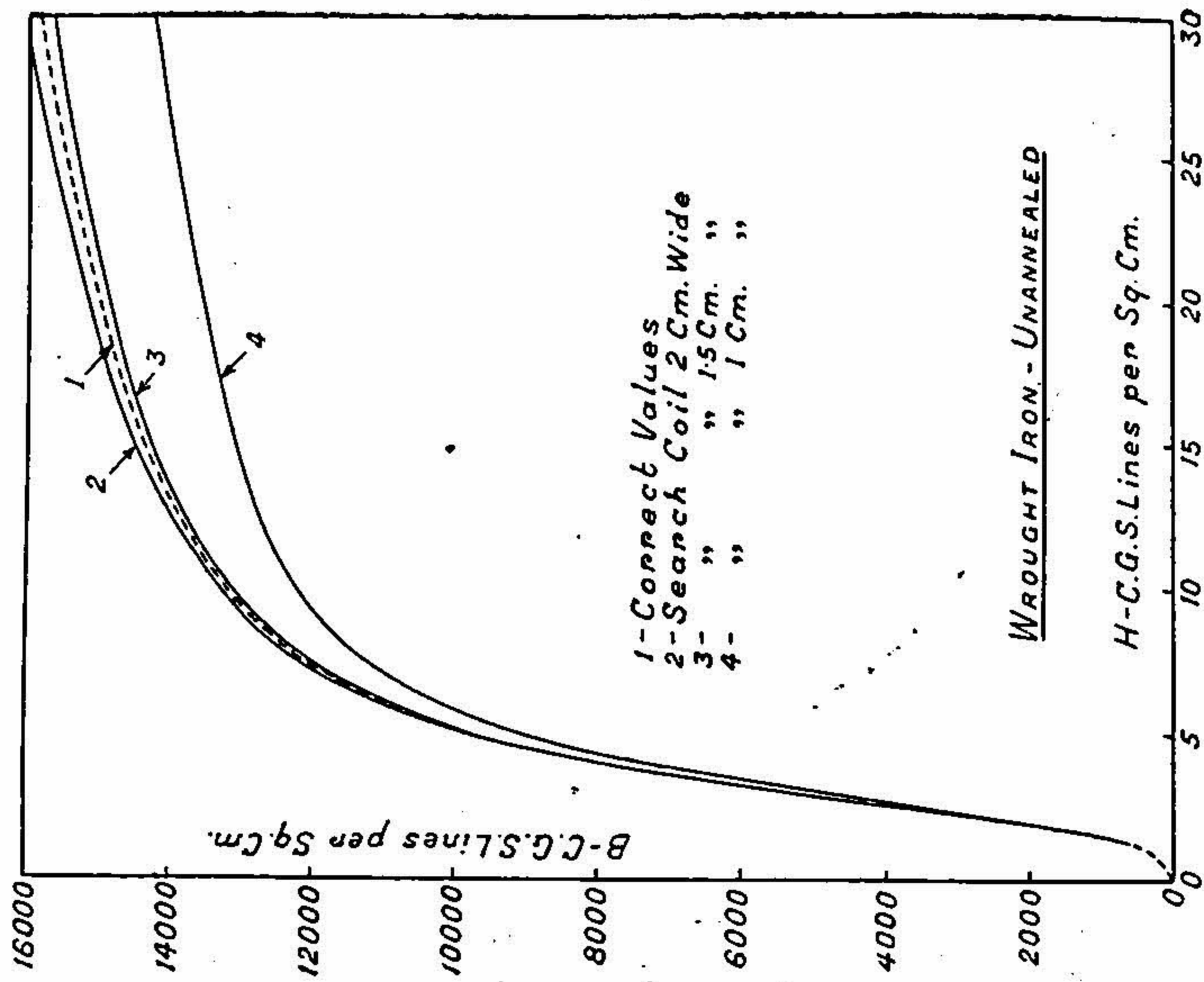


Plate 12. EFFECT OF SEARCH COIL WIDTH.

