UNIVERSITY OF DETROIT

COLLEGE OF ENGINEERING

THE UNIVERSITY OF DETROIT FAHY SIMPLEX PERMEAMETER REDESIGN AND CONSTRUCTION

A THESIS

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IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

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OF

ELECTRICAL ENGINEERING

BY

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307 East 27 Street
Erie, Pennslyvania
May 10, 1953

Mr. T. Janisz,
Department of Electrical Engineering,
University of Detroit,
Detroit 21, Michigan.

Dear Sir:

The following is a joint thesis which is entitled, "Redesign of a Fahy Simplex Permeameter". It was written by Messers R. J. Schumacher and N. J. Kraus and is hereby submitted for your consideration and approval. The date of completion was May 3, 1953.

Sincerely,

Norbert J. Kraus
Norbert J. Kraus

Richard J. Schumacher
Richard J. Schumacher

PREFACE

This paper is titled as a redesign, since it is a revision of a previous thesis design by Messers G. Taylor and M. DuBay[1]. In the construction of the permeameter, some parts of the previous work of these men were used; the rest were discarded. Therefore, only the construction of the magnetic circuit, "B" coil, and "H" coil, will be described in this thesis.

The basic ideas of the original design were used in building this instrument, however, the shape and arrangement of the parts, and materials used, are quite different.

The wish of the authors of this paper is that this instrument will serve to facilitate the teaching of magnetic measurements in the electrical engineering curriculum at the University of Detroit.

Appreciation is hereby expressed of the Marathon Electrical Corporation and of the Armour Electric Company, Erie, Pennsylvania, for donating samples of electrical steel.

1. G. Taylor and W. DuBay, The Design and Construction of a Fahy Permeameter, November, 1952.

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CHAPTER I

EXPLANATION OF A PERMEAMETER

In the design of magnetic circuits, curves showing the characteristics of magnetic steels are very necessary. For proper design work, the core loss, magnetization, hysteresis, volt-ampere, and high frequency curves are essential. The permeameter is an instrument used to obtain two of these, namely the magnetization curve and the hysteresis loop.

The Fahy Simplex Permeameter is much used for routine testing, because it is simpler in both construction and operation than the Burrows Permeameter, and is less sensitive to the effects of magnetic inhomogeneities in the specimen. It also requires only a single specimen for testing. The specimen is clamped across the poles of an electromagnet which carries the magnetizing winding. A uniformly wound test ("B") coil extends over the entire active portion of the specimen for measuring induction. The magnetizing force is measured by means of a second test ("H") coil wound uniformly on a non-magnetic form; and mounted between the ends of two iron blocks, which clamp the specimen against the pole pieces of the yoke. Actually, it measures the change in magnetic potential between its ends when the magnetizing force is changed. The function of the iron blocks is to bring the potential of the ends of the specimen to the ends of the "H" coil, and the combination is in effect a magnetic potentiometer[1].

The core of the exciting coil is constructed of high grade steel laminations in order to obtain a low reluctance path for the flux. This core, along with the steel specimen and the heavy steel blocks with a bakelite core mounted between them, make up the magnetic circuit of the permeameter. It is assumed there is no appreciable mmf drop from the point of contact of the specimen to the ends of the "H" coil, all of the drop being considered across the length of the bakelite cored coil. It is necessary, therefore, to have good contact between the blocks and specimen in order to eliminate the effect of an air gap. The heavy blocks also serve to clamp the specimen into position. The magnetic circuit may be considered as having two parallel paths for the flux, one of high reluctance through the bakelite or air core, and one of low reluctance through the specimen. This is comparable to the connections of an ammeter and voltmeter in an electrical circuit; the ammeter measuring the flow of current, and the voltmeter the potential difference.

