Thesis

Permeability Measuremants

by

Virgil F. Morse

Class of Nineteen Hundred and Fourteen

Department of Electrical Engineering

THROOP COLLEGE OF TECHNOLOGY

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The problem treated in this paper is the measurement of the permeability of iron and steel in straight bars. After the permeability has been determined over the entire length of the bar it may reveal various kinds of mechanical or structural differences in the steel which otherwise could not be detected without destruction of the specimen.

The apparatus used in making these determinations was:

(1) a Permeameter constructed by Mr. R. W. Parkinson and Mr. Ray Gerhart of the class of 1913 THROOP COLLEGE OF TECHNOLOGY according to the specifications of the United States Bureau of Standards as set forth in Bulletin Vol. 6 No. 1 under the heading, "The Determination of the Magnetic Induction in Straight Bars", by Mr. Charles W. Burrows, Assistant Physicist:

(2) a Leeds and Northrup Deflection Potentiometer for measuring the current accurately:

(3) a Storage cell of about 2.1 volts for the Potentiometer:

(4) an Edison five cell 6 volt alkaline battery for producing the current in the magnetizing coils and in the primary of the Mutual Inductance:

(5) a Ballistic Galvanometer for obtaining balances between inductions as subsequently explained:

(6) a Switchboard with Mercury contact reversing rocking switches for manipulating the currents in the various circuits:

(7) a Mutual Inductance of .1013 henries which I constructed for these experiments.

In making the determinations of the permeability the first step is to get the specimen into a "cyclic" condition and thoroly demagnetized. This is done by reversing the current in the magnetizing coils about twice per second beginning with a value high enough to carry the induction well beyond the point of maximum permeability, and gradually reducing the current to a value slightly below the lowest induction to be measured. It may be necessary to go thru this operation of demagnetization several times before the steel reaches a cyclic condition such that a reversal of the magnetizing current reverses the direction of magnetization without changing its magnitude.

After the specimen has been reduced to a cyclic condition a uniform magnetic flux is obtained thruout the specimen by balancing the induction of a test coil around the test specimen against the induction of a similar test coil around an auxiliary rod. This shows equal flux on the two rods and the final adjustment is made by passing sufficient current thru small compensating coils on the ends of the rods so that testcoils show equal flux thruout the test rod.

When this condition is obtained the test coil is connected in series with the secondary of the mutual inductance. The primary current is adjusted until the induction of the test coil equals that of the mutual inductance on reversal of their respective primary currents. Then readings are made of the current in the primary of the mutual inductance and in the magnetizing coil on the test specimen. These readings are made with the Deflection Potentiometer and are easily obtainable to one-tenth of one percent. The mutual inductance was carefully calibrated and found to have a value of .1013 henries. Then

$\underline{B} = 790000 \times .1013 \times I_m - .318H$, where I_m = the current in amperes in the mutual inductance primary;

$\underline{H} = 39.5 \times I_t$, where I_t = the amperes in the magnetizing coil of the test specimen;

$\mu = \underline{B}/\underline{H} = 2026 \times I_m/I_t - .318$

In ordinary testing the constant .318 may be neglected, tho in very careful determinations at low values of μ it should be considered.

For further definite information concerning the constants of the permeameter, reference should be made to the thesis of Mr. Ray Gerhart and Mr. R. W. Parkinson of THROOP COLLEGE OF TECHNOLOGY 1913, which is on file at the College.

With a variable mutual inductance of about 100 millihenries maximum, such as designed by Mr. Burrows and set forth by him in his bulletin, the work of making the measurements of permeability would be greatly simplified. With such apparatus at hand, the primary of this mutual inductance would be connected in series with the magnetizing coil on the test specimen, and a balance of the induction in their secondaries obtained by varying the mutual inductance.

Then μ = 20000 M - .318, where M = the value of the mutual inductance in henries. This variable mutual inductance could then be calibrated to read directly in terms of μ, - the permeability.

Improvements desirable are as follows in the order of their importance:

(1) a variable mutual inductance of about 100 millihenries maximum, carefully calibrated to read both in millihenries and in terms of permeability when used with the THROOP COLLEGE permeameter;

(2) sufficient storage battery capacity to give 3 or 4 amperes continuously without an appreciable drop for one minute: two Edison 5-cell, 6-volt batteries should do this;

(3) a separate mounting for the Galvanometer so that it will not be jarred by reversing the switches.