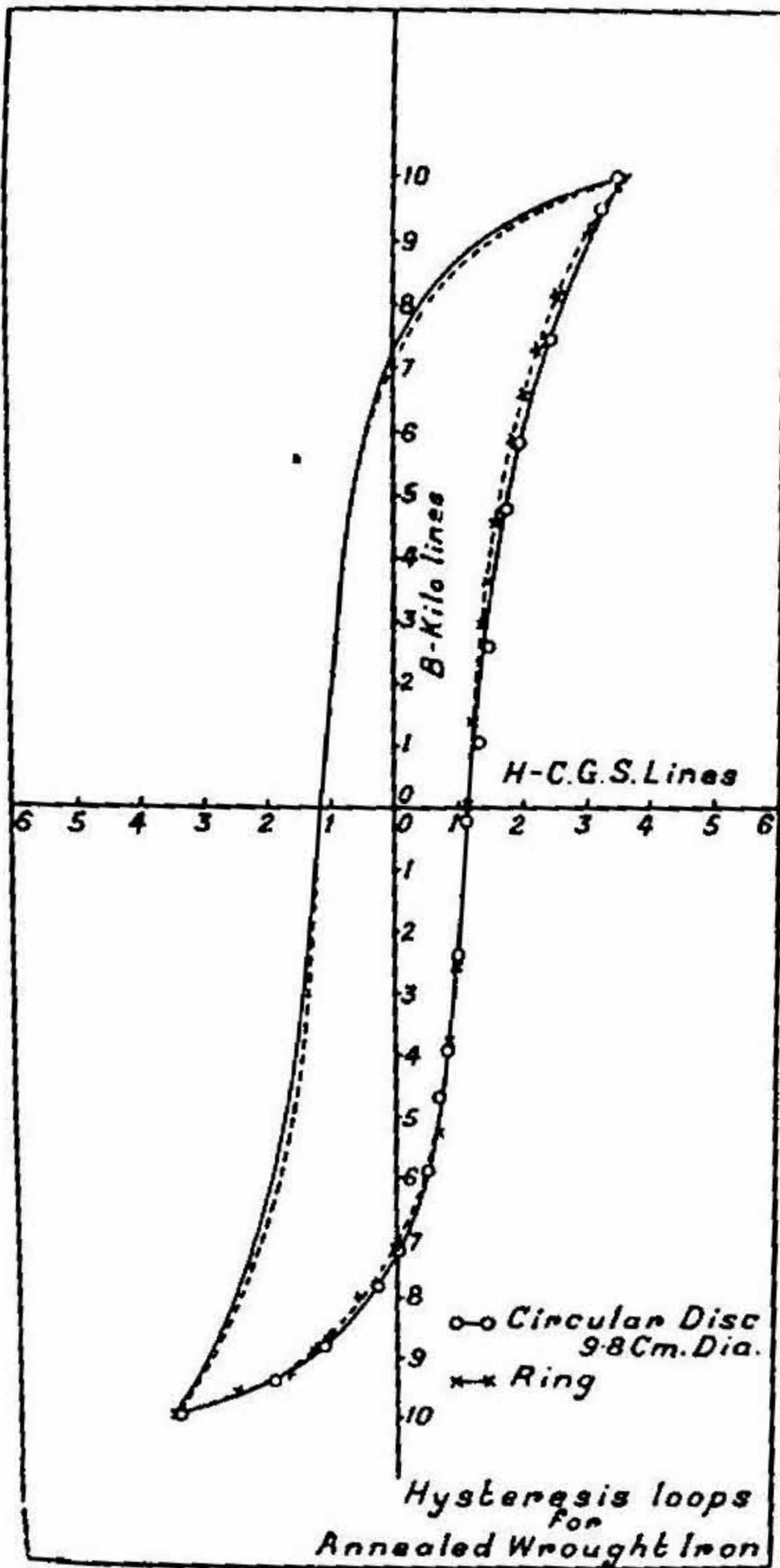


Plate 13.