1. Forest K. Harris, Ph.D., "Electrical Measurements," P. 374.

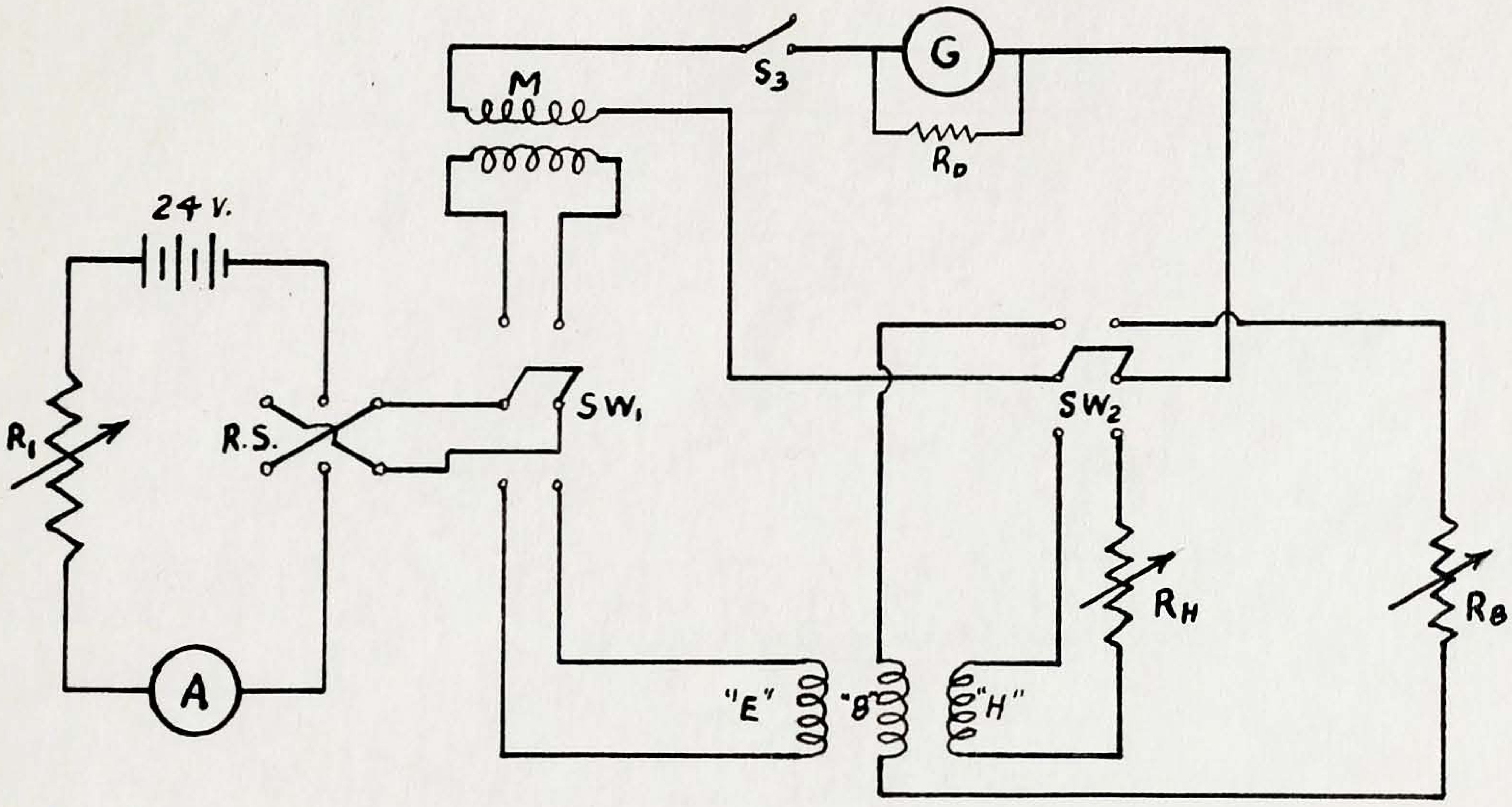

Fig. 1. General Circuit Diagram.

The above circuit diagram represents the connections used when testing the completed permeameter. Essentially the above circuit is used; however, different methods of connecting the apparatus can be employed depending upon the equipment available.

R.S.	-	Reversing switch
M	-	Mutual inductance coils (measured in henries)
G	-	Ballistic Galvanometer
R_D	-	Damping Resistance (ohms)
"E"	-	Exciting coil
"B"	-	Search coil around specimen
"H"	-	Bakelite cored coil
R_H	-	Resistance in "H" coil circuit (ohms)
R_B	-	Resistance in "B" coil circuit (ohms)
A	-	Ammeter (D.C. amperes)

Magnetic Definitions and Concepts[1]. Lines of force in a magnetic circuit always return on themselves to form closed paths; hence, a magnetic circuit is always closed. The total number of magnetic lines existing in a magnetic circuit is called "magnetic flux". Its unit is a single line of force called the maxwell. Magnetic flux is usually designated by the Greek letter "ϕ".

Magnetizing force. For the purpose of simplicity, magnetizing force is considered to be the total force tending to set up a flux in a magnetic circuit. It is usually designated by the letter "H". Its units are oersteds or gilberts/cm.

Flux density or induction. This is the flux per unit area through an element of area at right angles to the direction of flux. It is usually designated by the letter "B", and its unit is the gauss, or maxwell/cm^2.

Permeability is a term used to refer to the ease with which a magnetic flux can be established in a given magnetic circuit. It is numerically equal to B/H or the ratio of flux density to magnetizing force. It is designated by the Greek letter μ.

Hysteresis. When an unmagnetized piece of steel is exposed to a varying magnetizing force, and the strength of the field is plotted against the applied magnetizing force, the curve obtained is called a hysteresis curve or loop.