The set-up and operation of the THROOP COLLEGE Permeameter.

The following drawings are taken from the thesis of 1913, to which reference is made for more complete data on the construction and calculation of the constants of the permeameter.

Fig. 10 shows the positions of the windings;

Fig. 12 shows the diagram of wiring connections;

Fig. 13 the internal connections of the Permeameter;

Fig. 14 the connections on the mercury contact switchboard.

Connection to the Potentiometer are made thru shunts placed in the primary circuit of the mutual inductance "M" Fig. 12, and in the circuit "T" Fig. 12, which is the magnetizing coil around the test specimen. Care should be taken to avoid measuring the current in both "T" and "A" Fig.12, which are in multiple.

I_m = amperes in circuit "M" Fig. 12

I_t = amperes in circuit "T" Fig. 12

M = henries of mutual inductance "M" Fig. 12 = .1013

$B = MI_mK_1 - K_2H$ $\quad K_1 = 790000.$

$H = K_3I_t$ $\quad K_2 = .318$ $\quad K_3 = 39.5$

$\mu = B/H = MI_mK_1/K_3I_t - K_2H/H = 2026\ I_m/I_t - .318$

$\mu = 2026\ I_m/I_t$ approximately.

In Fig. 12 the batteries Bt, B_j and Bm may be all taken as one but the Potentiometer battery <u>must</u> be separate.

When all the wiring connections have been properly made and the test and auxiliary bars have been placed in the Permeameter with the yokes firmly clamped, the test is ready to be started.

First demagnetize the test bar by applying a cyclic magnetizing force of about one period per second, which is gradually reduced from an initial intensity which carries the induction well beyond the point of maximum permeability to a final value somewhat below the lowest induction to be studied. It was found that the initial intensity of the magnetizing force was sufficient with a current of about three (3) amperes in circuit "T".

Now set the switch K_3 Fig. 14 on t-m and after demagnetization the lowest force to be used is applied and repeatedly reversed, by rocking the reversing switches S.T. and S.J. Fig. 14, until the test rod is brot to a cyclic magnetic state. To ascertain when the cyclic state has been obtained, close the Galvanometer switch S.G. and note the deflection. If it is equal in magnitude on reversal of the current in either direction, the cyclic condition has been reached.

Now move K_3 to t-a and adjust the resistances R.A. and R'.A. for uniformity of flux. This may be done while bringing to the cyclic state as it involves only very small changes in the magnetizing force.

If the connections have been properly made the test coils "t" and "a" will be in series-opposition such that on reversal of the current in the magnetizing coils "T" and "A" the current induced in "t" will be exactly neutralized by that in "a" when the flux is the same in both bars and will be observed as a zero deflection of the Galvanometer "G".

Now move K_3 to t-j and adjust R.J. until uniformity of flux along the test rod is obtained as above. This operation consists in passing sufficient current thru the compensating coils J_t, J'_t, J_a and J'_a Fig. 13, to compensate for the magnetic flux leakage at the magnetic joints and for the effects of the yoke.

Having made the adjustments necessary to secure uniformity of flux and brot the steel to a cyclic state, the induction is measured by balancing the electromotive force induced in "t" on reversal of the magnetizing current against that induced in the secondary "m" of the mutual inductance on reversal of the current in its primary "M", This current is adjusted to give a zero deflection on the Galvanometer "G" when K_3 is on t-m and the switches S.T., S.J. and S.M. are reversed simultaneously.

In order to exclude any influence due to mechanical vibrations the entire magnetic circuit is mounted on a layer of felt. These lower values of the induction are produced by small magnetizing forces and therefore are easily altered by incompleteness of demagnetization or failure to reduce to a cyclic state. As a check, therefore, after determining this first point on the induction curve , it is well to carry the steel again thru the demagnetizing process, readjust the compensation, reduce to a cyclic state and redetermine the point. If this second determination does not yield the same result as the first induction, the full process should be repeated more carefully until concordant results are obtained.

