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MAGNETIC AND OTHER PROPERTIES OF ELECTROLYTIC IRON MELTED IN VACUO

BY
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BY TRYGVE D. YENSEN, ASSISTANT, ELECTRICAL ENGINEERING DEPARTMENT, ENGINEERING EXPERIMENT STATION

CONTENTS

MAGNETIC AND OTHER PROPERTIES OF ELECTROLYTIC IRON MELTED IN VACUO.

I. Introduction.

1. *Scope of Bulletin.*—Numerous attempts have been made in recent years to determine the properties of pure iron and the influence of other elements upon these properties. Electrolytically deposited iron of a high degree of purity and the finest grades of Swedish charcoal iron were used in these experiments. On account of the high affinity of pure iron for other elements, especially at high temperatures, it is very difficult to expose it to such temperatures without having it contaminated by the substances with which it comes in contact. Among the elements exerting the most influence upon the properties of pure iron in proportion to the quantities added are carbon and oxygen. It has been shown that pure iron in the molten state will even reduce carbon monoxide and combine with the carbon. Other reducing and neutral gases, such as hydrogen and nitrogen, are partly dissolved by iron in the molten state, and, although again partly dispelled in cooling, are liable to be entrapped and cause blowholes.

On account of the difficulties above enumerated, the only means of melting pure iron without contamination appears to be to melt it in vacuo. Consequently, after numerous attempts with other furnaces, the author constructed a vacuum furnace for melting the electrolytic iron and its alloys with other elements.

It was originally intended to include in this bulletin the results obtained not only with pure iron, but also with certain alloys of iron with other elements. The results obtained with pure iron seem, however, sufficiently interesting to justify devoting one bulletin to its properties alone. There has been included for the sake of comparison: 1, two samples of Swedish charcoal iron, one as cut from the original plate and the other as remelted in the vacuum furnace; 2, three samples of electrolytic iron to which have been added small amounts of carbon; and 3, two samples of commercial steel used for electrical purposes and supplied by the manufacturer. It is expected that other bulletins containing the results of experiments upon various iron alloys will appear in the future. The magnetic, electrical, mechanical and metallurgical prop-

erties have been studied. No attempt has been made to study the magnetic properties in very strong fields.

2. *Historical Review.*—To mention only briefly all the researches upon the magnetic properties of iron and other ferromagnetic substances would be beyond the scope of this bulletin. However, it seems desirable to review briefly the experiments, the results of which have a definite bearing upon the present investigation. In Appendix V will be found a bibliography relating to the magnetic and allied properties of iron. While this bibliography is not complete, it covers the field quite thoroughly.

Considering first the researches made upon electrolytic iron as deposited, it is found that electrolytic iron was used as a basis for magnetic investigations as early as the middle of the nineteenth century. Beetz[1]* in 1860 deposited iron under the influence of a powerful magnet, and the plates thus produced were found to be very hard and have a large permanent magnetism. Holz[6] in 1871 made a statement to the same effect. Other investigators, Kramer[2] in 1861 and Klein[3] in 1868, claimed that electrolytic iron is soft and possesses no permanent magnetism. Leick[10] in 1896 deposited iron on brass rods from solutions of ferrous sulphate and ferrous chloride with or without sal ammoniac, and obtained perfectly uniform deposits. The rods were measured as deposited and were found to have a residual magnetism of above 70 per cent of the temporary magnetism, the thinner the deposit the higher the percentage. The coercive force was found to be 20 to 30 c. g. s. units, and the saturation value about the same as for soft iron. For $H = 90$† he obtained an induction of 18,900. Burgess and Taylor[20] in 1906 tested the iron as deposited after being cut into rings. They found the deposit hard and brittle. For $H = 100$ they found $B = 15{,}750$, the retentivity $= 10{,}300$, and the coercive force $= 11$. Schild[21] in 1908 confirmed the results of Burgess and Taylor. In 1910 Terry[226], in an excellent paper that will be referred to later, in the case of iron as deposited and unannealed, found for $H = 100$, $B = 17{,}400$, the retentivity $= 9{,}560$, and the coercive force $= 7.53$.

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*Numerals refer to the bibliography given in Appendix V.

†The following notation is used throughout this bulletin:

H = magnetizing force = $.4\pi n I$—gilberts per cm.

Hc = coercive force—gilberts per cm.

B = flux density—gausses.

Br = retentivity—gausses.

μ = permeability = $\frac{B}{H}$—gausses per gilbert per cm.