1. Doan, F.B. and Bety, C.C., "Principles of Magnaflux", P. 50.

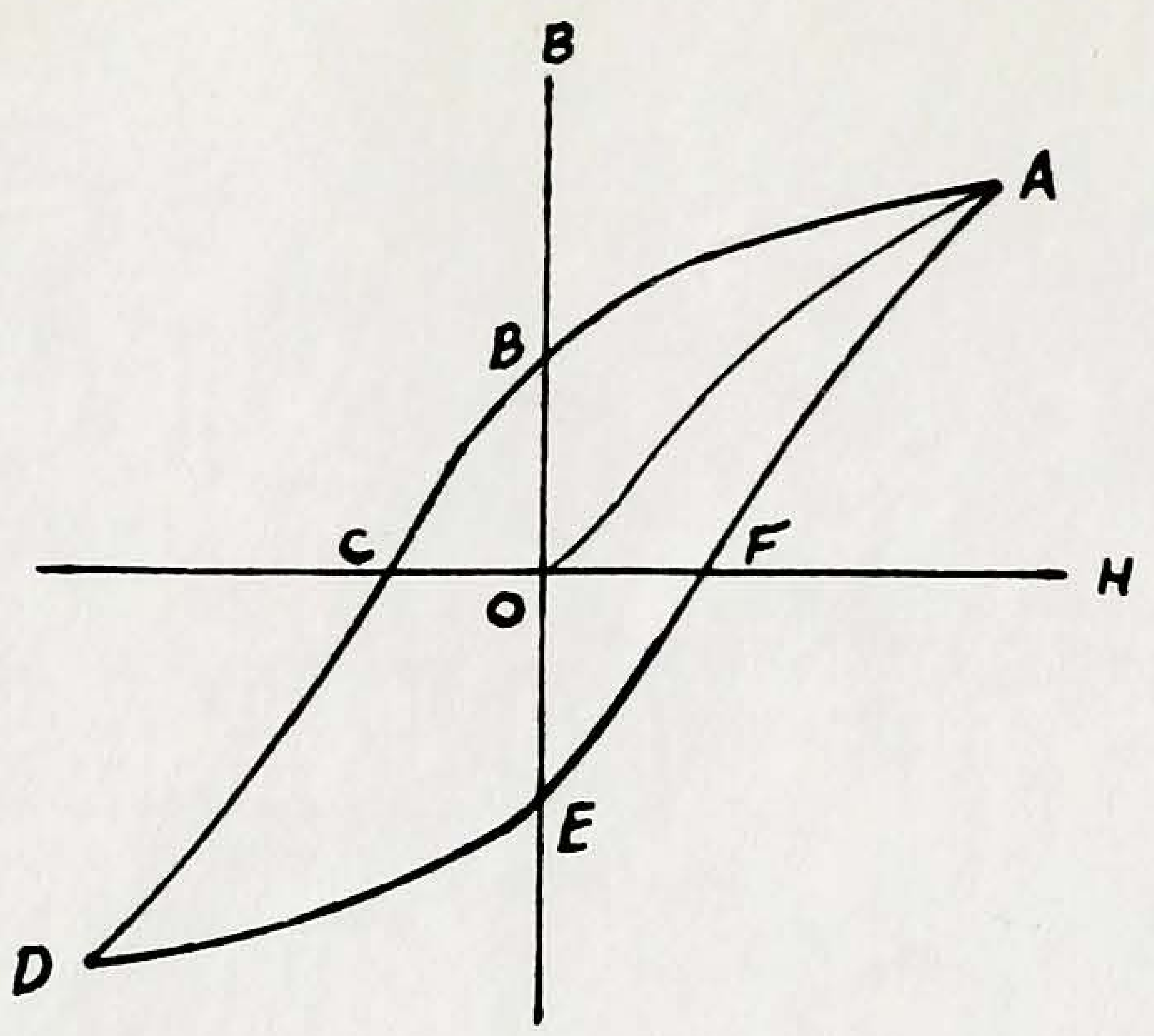

Fig. 2. Hysteresis Curve.

Starting from zero with a specimen in the unmagnetized condition and increasing the magnetizing force in small increments, we find the flux in the material increases quite rapidly at first, then more slowly until it reaches a point beyond which any increase in the magnetizing force does not increase the flux. This is shown by the curve "OA". In this condition, the piece is said to be magnetically saturated. Now, if the magnetizing force is gradually reduced to zero, the curve "AB" will result. If the magnetizing current is reversed and gradually increased in value in this reversed direction, the flux continues to diminish. The flux does not become zero until the point "C" is reached, at which time the magnetizing force is represented by "CO". The line "CO" graphically represents the coercive force of the material. As the reversed field is increased beyond "C", the point "D" is reached, at which point the specimen is again saturated. The magnetizing force is now decreased to zero and the portion of the curve "DE" is formed.

Again increasing the magnetizing force in the original direction completes the curve "EFA". At the point "A" the cycle is complete, and the area within the loop "ABCDEFA" is called the "hysteresis loop". As is seen from the curve, there is a definite lag between the magnetizing force and the flux throughout the cycle which is called "hysteresis". The curve "OA" is called the virgin curve of the steel; having once followed this curve, it cannot be made to do so again without first returning it in some manner to the demagnetized state. Without complete demagnetization, the steel will remain in what is termed a cyclic condition, and continuing the processes of increases, decreases, and reversals of "H" will merely carry "B" around the loop.

CHAPTER II

CONSTRUCTION AND CHANGES OF ORIGINAL DESIGN

"B" Coil. A new "B" coil was constructed because the turns of wire on the old coil were not wound uniformly, especially near the ends of the form.

The new "B" coil was wound on a fabricated plexiglass form. The plexiglass core was made of 1/16" sheet stock, cut and assembled into a hollow square tube. HP-Bond Plastic Cement was used to fasten the edges of the form. The form was then wound uniformly with 80 turns of #18 copper enamaled wire. When the form of the coil was completed the cross-sectional area was 12.62 cm^2.

