

Notes on a Method of Testing Bars of Magnet Steel

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XVII. *Notes on a Method of Testing Bars of Magnet Steel.*
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Introduction.

THE present Paper is an outline of a series of tests on magnet steels carried out several years ago. Ewing's double permeameter method* for round bars was adopted, a modification being introduced in the fitting of the yokes to the bars. Although this method gives results which are sufficiently accurate for most practical requirements, it is more laborious and less accurate than that developed by Messrs. Campbell and Dye,† in which differential search coils are used to measure the value of the magnetising force. The latter method possesses the advantage that the value of the flux density and the corresponding value of the magnetising force can be measured at any part of the bar. In Ewing's method the value of B is not uniform along the bar, owing to leakage between the bars in the two limbs of the permeameter. Since leakage occurs with both the long and the short permeameters, there is a certain amount of compensation, when the B - H curve is obtained by the method outlined by Ewing, as will be shown later when dealing with the correction to be applied for leakage. Moreover, the value of B being found experimentally with a search coil at the centre of the bar (where the leakage is small), and that of H (at the centre), calculated from the permeameter constants, it follows that, provided the leakage effect was the same for both permeameters, the values of B and H would be correct. The leakage effect is not the same for both permeameters, and the value of H as found by calculation is in error. The error for any of the bars tested, which were of low permeability, does not exceed 1 per cent. As a method of precision the above has little to recommend it, whilst the additional labour required in taking two sets of readings, combined with the fact that the final result is only found after reduction from two B - H curves, is such as to make it inferior to the differential coil method.

* "Magnetic Induction in Iron and other Metals," "The Electrician," Vol. XXXVIII., p. 110, 1896.

† "Journal," I.E.E., Vol. LIV., p. 35, 1915.

Description of Apparatus.

A plan and elevation of the long permeameter is shown in Fig. 1. The short permeameter is the same in every respect as that in Fig. 1, excepting that the length of the winding is $3\frac{1}{2}$ in. instead of 7. Six layers of 324 series turns are wound on each limb, the maximum value of H obtainable being 450 C.G.S. with a current of 20 amperes. The coils are wound

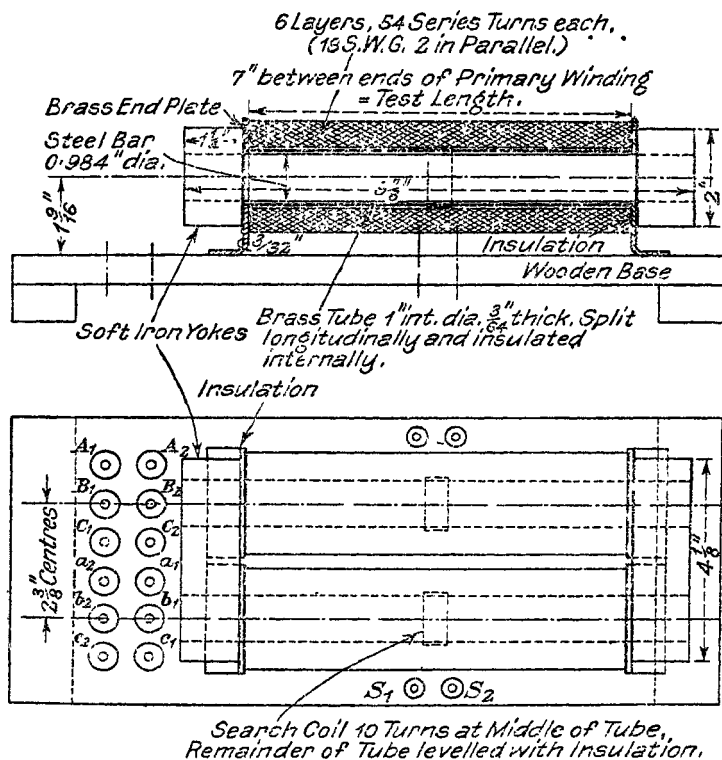


FIG. 1.—PLAN AND ELEVATION OF LONG PERMEAMETER P_1 .

A_1A_2 =Terminals of first layer. 54 turns ($H=3.82I$).

B_1B_2 =Terminals of second layer. 108 turns.