Having thus obtained satisfactory data for the lowest magnetizing current it is not necessary to demagnetize again. The remaining points on the induction curve may be secured by passing to the next higher magnetizing force, adjusting the main and compensating currents, repeating the reversals till a cyclic state is reached and so on till the required data are secured. The curve determined by these points, the B and H, is called the Normal Induction Curve.

It was found to be much more satisfactory to get the final balance between the test coil "t" and the mutual inductance "m" by the deflection than by the zero method. That is, to read the deflection of the galvanometer on reversal of S.T. and S.J. with K_3 on t-m and then get an equal deflection by reversing S.M. The reason that the direct zero method was found to be not so accurate as the deflection method was that the discharge of the mutual inductance was practically instantaneous, whereas there was a noticeable time-lag of the discharge of the test coil, due to the steel or iron in the circuit. This lagging E.M.F. would cause some deflection of the galvanometer after the influence of the mutual inductance was past. Another difficulty was that it was practically impossible to reverse the three switches S.T., S.J. and S.M. absolutely simultaneously, so that the galvanometer would be deflected in one direction by the circuit first reversed and then in the opposite direction when the other was reversed.

With a mutual inductance of fixed value, readings thruout the tests are made with the Deflection Potentiometer of the current "I_m" in the primary of the mutual inductance and of the current "I_t" in the magnetizing coil of the test specimen only, not the current in the auxiliary circuit.

With the constants of the machine and the currents "I_m" and "I_t" known, data can be compiled and curves plotted showing any desired relation between B, H, and μ.

A very careful test was made of a piece of Stubbs' Drill Rod, a high grade tool-steel, and a curve plotted at all densities, the B-μ curve, of the rod as it came from the shop and then the same specimen was heated to redness at the center in a Bunsen flame. After cooling slowly in air this rod was again tested and marked differences in the permeability noted, the maximum being 100.% greater. Curves and data sheet are submitted as a part of this thesis.

A long rod of Bessemer steel was tested and then stressed in tension at one end beyond the elastic limit. A test now shows marked diminution of the permeability in the stressed portion altho the unstressed end was unchanged.

It was hoped at the beginning of this work that the Permeameter might be a good detective and the results have justified the assumption.

In the case of the Stubbs' drill rod the Permeameter revealed very positively the fact that there was a marked difference in the magnetic properties of this 15" specimen of which only about 2" at the center had been heated to redness, and the Bessemer rod showed distinctly in which portion it had been strained.

It is a well known fact that stressing steel beyond its elastic limit makes it harder and that heating to redness with subsequent slow cooling softens it, and now the Permeameter shows that hardening steel decreases its magnetic permeability and that softening steel increases the permeability. Therefore the Permeameter can be used to detect either hard or soft spots in a rod which might appear uniform. Mechanical or structural flaws would probably also be detected but as yet I have not done a sufficient number of experiments to make this certain.

BESSEMER STEEL DATA SHEET

Original					Stressed				
I_m	I_t	H	B	μ	I_m	I_t	H	B	μ
.0360	.090	3.56	2880	812	.0195	.12	4.74	1560	330
.0425	.10	3.95	3400	863	.023	.13	5.14	1840	360
.0495	.105	4.15	3960	957	.026	.14	5.54	2080	378
.0545	.115	4.54	4360	963	.03	.15	5.92	2400	406
.0640	.123	4.86	5120	1055	.0325	.16	6.33	2600	413
.0690	.132	5.21	5520	1060	.038	.18	7.04	3040	434
.0895	.163	6.44	7160	1116	.0465	.21	8.30	3720	450
.130	.225	8.89	10400	1170	.0666	.29	11.46	5328	466
.155	.30	11.9	12400	1048	.09	.40	15.8	7200	458
.174	.40	15.8	13920	883	.124	.60	23.7	9920	418
.198	.76	30.	15840	528	.147	.81	32.0	11760	468
.224	3.25	128.	18920	140	.195	1.88	74.3	15600	211
					.205	2.35	93.0	16400	177
					.212	3.25	128.4	16960	132

The data under "Original" gives the magnetic properties of the Bessemer steel rod as it came from the shop, and that under "Stressed" shows the magnetic properties of that portion of the same rod which had been stressed beyond the elastic limit in tension.