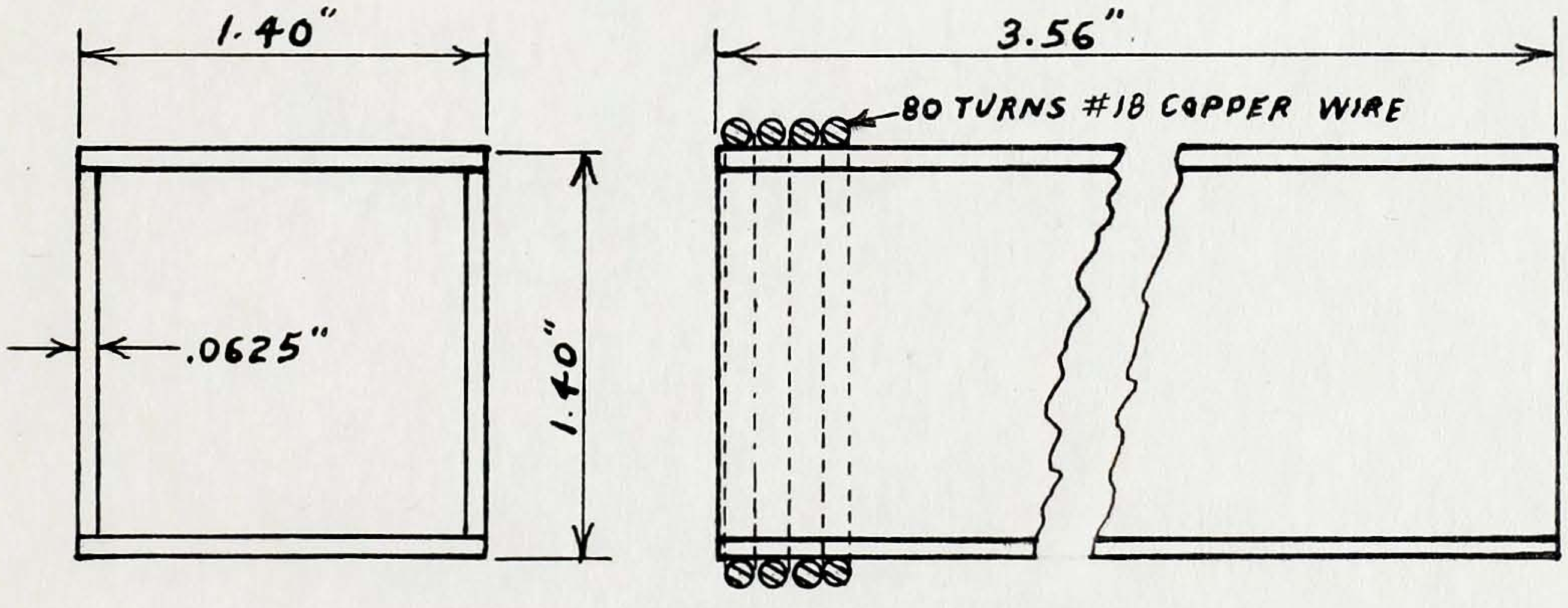

Fig. 3. "B" Coil and Core.

"H" Coil. The old "H" coil was removed from the permeameter because it did not completely fill the air gap between the steel yokes, and was wound with an insufficient number of turns.

The redesigned "H" coil consisted of 1100 turns of #26 varnished Formvar copper wire, wound uniformly upon a recommended bakelite core. The length of the "H" coil was made to be equal to the length of the "B" coil. The cross-sectional area of the "H" coil core was made to be 10.5 cm.^{2} The effective area, however, was determined later in Chapter IV to be 11.1 cm.^{2}

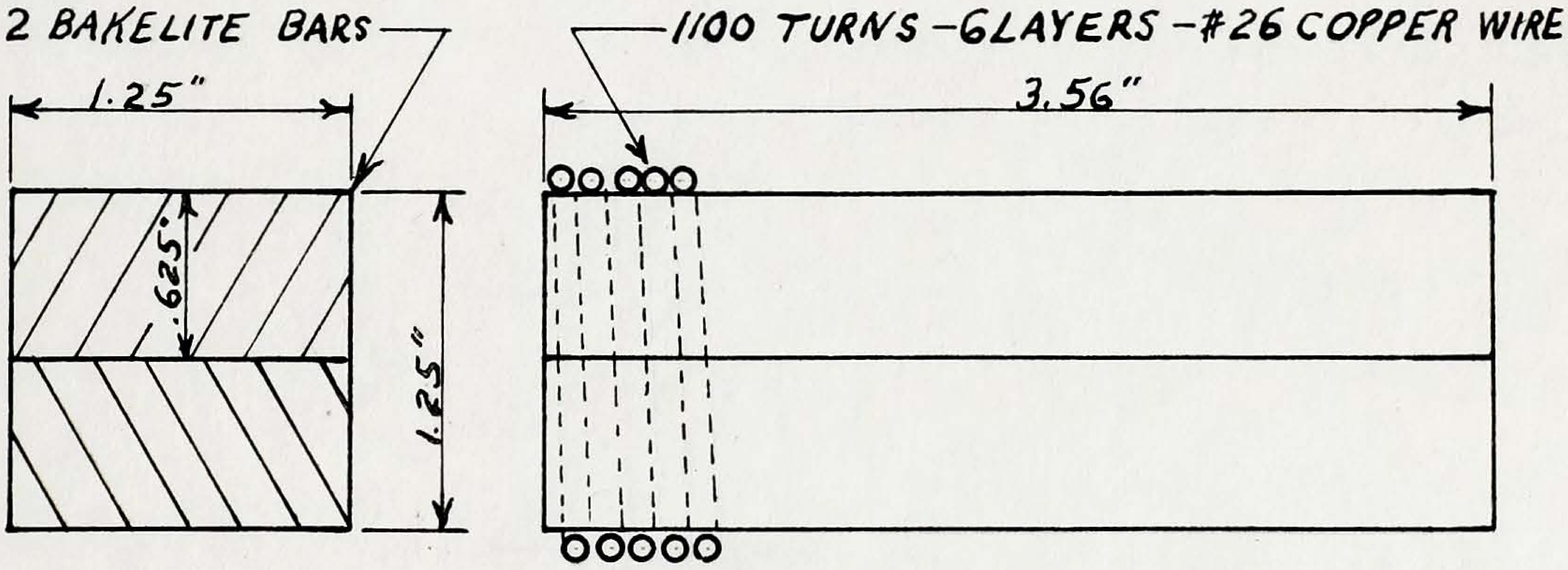

Fig. 4. "H" Coil and Core.

Magnetic Circuit. The chief changes in the magnetic circuit were the machining of the ends of the sliding steel yokes to insure perfect contact with the sample to be tested. This was done to eliminate any air gap between the sample and the sliding steel yokes, in order that there be no appreciable difference between the magnetomotive force impressed on the sample and the magnetomotive force impressed on the "H" coil.

Further refinement of the magnetic circuit was made by eliminating the air gap present in the old design between the ends of the "H" coil and the sliding steel yokes. The entire magnetic circuit was then assembled and aligned so as to make flat surface contact between the sample and exciting coil core, sample and sliding yokes, and between sliding steel yokes and "H" coil core; as shown below.