C_1C_2 =Terminals of third layer. 162 turns ($H \text{ total}=22.92I$),
where I =current.

on brass tubes fitted with end plates, split longitudinally to minimise eddy current effects. The space in a tube due to the removal of metal was filled with insulation to prevent the ends being drawn together when the coils were being wound. Although no deleterious effects were observed as a result of

the use of brass, it is better to use an insulating material on which to wind the coils. Such a material is not likely to be so permanent, of course. The terminals are arranged so that one or more layers can be used, and in this way small values of H are obtained without using a very small current.

The bars tested were nominally 1 in. diameter as taken from the rolls. These were ground down by means of a precision grinding machine, to 0.984 in. diameter, thus removing the material which had been in immediate contact with the rolls. The cuts taken by the grinder were less than $1/1,000$ in., and the mass of metal, beneath the surface, affected by the grinding was the least possible. Two yokes of very soft and permeable iron were accurately bored to fit the bars, so that the former could easily be drawn on (the bars being slightly lubricated) by means of a small screw jack. In this way the air gap between the bars and yokes was reduced to a minimum, and the necessity for pinching screws, whereby a variable amount of stress is applied to the bars when tested with different permeameters, was therefore eliminated. In making tests with two permeameters, it is essential that the reluctance of the yokes and joints should be the same for each permeameter for any given value of the flux density. Accurate machining of the bars and yokes is necessary to secure this condition. Tests were made with both permeameters by putting a mark on each bar and rotating the bar to a different position for the various tests. The results obtained in this way were in agreement within the limits of experimental error. When the bars are magnetised there is a force between them and the yokes, which tends to reduce the air gap. This introduces a certain amount of compressive stress, which will affect the magnetic properties of the materials where it occurs. For any given value of B , however, this condition is the same for both permeameters and the effect does not make its appearance in the corrected B - H curve.

The apparatus required to obtain B - H curves and hysteresis loops is shown diagrammatically in Fig. 2. The ammeter A could be used to read from $1/1,000$ th to 20 amperes, using four different shunts all of which were enclosed within the instrument case. The B - H curves were obtained by the method of reversals using a moving-coil ballistic galvanometer having a free period of 12 seconds. The calibration of the galvanometer was effected by means of a standard solenoid about 2 metres long, having a search coil of 400 turns, situated at its centre,

and giving up to 5×10^6 interlinkages, *i.e.*, line turns, on reversal of the current. The search coil of the solenoid was permanently connected in the galvanometer circuit, so that the conditions under which the B - H curves were taken were identical with those when the galvanometer was calibrated, except that the iron was removed from the permeameter for the latter operation. In order to destroy any residual magnetism in the yokes, each yoke was subjected to a few sharp blows before being fitted to the bars.

It was thought that errors might be introduced owing to time lag of the flux in the interior of bars nearly 1 in. diameter,

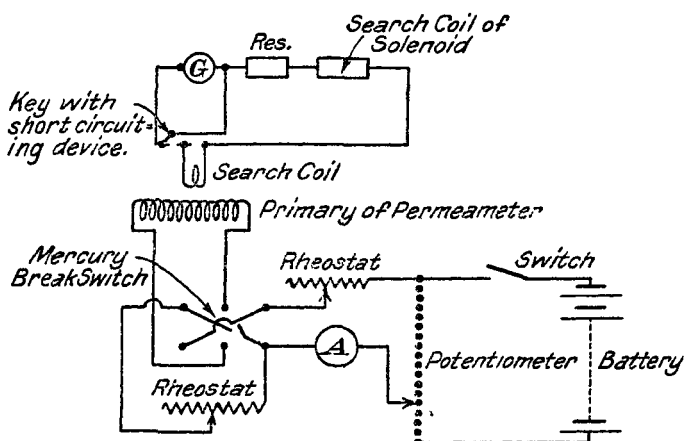


FIG. 2.—DIAGRAMMATIC SKETCH OF APPARATUS FOR OBTAINING B - H CURVES AND HYSTERESIS LOOPS.

thereby giving a smaller galvanometer throw than if the flux change had been transient. This point was investigated by using a Grassot fluxmeter to measure the flux change on reversal of various values of the current and comparing the results with those obtained with the galvanometer under identical conditions. The agreement between the results found by the two methods was accurate within the limits of errors of observation, although the flux change, especially on the steep portion of the B - H curve, with bars of relatively large permeability, was not complete before the galvanometer coil began to move (*see* Appendix).

Meaning of Symbols Used.