STUBBS DRILL ROD DATA SHEET

Original					Annealed				
I_m	I_t	H	B	μ	I_m	I_t	H	B	μ
.004	.11	4.35	320	73.2	.0056	.11	4.35	448	103
.005	.13	5.14	400	77.6	.0072	.13	5.14	576	112
.010	.24	9.48	800	84.0	.0085	.15	5.92	680	115
.0135	.305	12.05	1080	90.0	.017	.235	9.3	1360	146
.0238	.402	15.9	1900	119.5	.036	.335	13.2	2880	220
.0305	.481	19.0	2440	128.5	.0845	.452	17.9	6760	378
.0343	.500	19.75	2740	139	.088	.470	18.6	7040	379
.042	.569	22.5	3360	149	.0905	.49	19.3	7240	374
.048	.612	2.42	3840	159	.0935	.515	20.3	7480	368
.064	.72	28.4	5120	180	.101	.58	22.9	8080	352
.070	.77	30.4	5600	184	.113	.7	27.6	9050	327
.079	.825	32.6	6320	194	.117	.75	29.8	9350	313
.0865	.898	35.5	6920	195	.122	.80	31.7	9760	308
.092	.95	37.5	7360	196	.129	.9	35.5	10300	290
.1065	1.1	43.5	8520	196	.134	1.0	39.5	10700	272
.1213	1.265	50.0	9700	195	.149	1.29	51.	11900	235
.136	1.48	58.5	10880	187	.158	1.53	60.5	12640	210
.146	1.73	68.3	11680	172	.179	2.5	98.8	14320	145
.158	2.01	79.5	12650	160	.182	3.	118.5	14550	123
.164	2.21	87.4	13120	150	.186	3.5	138.2	14880	108
.169	2.43	96.0	13520	141					
.178	2.98	117.8	14240	121					
.182	3.5	138.2	14550	105					

The data given here show the magnetic properties of the rod before and after annealing.

Steel Core of the PACIFIC LIGHT and POWER Corp.

BIG CREEK Transmission Line Cable. DATA SHEET.

I_m	I_t	H	B_1	B_2	B_3	μ
.0020	.155	6.12	160.	143.2	140.4	259.
.0030	.23	9.10	240.	215.0	210.9	265.
.0040	.30	11.85	320.	287.4	282.1	271.
.0060	.33	13.00	480.	444.3	438.4	369.
.0075	.39	15.40	600.	557.7	550.7	390.
.0080	.46	18.15	640.	590.0	582.0	353.
.0115	.54	21.30	920.	861.4	851.8	433.
.0160	.63	24.85	1280.	1211.7	1200.5	515.
.0205	.66	26.05	1640.	1568.4	1556.6	631.
.0400	.82	32.40	3200.	3110.8	3096.3	990.
.0470	1.05	41.5	3760.	3646.0	3627.3	910.
.0620	2.47	97.6	4960.	4691.0	4648.0	510.
.0665	3.33	131.5	5328.	4966.0	4907.0	405.

This test was made on a "seven strand plow-steel cable" taken from the core of the Aluminum cable used on the BIG CREEK Transmission Line. Area - 78500. cir. mils - .3978 cm.