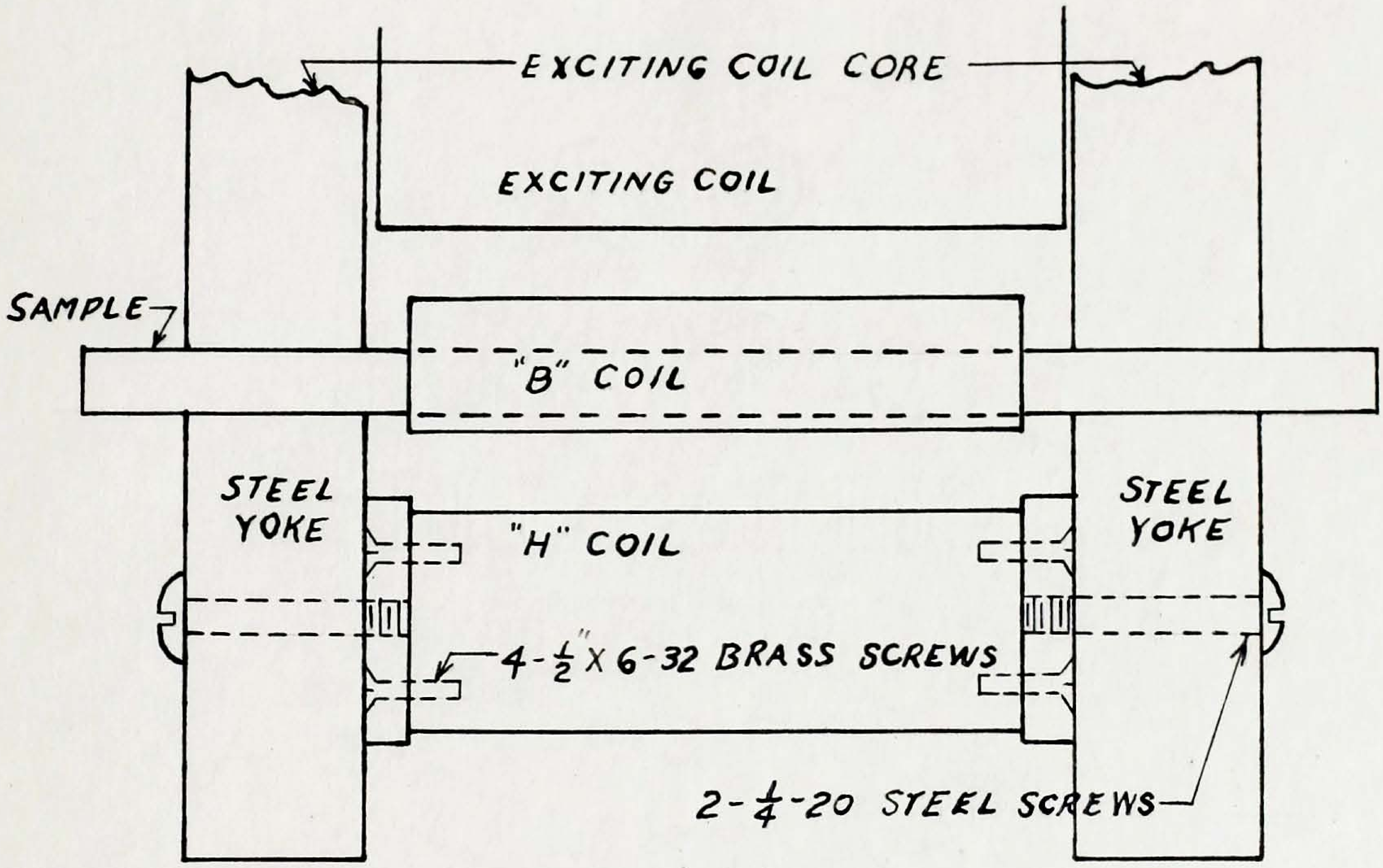

Fig. 5. Top View of Magnetic Circuit

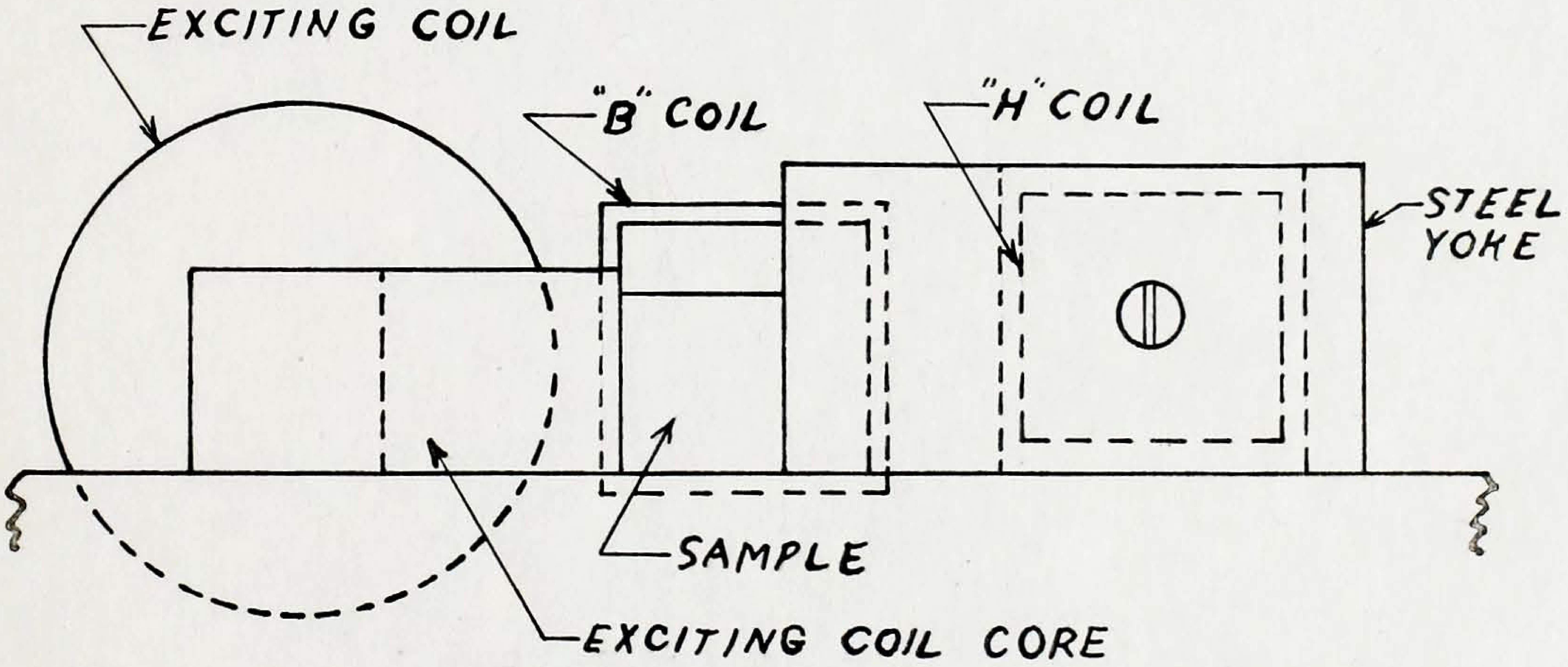

Fig. 6. Side View of Magnetic Circuit

CHAPTER III

PROCEDURE FOR USING THE FAHY PERMEAMETER

Connections for Permeameter Circuit. The following circuit can be used to calibrate, that is, make the galvanometer direct reading for (B) and (H), and also be used to obtain the B-H curve of a sample bar.