B = flux density in lines per square centimetre.

$B_{\text{rem.}}$ = Remanence, *i.e.*, the value of B on the hysteresis loop for which $H=0$.

J = Intensity of magnetisation = $(B-H)/4\pi$.

$J_{\text{rem.}}$ = Remanent intensity of magnetisation on the hysteresis loop for which $H=0$.
 $= B_{\text{rem.}}/4\pi$.

H = Magnetising force in C.G.S. units.

H_c = Coercive force, *i.e.*, the negative value of H required to reduce the remanent intensity of magnetisation $J_{\text{rem.}}$ to zero, when proceeding from $J_{\text{max.}}$ round a hysteresis loop. In the case of magnet steels the slope $\left(\frac{dB}{dH}\right)$ of the hysteresis loop in the neighbourhood of $B=0$, is sufficiently steep that the negative value of H corresponding to $B=0$, is almost equal to that when $J=0$. The difference between the two values of H falls within the limits of experimental error. In these tests, therefore, the coercive force has been taken as the negative value of H corresponding to $B=0$. The above definitions are almost identical with those used by Messrs. Campbell and Dye.

Treatment of Bars Before Testing.

In carrying out tests on magnet steels using the double permeameter method, it is essential that the treatment of the bars should be the same before being tested by individual permeameters, *i.e.*, the bars should have the same magnetic history. Each bar was, therefore, placed in a solenoid about 15 in. long, through the winding of which an alternating current of from 1 to 2 periods per second was passed for about 1 minute and then gradually reduced to zero. The condition of the bars was tested by slipping off a coil and observing the throw on a ballistic galvanometer connected to it. By this means it was possible to reduce the remanence ($B_{\text{rem.}}$) below 30 lines per square centimetre. To secure reliable results, the magnetic qualities of each of the pair of bars should be in close agreement, and in the experiments herein described, the permeability of individual bars of each pair differed by less than 1.5 per cent. By connecting the search coils on the two limbs of the permeameter in series, an average of the two bars is obtained.

Leakage.

Both permeameters were tested for magnetic leakage by winding a search coil, having the same number of turns as that on one of the brass tubes, on each yoke. The leakage value of B was ascertained by connecting the search coil on a yoke in opposition to that on one of the brass tubes, raising the sensitivity of the galvanometer by cutting resistance out of the secondary circuit and noting the throw on reversal of the current. Assuming that the rate of change of flux $\left(\frac{dB}{dt}\right)$ is the same through each coil, the throw is a measure of the flux which does not pass through the centre of the yoke, *i.e.*, the leakage flux.* The leakage can also be found by observing separate galvanometer throws with each coil.

Let δ_1 = deflection with search coil on bar.

Let δ_2 = difference in deflection with search coil on bar and that on yoke ; then leakage fraction = $\frac{\delta_2}{\delta_1} = \lambda$.

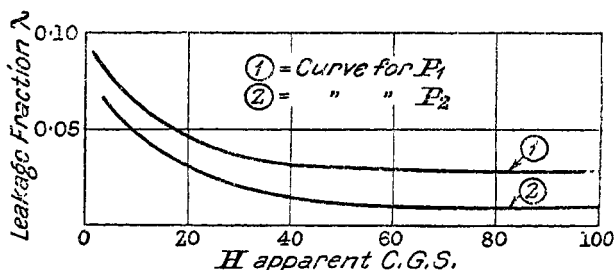


FIG. 3.—DIAGRAM SHOWING LEAKAGE FRACTION PLOTTED AGAINST APPARENT VALUES OF H , FOR BOTH PERMEAMETERS.

The circuits followed by leakage lines and lines through the yoke are in parallel ; thus the same value of H produces the lines in both circuits. Since P_1 (long permeameter) is twice as long as P_2 (short permeameter), the leakage will be greater with the former than with the latter. This is borne out by experimental results, as illustrated in Fig. 3.

* The value of B can be made almost uniform throughout the whole magnetic circuit by means of compensating coils at the ends of the permeameter limbs. The magnetising force due to these coils, however, affects the value of H at the centre of the bars by an amount which cannot be accurately calculated. The use of compensating coils on both permeameters would modify the two sets of results making it impossible for the true values of H to be easily and accurately found, since the test length with P_1 is twice that with P_2 .