Turning now to the experiments upon soft commercial iron and electrolytic iron after being melted, we find one of the earliest investigators to be Stoletow of Moscow, who in 1873, using a ring of soft iron with two coils wound on it, found that the permeability of iron first increased and then decreased as the magnetizing force increased. At the same time Rowland[5] gave a most important contribution to the knowledge of magnetism of iron. He expressed his results in terms of absolute units, and discovered the shape of the magnetization curve as it is known today. He found for a ring of Norway iron a maximum permeability of 5,515, at that time considered a remarkably high value. In 1885 J. Hopkinson[7] published the results of his investigations on 35 different samples of iron and iron alloys, giving chemical analyses. The specific electrical resistance he found to vary from 13.78 microhms for wrought iron to 100 microhms for cast iron. For wrought iron he found for a maximum induction of 18,251: the retentivity = 7,248, the coercive force = 2.30, the energy loss = 13,356 ergs per c. c. per cycle. He employed the double bar and yoke method of testing, but instead of reversing the magnetizing current, as the practice is today, he jerked the rod to be tested out of its solenoid and obtained a kick of the galvanometer needle proportional to the magnetism in the rod. In 1896 Parshall[9] published additional data upon the magnetic properties of commercial iron. In 1900 and 1902 Barrett, Brown and Hadfield[15] published what will probably be regarded as the most important results ever published on the magnetic and electrical properties of iron and iron alloys. They used as their standard iron Swedish charcoal iron, containing the following impurities:

C —.028%
Si —.070%
S —.005%
P —.044%
Mn —trace

Considering first the specific resistance, these investigators found that their pure iron standard had a resistance of 10.2 microhms per c.c. and that 1 per cent of any element added to pure iron increased its specific resistance by an amount approximately proportional to the specific heat or inversely proportional to the atomic weight of the alloying element. This relation was first suggested by Le Chatelier[13] in 1898, and was confirmed by Barrett[19] in 1902, who published the following table:

TABLE 1.

EFFECT OF DIFFERENT ELEMENTS UPON THE ELECTRICAL RESISTANCE OF PURE IRON. (FROM BARRETT.)

Alloy of Iron with	Increase in Spec. Resist. for 1% Added of Element of Col. 1. microhms	Spec. Heat of Alloying Element	Atomic Weight of Alloying Element
Tungsten	2.0	.035	184
Cobalt	3.0	.107	59
Nickel	3.5	.109	59
Cromium	5.0	.100(?)	52
Carbon	5.0	.160*	12
Manganese	8.0	.122	55
Silicon	13.0	.183	28
Aluminum	14.0	.212	27

*For graphite

Considering next the magnetic properties of the 100 or more rods investigated by Barrett, Brown and Hadfield, it is found that the only alloys that are more magnetic than the purest commercial iron are those containing small percentages of silicon and aluminum. Carbon appears to be the element most detrimental to magnetic quality. The magnetization curves for the iron standard together with their best silicon alloy, containing 2½ per cent Si., and their best aluminum alloy, containing 2¼ per cent Al. are shown in Fig. 1. These curves were obtained after careful annealing. In Table 2 is given some additional data for these rods.

TABLE 2.

SUMMARY OF THE MAGNETIC AND ELECTRICAL PROPERTIES OF HADFIELD'S BEST MAGNETIC IRON. (FROM BARRETT, BROWN & HADFIELD.)

Rod No.	Description of Iron	Maximum Permeability μ_{max}	B for μ_{max}	Hysteresis Loss for B max =9,000. Ergs per c. c. per cycle	Hysteresis Loss for B max =4,000. Ergs per c. c. per cycle	Retentivity for B max =17,700	Coercive Force for B max =17,700
S. C. I.	Stand.	2,100	4,000	2,334	638	10,800	1.10
898E	2½% Si	5,000	4,000	1,549	436	8,000	0.80
1,167H	2¼% Al	5,400	5,000	1,443	386		0.80
	Lohy.*				537		

*From Messrs. J. Sankey & Sons.

In 1901 Gumlich and Schmidt[16] published results obtained at the Physikalische Teknische Reichsanstalt. They investigated a large number of commercial irons. Their best iron, magnetically, had a maximum permeability of 8,350 with the retentivity = 10,300, the coercive force = 0.6, and the electrical resistance = 11.3 microhms.