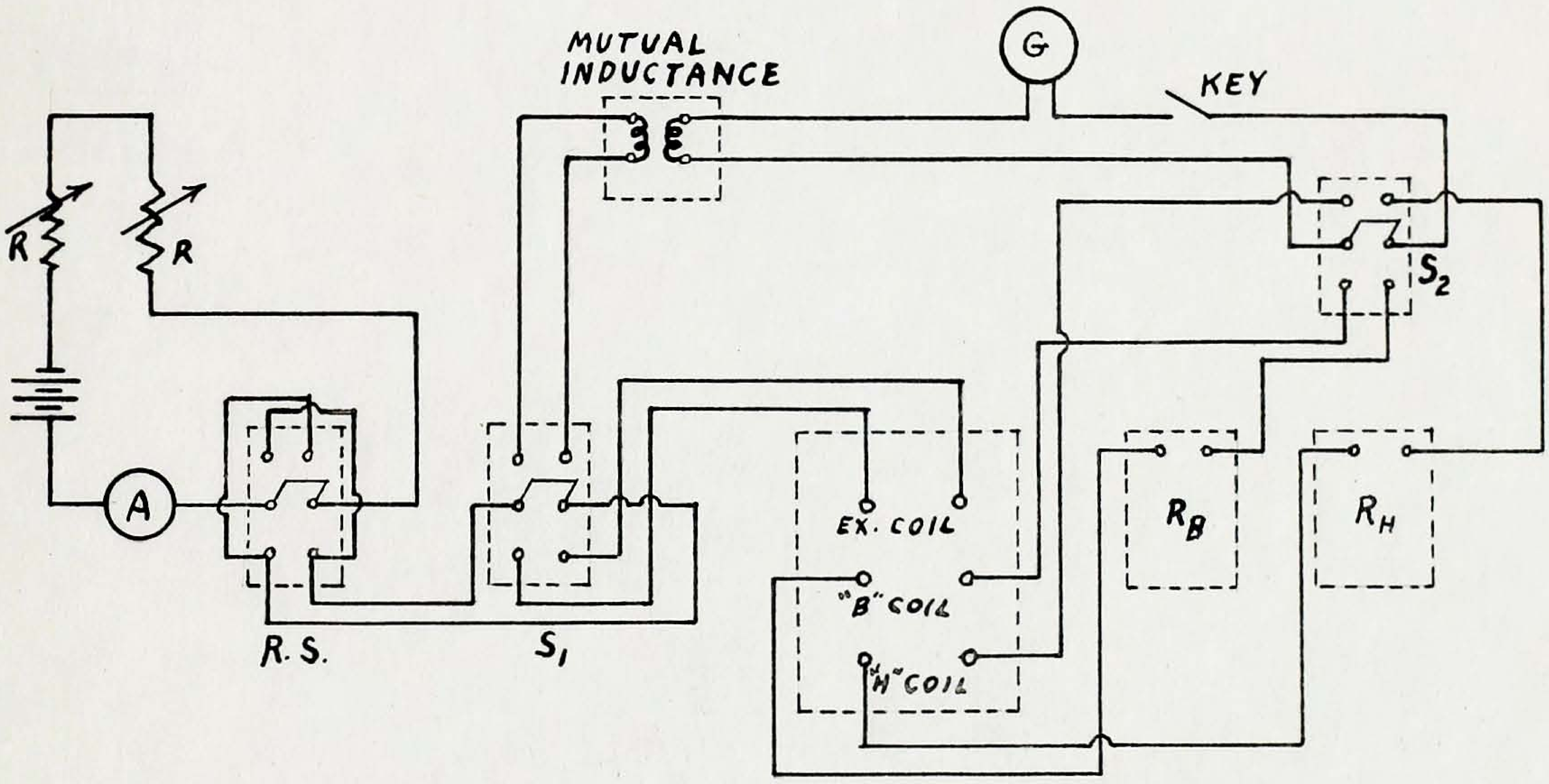

Fig. 7. Calibrating Circuit.

Making the Galvanometer Direct Reading. Assume a reference flux density such as 10,000 gausses when the "B" coil is in the circuit. Then let each centimeter of deflection on the galvanometer scale equal, for instance, 1,000 gausses. Therefore, 10 cm. of deflection will equal 10.000 gausses in the "B" coil.