If the correction applied to find the "true" value of H at the middle of the bar is comparatively large, the effect of leakage may be appreciable. As the leakage is different for each permeameter, the reluctance of the paths (including leakage paths) other than the test lengths will also be different. Thus the additional ampere turns necessary to overcome this reluctance will not be the same for each permeameter, and the corrected value of H obtained from the curves, as shown in Fig. 7, will not be the "true" value of H . The error from this cause is most liable to occur on the steep portion of the B - H curve, where the correction for the effect of the yokes and air-gaps is large compared with the true value of H . It will

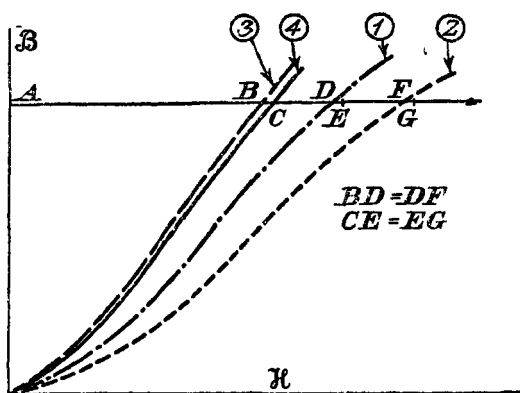


FIG. 4.

- (1) Curve obtained with long permeameter.
 - (2) Curve obtained with short permeameter.
 - (3) Curve obtained from (1) and (2) by setting back DF from D .
 - (4) Curve obtained with zero leakage, *i.e.*, the true B - H curve. E and G are points in which curves (1) and (2) would cut AN for zero leakage.
- BC =correction to be applied to (3) to obtain (4).

be seen from Fig. 3 that the leakage is greatest at low values of H , and therefore at low flux densities. This is due to the fact that the yokes are being worked at very low permeability. It would not be advantageous to decrease the cross-sectional area of the yokes, thereby working them at higher permeability, since this would necessitate large corrections for high values of B , an increase in the leakage and a diminution in the largest value of the corrected magnetising force obtained with the permeameters.

Owing to the complex nature of the leakage, it is difficult to estimate its effect on the "true" value of H to any degree of precision. In the following an attempt has been made to calculate approximately the correction to be applied in order to obtain the true value of H .

Correction for Leakage.

If it be assumed that B is proportional to H for the portions of the circuit other than the test lengths, a leakage fraction entails a corresponding diminution in the magnetising force necessary to overcome the reluctance of these portions, due to the decrease in B through them. If the true value of this force, i.e., for zero leakage* is H , the actual value required with the permeameter is $H(1-\lambda)$. Thus the distance DF between curves (1) and (2) is in error by an amount depending, among other things, on λ_1 and λ_2 , these being the leakage fractions with P_1 and P_2 respectively.

An approximate correction to be applied to curve (3), [obtained from (1) and (2)] in order to find the true curve (4), can be derived as follows :—

$$CD = CE(1 - \lambda_1)$$

$$CF = 2CE(1 - \lambda_2) \quad \dots \quad CF = 2CD \frac{(1 - \lambda_2)}{1 - \lambda_1}$$

$$BC = DF - CD, \text{ since } BD = DF;$$

$$= CF - 2CD$$

$$= 2CD \left(\frac{\lambda_1 - \lambda_2}{1 - \lambda_1} \right)$$

$$= 2BD \left(\frac{\lambda_1 - \lambda_2}{1 + \lambda_1 - 2\lambda_2} \right) \text{ substituting } BD - BC \text{ for } CD;$$

$$= 2BD(\lambda_1 - \lambda_2) \text{ approx., since } (\lambda_1 - 2\lambda_2) \text{ is small, compared with unity.}$$

Now $AC \doteq AB$, and hence the percentage error on the true value of $H \doteq \frac{100(\lambda_1 - \lambda_2)}{a}$, where $AB = 2aBD$, and λ_1, λ_2 are the

leakage fractions for the apparent values of H (corresponding to the value of B under consideration) found with P_1 and P_2 . It is of interest to observe that when $\lambda_1 = \lambda_2$ the error vanishes. Using the above formula and the curves shown in Fig. 3, the error in the corrected value of H (as found by the method

* This, of course, can never be realised in practice.

shown in Fig. 7) for the bars used, does not exceed 1 per cent. at any point on the B - H curve. As it is impossible to produce magnet steel in which the magnetic qualities *always* agree within 1 per cent., this error can be disregarded.