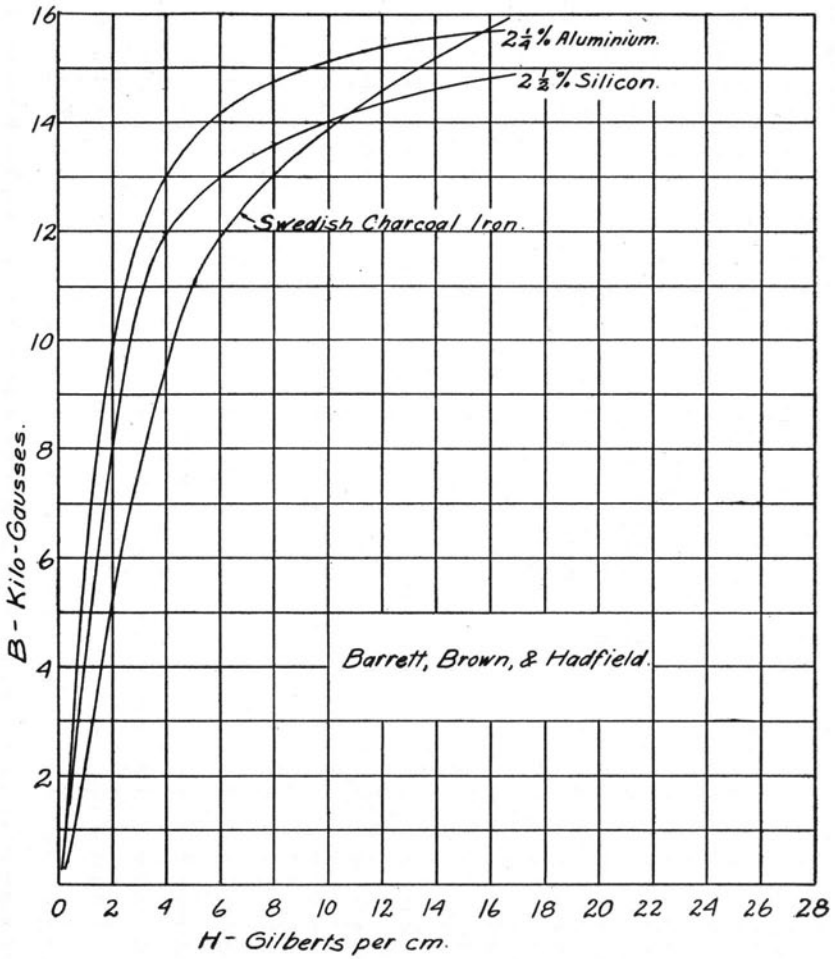

FIG. 1. HADFIELD'S BEST MAGNETIC IRON. THOROUGHLY ANNEALED.

In 1909 and 1910 Burgess and Aston published a series of articles on the magnetic properties of electrolytic iron after being melted[28], and on the influence on these properties of arsenic[22-23], antimony[28], tin[23], bismuth[22], silicon[27], copper[26] and nickel[25]. They also published an article comparing the magnetic properties of electrolytic iron with those of some commercial steels[28]. The iron used by them was doubly refined electrolytically of the following composition: C =.012 per cent, Si = .01 per cent, Fe = 99.97 per cent. This iron was melted in a resistance furnace in a covered magnesia crucible placed inside a covered graphite crucible,

buried in crushed carbon. The ingots thus produced were forged into rods and turned. After being melted and forged, the carbon content was found upon analysis to vary from .012 per cent in some specimens to 0.12 per cent in others, showing that the iron had absorbed carbon in the process. On account of this variation in absorbed carbon, and because also of the variation in mechanical treatment, which can hardly be altogether avoided, the magnetic properties varied considerably, even for samples with no alloying element added to them. Table 3 gives the magnetic properties of their best electrolytic iron rod, No. 117A.

TABLE 3.

SUMMARY OF THE MAGNETIC PROPERTIES OF BURGESS' BEST ELECTROLYTIC IRON (FROM BURGESS AND ASTON). ROD NO. 117A.

Heat Treatment	Values of B in Gausses for				Coercive Force	Retentivity	Specific Elec. Res. microhms
	H=10	H=20	H=50	H=100			
Unannealed.	13,100	15,750	17,600	18,850	5.5	12,300	12.1
Ann. 675° C.....	10,000	15,950	17,700	18,850	6.2	13,800	
Ann. 1000° C.....	13,350	15,450	17,050	18,200	3.1	10,000	
Quenched 900° C..	11,800	14,600	16,950	18,150	2.5	8,000	

This result shows an improvement over the Swedish charcoal iron.