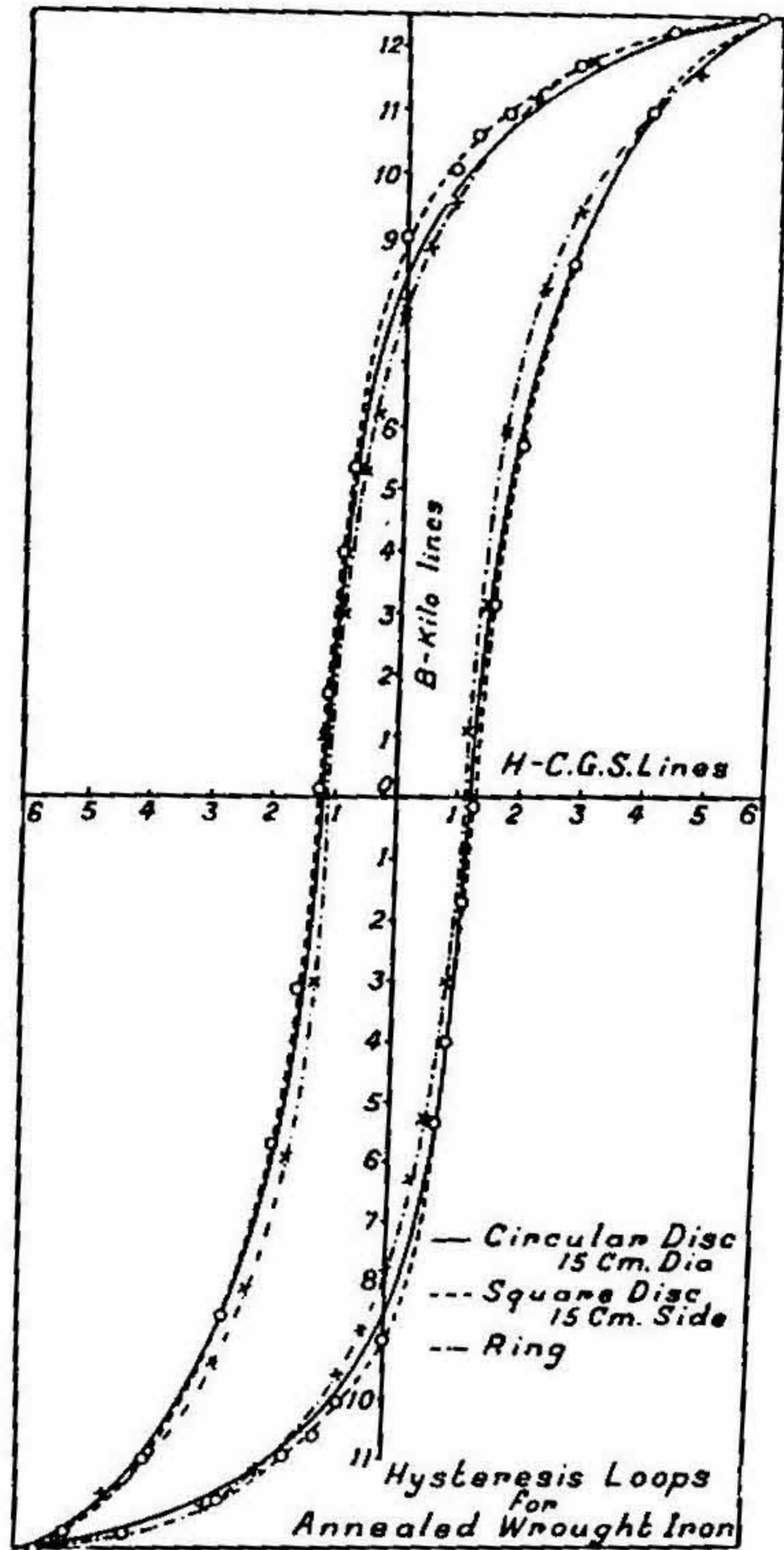


Plate 14.