B-H Curves, Hysteresis Loops, Remanence and Coercive Force.

After carefully demagnetising a pair of bars, as explained above, the B - H curve was taken with P_1 . The bars were then demagnetised in a similar manner and the B - H curve taken with P_2 . Having obtained these B - H curves, the corrected B - H curve was found by setting back the horizontal distance between the curves, so that AB is equal to BC , as shown in Fig. 7. This curve requires further correction, since the area of the search coil on the brass tube is 1.4 times the area of the bar. It is necessary, therefore, to subtract $0.4 H$ from the

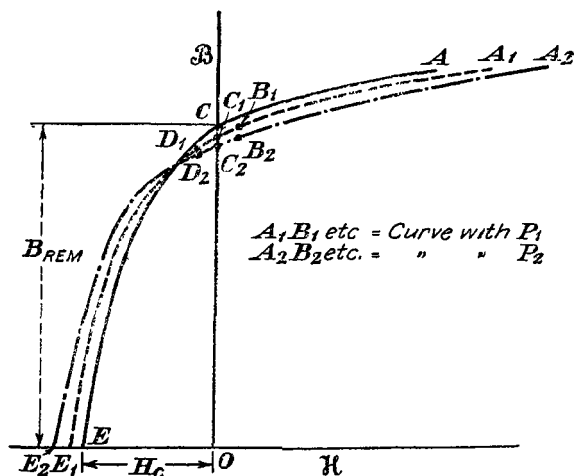


FIG. 5.—DIAGRAM ILLUSTRATING THE METHOD OF FINDING H_c' AND B_{rem} .

ordinates of the curve, H being the value read on the curve found by the above procedure. Messrs. Campbell and Dye* subtract this amount, automatically using a mutual inductance, the primary of which carries the current through the permeameter winding (or a fraction of it, using a shunt), the secondary being in series with the search coil. This procedure was

* *Loc. cit.*

inapplicable in the present case because the current through the primary of the permeameter is proportional to the "apparent" H and not to the corrected H .

In order to get the corrected value of $H_{\max.}=100, 200$ and 400 for the hysteresis loops, the "apparent" values of H required for P_1 and P_2 were taken from the $B-H$ curves. Complete hysteresis loops were not taken for $H_{\max.}=200$ and 400 , but five points, viz., A, B, C, D and E , were determined with each permeameter (Fig. 5). A corresponds to the maximum value of H, B and D to points near the B axis, i.e., near the point $B_{\text{rem.}}$, while C corresponds to the "apparent" remanence. The corrected value of $B_{\text{rem.}}$ can then be found

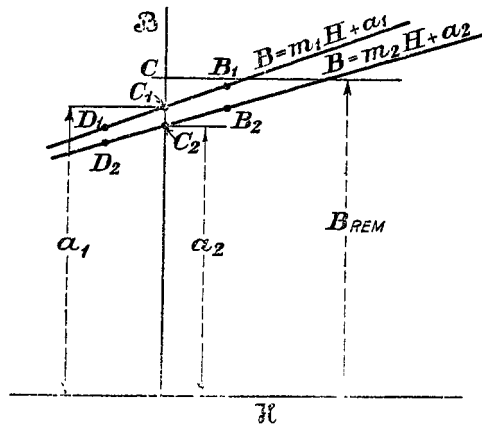


FIG. 6.—DIAGRAM ILLUSTRATING THE METHOD OF CALCULATING $B_{\text{rem.}}$

quite accurately as shown in Fig. 5, by plotting the points B, C, D for each permeameter, and setting back the difference between the curves. The point in which the corrected curve cuts the B axis is the corrected value of $B_{\text{rem.}}$. Since the points are almost collinear $B_{\text{rem.}}$ may be found by calculation, using the co-ordinates of the points B and D . The equations to the lines through the respective pairs of points are given in Fig. 6. If m_1 and m_2 are the slopes of these lines, we have

$$B_{\text{rem.}} = \frac{2m_1A_2 - m_2A_1}{2m_1 - m_2}$$

H_c is found by subtracting E_1E_2 from OE_1 (see Fig. 5).