Of the various alloying elements investigated, arsenic (3 to 4 per cent), tin (1 to 2 per cent), and silicon (up to 5 per cent) were found to increase the permeability slightly at low densities and bismuth at high densities, while copper, manganese, antimony and nickel were found to decrease the permeability to a greater or less extent. The electrical resistance of the electrolytic standard measured 12.1 microhms.

Guggenheim[29] in 1911 has shown, for iron containing 0.2 per cent carbon, that silicon in quantities up to 1.8 per cent decreases the permeability, but that from 1.8 to 5.0 per cent silicon improves the permeability and decreases the hysteresis loss. He found for $B_{max} = 10{,}000$ in sheets $\frac{1}{2}$ mm. thick the following values for the hysteresis loss:

For ordinary sheet iron....6,000 ergs per c. c. per cycle

For best silicon steel.....2,910 ergs per c. c. per cycle

Later, Hamlen and Rossiter[30] gave some data for Stalloy, the trade name for a commercial transformer steel. The maximum permeability was found to be:

μ_{max} for unannealed Stalloy.....3,100 at $B = 4{,}500$

μ_{max} for annealed Stalloy.....4,200 at $B = 7{,}000$

The hysteresis loss $= 2{,}500$ ergs per c. c. per cycle for $B = 10{,}000$.

In 1912 De Nolly and Veyret[31] summarized their results in the following recommendation for dynamo iron:

Composition: Carbon < 0.1 per cent, silicon $= 4$ per cent, manganese < 0.3 per cent, sulphur and phosphorus as little as possible. The final iron should be annealed at 800° C. and slowly cooled.

Besides the researches upon iron at ordinary temperatures in low and medium fields, a large amount of work has been done to determine the properties of iron in intense fields and at temperatures ranging from —200° C. to +1,300° C. Among the earliest investigators working with iron in intense fields are found Ewing and Low, who, in 1887[101] and 1889[102], published the results of their investigations on the properties of iron in fields ranging from 3,000 to 25,000 gilberts per cm. To obtain these fields they employed test-pieces machined into the shape of double cones with a short "isthmus" at the apex. They found the following values for the saturation intensity of magnetization, I:

For "Lowmoor" iron $I = 1{,}680$ for $H = 6{,}000$
For Swedish iron $I = 1{,}700$ for $H = 6{,}000$

DuBois[103] in 1890 obtained 1,700 to 1,750 for $H = 2{,}500$. Gumlich[104] in 1909, using electrolytic iron, obtained 1,725 for $H = 6{,}000$. The most important investigation in this field is that by Hadfield and Hopkinson[105], who investigated the saturation values for I (they termed this value the "Magnetism" or the "Specific Magnetism" of the substance) for a large number of alloys. Their results are summarized as follows:

1. Every alloy has a definite saturation intensity ("specific magnetism"), in most cases reached for $H = 5{,}000$. Alloys behave as if consisting of a mixture of magnetic and non-magnetic substances.
2. No alloy has a higher specific magnetism than pure iron.
3. The specific magnetism for pure iron of density 7.80 is 1,680.
4. The effect of carbon is to decrease the specific magnetism by a percentage equal to six times the percentage of carbon. As the percentage of iron carbide is 15.5 times the percentage of carbon, the specific magnetism of iron carbide is 2/3 that of pure iron.
5. Quenching iron-carbon alloys from a high temperature decreases the specific magnetism by a large but uncertain amount.
6. Additions of silicon or aluminum reduce the specific magnetism as if they are inert materials. Silicon seems to neutralize the effect of carbon to some extent.

The effect of temperature upon the magnetic properties of iron was studied as early as 1874 by Rowland[201], followed by a large number of investigators (see Appendix V). Fleming and Dewar[213] in 1896 found the permeability to be lower at —200° C. than at ordinary temperatures. For Sankey's best transformer iron they found for a temperature of — 185° C. $\mu_{max} = 2{,}800$, and for a temperature of + 15° C. $\mu_{max} = 3{,}300$ for $B = 7{,}000$. The hysteresis loss was found to be the same at both temperatures, namely 2.1 watts per pound per 100 cycles (= 3,000 ergs per c. c. per cycle), for $B_{max} = 10{,}000$.