The current required in the primary of the mutual inductance to produce the assumed value of flux in the secondary is calculated from the following formula;

Let, 10,000 = assumed value of flux density (B)

A = area of steel sample

N_b= number of turns in "B" coil

M = value of mutual inductance in henries

Then, $I_m = \frac{10,000\ A\ N_b}{M \times 10^8}$ amperes[1].

Place switch R_s and switch S_1 in the "up" position, switch S_2 in the "down" position and adjust the battery current to the computed value by varying the variable resistance in the battery circuit. The flux in the secondary of the mutual inductance would be equal to the flux linkages in the "B" coil if the sample had been magnetized with a density of 10,000 gausses.

The reversing switch R_s is thrown and the deflection of the galvanometer is observed. If the deflection does not equal 10 cm. the resistance of the decade box R_b is adjusted until 10 cm. of deflection is obtained. The galvanometer is now direct reading for flux density and the value of R_b is not changed while making B-H curves or hysteresis loops.

The galvanometer is calibrated for "H" in the same manner. Assume a value of "H" such as 10 oersteds, and let 1 cm. of deflection of the galvanometer equal 1 oersted. Therefore, a 10 cm. deflection would equal 10 oersteds.

Change S_2 to the "up" position, and change the

1. Marshall, Roland B., "Measurements in Electrical Engineering", Second Edition, Part 1, P.189.

battery current to the value computed by the following formula:

Let, 10 = assumed value of "H"(oersteds)

N_h = number of turns in "H" coil

A = cross-sectional area of "H" coil

Then, $I_m = \frac{10\ N_h\ A}{M \times 10^8}$ amperes[1]

The reversing switch R_s is then thrown and the deflection observed on the galvanometer. If the deflection does not equal the assumed value of 10 cm. the value of the decade resistance box R_h is changed until a 10 cm. deflection is observed. The galvanometer is now direct reading for "H". The value of R_h is not changed while making B-H curves or hysteresis curves.

A Method of Obtaining a B-H Curve. With the permeameter calibrated as outlined above, switch S_1 is thrown to the "down" position with the key K open. The reversing switch R_s is reversed slowly, about once a second, while the current is decreased slowly to a negligible amount. This procedure demagnetizes the sample by putting it through sucessively smaller hysteresis loops.

The current is then increased and the sample put in a cyclic state by reversing the current several times. While key K is closed switch R_s is thrown once again. The value of "B" is then read directly on the galvanometer. Without changing the current, switch S_2 is thrown in the

1. Ibid.

"up" position, switch R_s is thrown again and the value of "H" is read directly on the galvanometer. Any number of points may be obtained this way for different value of current provided the sample is put in a cyclic state for each new value of current. It is advisable to plot the points as the work progresses so that any questionable data may be checked.

A correction for air surrounding the sample in the "B" coil is made from the following formula[1]:

Where, B = true flux density in the sample

B_a = apparent flux density before correction

H = corresponding value of oersteds

a = cross-sectional area of air enclosed by the B coil

A = area of the steel sample

then,

$$B = B_a - \frac{H(a-A)}{A}$$

1. Ibid.

CHAPTER IV

CALIBRATION AND EXPERIMENTAL RESULTS

Calibration. The area of the "H" coil was measured, of course, when it was constructed. However, this did not represent its true area. This can best be explained by the following quotation:

> In presenting the theory of the Fahy Permeameter, it is assumed that the flux between the two magnetic yokes passes in straight parallel lines through the "H" coil. Actually this is not the case and the error in assuming this is very great. For this reason, the product of N_h and A_h is found experimentally by placing a standard bar in the instrument. The standard bar is calibrated by means of another permeameter such as the Burrows. Calibrated standard bars were previously sold for a small fee by the National Bureau of Standards but this practice has been discontinued because of the difficulty in obtaining a quantity of homogeneous material. The magnetic qualities vary so much that a uniform sample can only be found by testing a great number of samples at intervals along the length of the bar. When a sample of non-uniform metal is tested in a Fahy Permeameter the resulting B-H curve, or hysteresis loop, represents the average characteristics of the bar.[1]

Another reason for finding the true area of the "H" coil is the fact that it was wound on a square bakelite core. This resulted in an air space between the coil wires and the core material as illustrated by the shaded area in Figure 8, page 15.

A standard sample of cold rolled steel was obtained

1. Ibid, P.184.

from the Physics Department of the University of Detroit, which was calibrated for a value of 14,500 gausses when a magnetizing force of 50 oersteds was impressed. It was

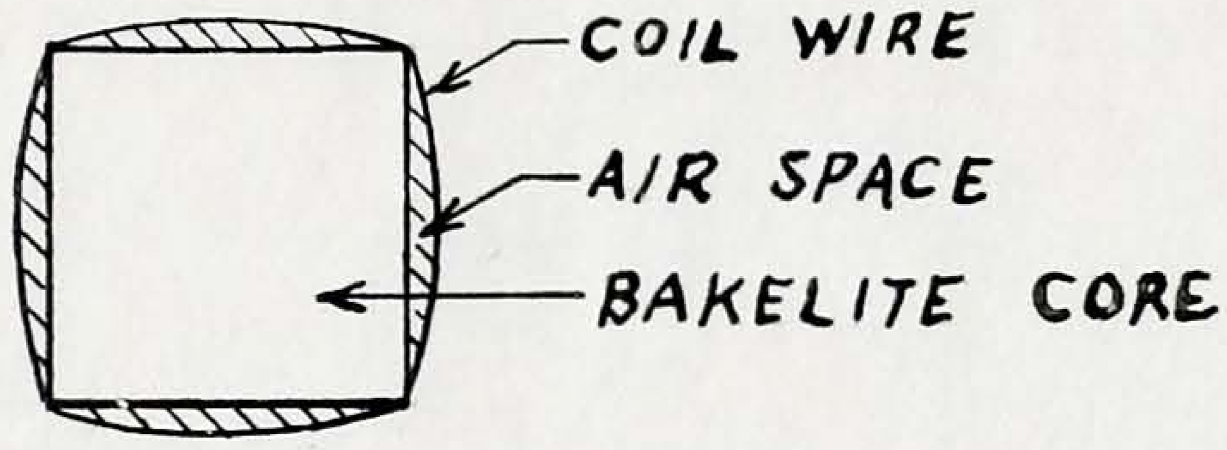

Fig. 8.