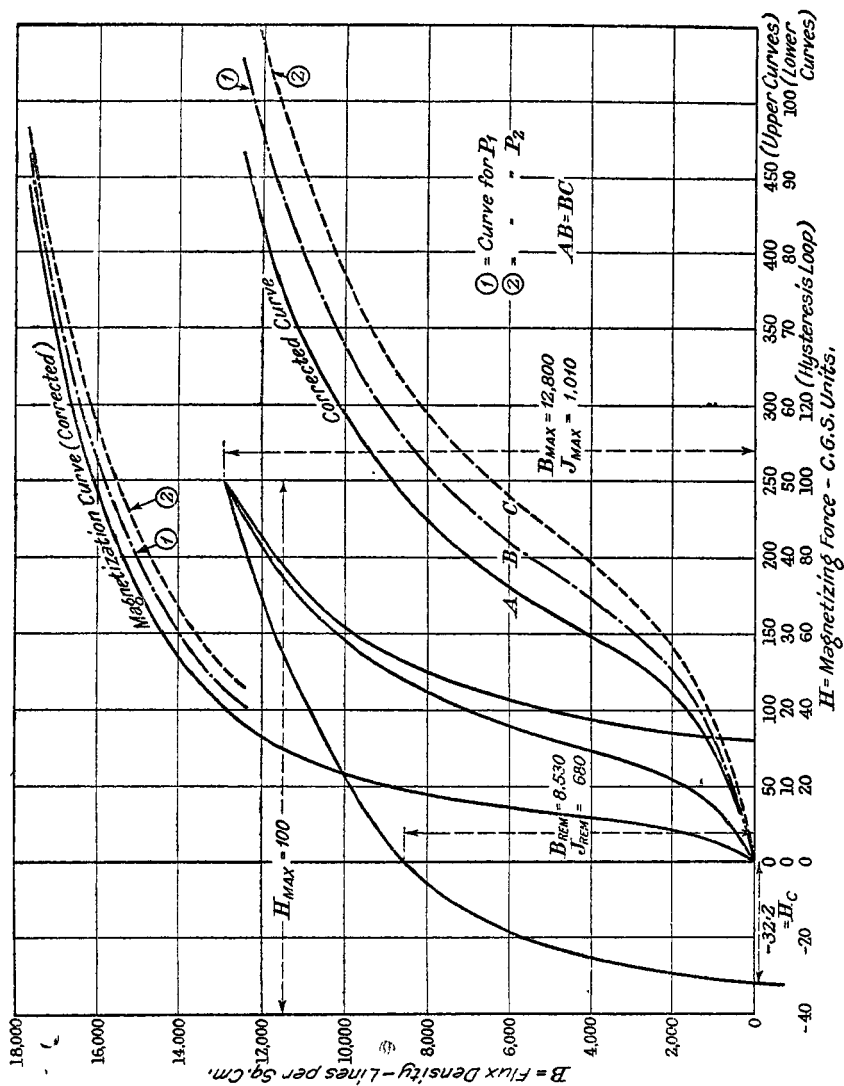


FIG. 7.—DIAGRAM SHOWING B - H CURVE AND HYSTERESIS LOOP OBTAINED WITH TWO SIMILAR BARS OF MAGNET STEEL.

In conclusion, the author wishes to convey his best thanks to Prof. E. W. Marchant, D.Sc., and to the Council of the Liverpool University for the facilities provided to enable the work to be carried out.

ABSTRACT.

In the Paper tests on cylindrical bars of magnet steel 1 in. diameter and 10 in. long are described. The tests were conducted using a slight modification of Ewing's double permeameter method. Instead of employing pinching screws in the yokes, the bars and yokes were ground accurately to 1/1,000th in., and arranged to make a good push fit. The method is compared with that in which use is made of differential coils for measuring the value of the magnetising force *in situ*, as developed at the National Physical Laboratory. It is shown that tests with the latter method can be conducted more speedily and accurately than with the double permeameter method. The variation in the magnetising force along the bar and the leakage between the pairs of bars in the permeameter is treated. A formula is developed, by means of which, with the aid of experimental data given in the Paper, a correction can be applied to allow for leakage effects. A *B-H* curve and hysteresis loop are given for a certain sample of magnet steel; also the details of the permeameter.

DISCUSSION.

Dr. D. OWEN said it was evident that the leakage did not occur only at the yokes, but began near the centre of the bars. The applied field would therefore be strongest at the centre, so that taking the average field, as done by Ewing, would give too low a value.