$B_1 = MI_mK_1 = 80000.I_m$ $B_2 = B_1 - K_2'H$ $B_3 = B_1 - K_2''H$

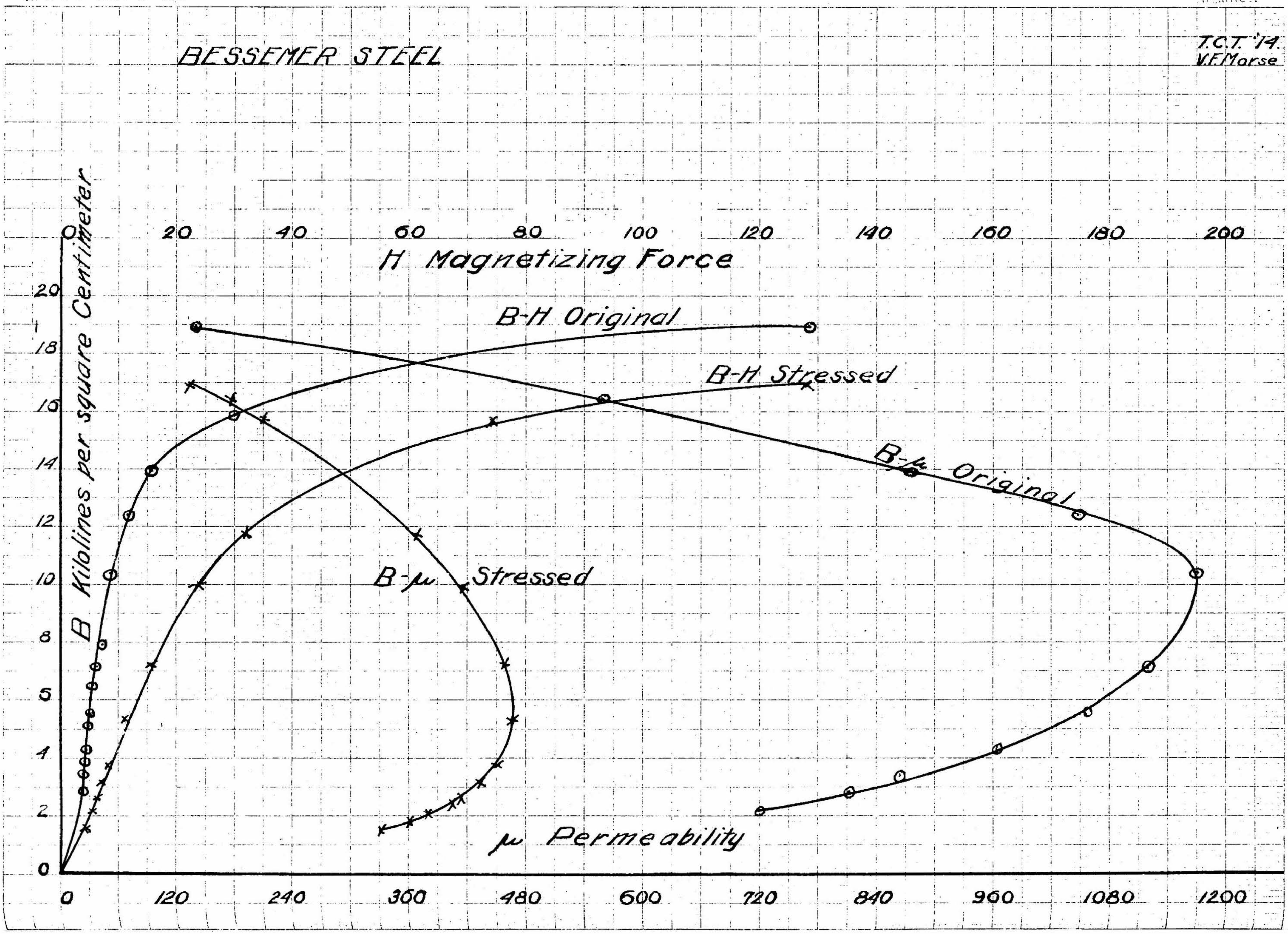
$H = 39.5I_t$ $K_1 = 790000.$ $K_2' = (a - A_1)/A_1 = 2.75$