placed in the permeameter and a flux density of this value was applied. The magnetizing force "H" was then measured and found to be too high. The measured area had been used in the calculation for making the galvanometer direct reading (see Chapter III). A larger area was then assumed and the galvanometer re-calibrated using this new area. The value of "H" was again measured.

This trial and error process was repeated until the readings of "H" corresponded closely with the values of the standard sample. The effective area was found to be 11.1 cm^2, and the instrument was then calibrated and ready for use.

Experimental Results. It was decided to try the instrument with samples of electrical sheet steel. Two samples were obtained, one of dynamo steel and another of motor steel. The laminated samples were then weighed and their true area was calculated by their weight, density, and length using the following relationship:

Let, W = weight

D = density

l = length; then, Area = W/Dl. The area was then marked on each sample and a magnetization curve was plotted for each sample. The following data and graphs represent the results of these tests on the permeameter.

EXPERIMENTAL DATA

#24 Gage USS Motor Grade Steel

Magnetizing Force "H" Oersteds	Flux Density Kilogausses*
0.50	1,900
0.70	3,000
0.90	4,300
1.00	5,900
1.26	8,200
1.50	9,700
2.05	10,500
3.50	11,580
5.03	12,250
8.05	12,900
20.10	14,300
28.55	14,700
38.45	15,100
49.00	15,500
63.50	15,590
82.50	16,490
93.00	16,670

#24 Gage Allegheny Ludlum Dynamo Grade Steel

Magnetizing Force "H" Oersteds	Flux Density Kilogausses*
0.50	5,500
0.65	6,800
0.75	7,900
0.875	8,800
0.95	9,750
1.15	11,350
1.55	12,000
1.95	12,600
2.50	13,180
3.50	13,550
4.85	13,990
6.35	14,200
8.15	14,500
9.60	14,700
12.50	14,950
16.50	15,250
23.00	15,600
31.50	16,000
41.00	16,350
53.00	16,750
61.50	17,000
75.75	17,300

*The apparent values of flux density as read on the galvanometer were plotted, as the correction for air surrounding the sample was very small.


MAGNETIZATION CURVE
U·S·S MOTOR STEEL
24 GAGE
FLUX DENSITY - B - KILOGAUSSES
18
16
14
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
10
20
30
40
50
60
70
MAGNETIZING FORCE - H - OERSTEDS
AVERAGE CURVE ----
TEST SAMPLE CURVE ——


MAGNETIZATION CURVE
ALLEGHENY LUDLUM DYNAMO STEEL
24 GAGE
FLUX DENSITY - B - KILOGAUSSES
0
2
4
6
8
10
12
14
16
18
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
10 20 30 40 50 60 70
MAGNETIZING FORCE - H - OERSTEDS
AVERAGE CURVE ----
TEST SAMPLE CURVE ——

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Upon examining the results obtained from the tests performed with this instrument it was seen there was a slight departure near the knee of the curve from the average curves as obtained from the engineering bulletins of the United States Steel and Allegheny Ludlum Corporation.

The reason for this can perhaps be explained by a quotation from a paper written by R.L. Sanford of the Bureau of Standards while he was conducting research on the effects of different electrical sheet steel samples.

> The differences between the results of normal induction tests on sheet steel by the Burrows permeameter and the Fahy Simplex permeameter are to be attributed to the character of the specimen rather than to errors inherent in either method. The greatest source of discrepancy is lack of magnetic uniformity along the length of the specimen. The Burrows permeameter is more sensitive to this condition than the Simplex. An excessive number of strips in the specimen causes bad flux distribution which leads to errors in the results. The Simplex permeameter is more sensitive to this factor than the Burrows. The width of the strips used in the sample also plays a part in the results. They should not be less that 3 cm. wide if the effect of punching or shearing strains is to be avoided.
>
> The degree of non-uniformity in a test sample of sheet steel made up in the usual way will generally not be as great as that of the samples used for testing this point in the present investigation, so it is probable that the results of tests with the Burrows permeameter will ordinarily be satisfactory. On the other hand there will always be uncertainty as to the accuracy obtained by this method unless the uniformity of the specimen is checked and it is generally not convenient to do this.
>
> From the above considerations the conclusion seems to be warranted that for routine normal induction of sheet steel the Fahy Simplex permeameter is the most satisfactory apparatus at present available, provided that the specimens tested are made up of not more than 15 strips (preferably 10) not less than 3 cm. wide.[1]

1. Sanford, R.L. and Barry, J.M., "Bureau of Standards Publication", Number 545, 1927.

When the experimental results were examined and it was discovered that our curves differed slightly from the average values, research was done in order to explain whether it was the fault of the instrument or of the samples. From the above quotation it is evident that our samples did not meet the recommended specifications since they were made up of 21 laminations, and were only 2.5 cm. wide. This would cause the galvanometer to read a lower value of magnetizing force "H" than if 15 laminations were used, because of the air gap present between the laminations of the sample.

Therefore, the authors feel that it is not due to faulty design of the instrument but rather to a poor selection of a sample. It is felt that in the future use of the instrument better results will be obtained if the operator conforms to the recommended specifications.

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