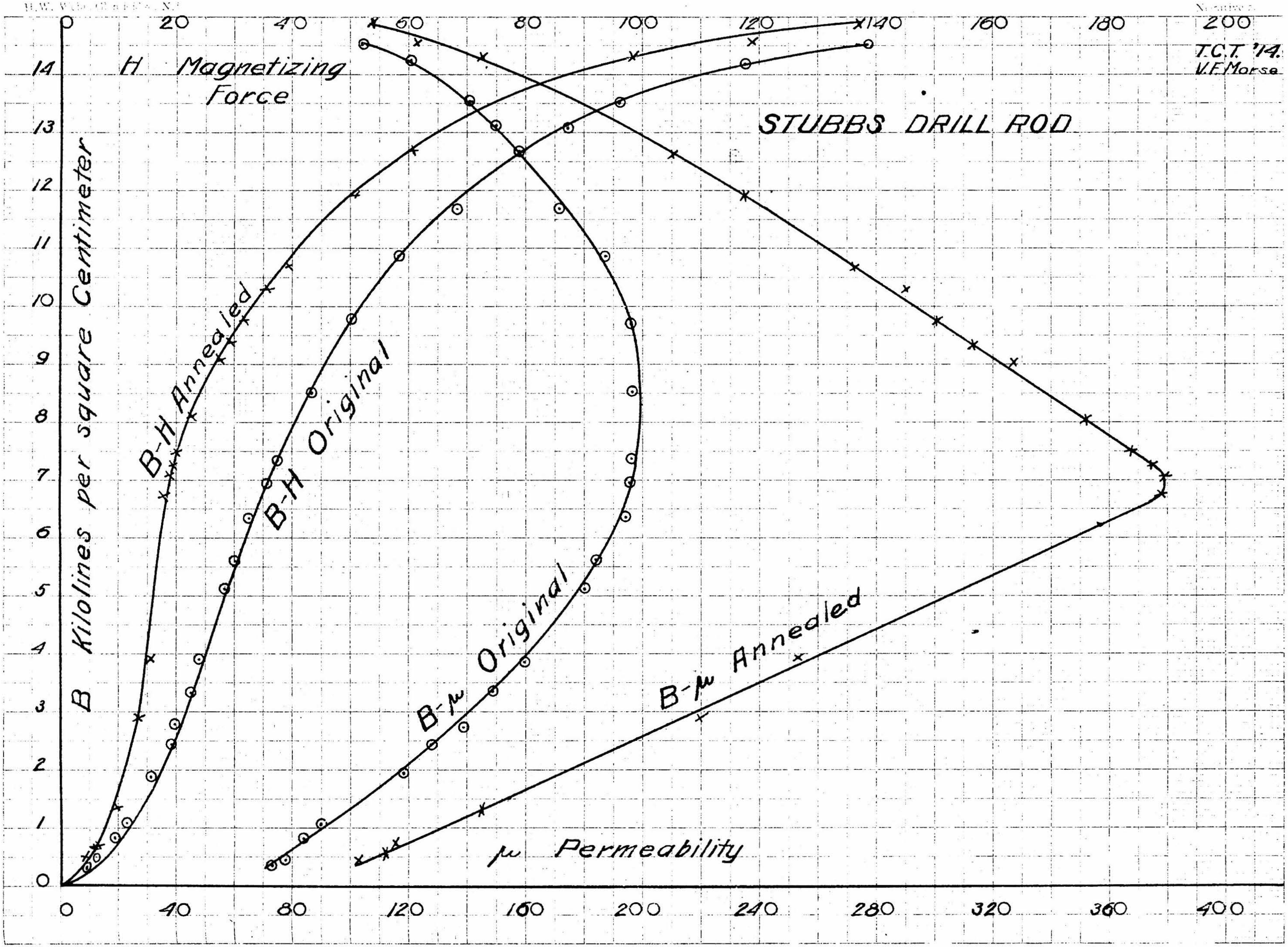
$A_1 = .518$ $A_2 = .3978$ $a = 1.6698$

$K''_2 = (a - A_2)/A_2 = 3.2$ A_2 was the actual area in sq. cm.

A_1 was the area calculated taking the radius over all =.406

The curves plotted were B_1H, B_3H, $B_1\mu$, and $B_3\mu$.


BESSEMER STEEL
T.C.T. '14.
V.F.Morse
H Magnetizing Force
B Kilolines per square Centimeter
B-H Original
B-H Stressed
B-μ Original
B-μ Stressed
μ Permeability
0
20
40
60
80
100
120
140
160
180
200
2
4
5
8
10
12
14
16
18
20
0
120
240
360
480
600
720
840
960
1080
1200


STUBBS DRILL ROD
H Magnetizing Force
B Kilolines per square Centimeter
μ Permeability
B-H Annealed
B-H Original
B-μ Original
B-μ Annealed
T.C.T. '14.
V.F. Morse
0
20
40
60
80
100
120
140
160
180
200
1
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4
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6
7
8
9
10
11
12
13
14
240
280
320
360
400

H.W. Wah Glen Ridge, N.J.

Negative 2.

T.C.T. '14.
V.F. Morse

Steel Core of the Pacific Light and Power Corp. Big Creek Transmission Line Cable.