Morris[217] in 1897 used Swedish charcoal iron in the form of rings. For Sankey's best transformer iron he found that for small values of H the permeability increased as the temperature was raised, reaching a maximum of 15,000 at a temperature of about 765° C. When the temperature was raised still further the permeability was found to drop off very rapidly and become nearly 1 at 780° C. For higher values of H, μ decreased steadily, until it made a sudden drop at the same critical temperature. The maximum value of μ at ordinary temperatures was found to be 4,580. Wills[222] in 1900 confirmed the results of Morris. He found a maximum value of permeability of 17,228 for $H = 0.172$ at a temperature of about 730° C., dropping almost to unity at 780° C. Honda and Shimizu[224] in 1905, using ovoids, determined the critical points for iron, cobalt and nickel, and found the magnetism in iron to disappear at 785° C., in cobalt at 1,100° C. and in nickel at 350° C.

In 1910 Terry published the results of a very extended investigation upon electrolytic iron as deposited. He summarized his results as follows:

1. Freshly prepared iron is very hard magnetically.
2. Different samples show marked dissimilarities at low fields which disappear upon annealing at 1,000° C.
3. For large fields, all samples are quite similar, the values obtained for susceptibility being intermediate between those of Leick and Schild.
4. Plunging into liquid air produces no permanent hardening.
5. The retentivity has a maximum in the neighborhood of room temperature.
6. Marked softening occurs magnetically at the hydrogen transformation points.
7. Ferro-magnetism reappears on cooling at the same temperature at which it disappears on heating. This temperature is 785° C.

8. The depression in the permeability-temperature curves obtained by Morris does not exist for this iron.

9. The best temperature for annealing is 1,100° C.

10. Although when properly annealed it has a lower coercive force and a higher permeability than Swedish iron, its high retentivity causes a large hysteresis loss.

From this brief review the following general conclusions may now be drawn:

1. No better agency than pure iron exists for conveying magnetism.

2. The purest iron obtainable is electrolytic iron. This iron as deposited is, however, magnetically hard but may be cured by certain heat-treatments.

3. As pure iron at high temperatures is very readily contaminated by elements that decrease its magnetic properties, it is necessary to protect it, by some means or other, from contamination, if subjected to high temperatures, and particularly if melted.

4. As it is almost impossible with ordinary methods to melt pure iron without having it slightly oxidized, it may be deoxidized by adding to it some deoxidizing agent such as silicon or aluminum, elements that have a higher affinity for oxygen than iron.

5. It is highly desirable that the electrical resistance of iron for magnetic purposes be as high as possible. It is, therefore, very fortunate that the deoxidizing agents mentioned under 4 have the property of increasing the electrical resistance to a very large extent, thus lowering the eddy current losses in the iron when subjected to alternating currents.

As already mentioned, it is not the intention to take up in this bulletin the effect of these deoxidizing agents upon pure iron. This will be deferred to some later date. This bulletin will show to what extent iron may be protected without the use of these agents, namely by melting it in vacuo.

3. *Early Experiences.*—The author of this bulletin took up the investigation of the magnetic properties of iron and iron alloys during the summer of 1911 and, with a short interruption, has continued it since that time. Electrolytically deposited iron has been the basis for the investigation. At first a Hoskins resistance furnace was used for the melting of the iron. The crucibles, after being well protected by two covers, were placed in the heating chamber, heated until the iron was melted and left until cool enough to handle. It was supposed that the atmosphere in the furnace was sufficiently reducing to prevent oxida-

tion of the iron, as the resistor consisted of carbon plates, but it was soon discovered that the iron was so badly oxidized that it went to pieces in the attempt to forge the ingots at forging temperatures. Little trouble was had in forging ingots heated to dull redness.

After this first experience the crucibles were covered with crushed carbon following substantially the method of Burgess and Aston. While no serious oxidation took place under these conditions, it was impossible to obtain uniform results. This was the case both with the electrolytic iron and with the Swedish charcoal iron. Attempts were made to use a definite fineness of carbon and to determine what effect changing the fineness had upon the results, but no relation could be discovered. Fifteen electrolytic and fifteen Swedish iron rods were made, and there are hardly two rods that have the same B-H curve either as forged or after being annealed at 900° C. The magnetic and electrical data for eight of the electrolytic iron rods are given in Table 4 for the sake of comparison. From these results it is seen that relatively large quantities of carbon were absorbed by the iron. On account of this difficulty it was decided to construct a vacuum furnace for the melting of the iron. While the results obtained with this furnace are not entirely uniform, the non-uniformity must be attributed chiefly to the unavoidable differences in the mechanical treatment of the rods.

4. *Acknowledgments.*—The author wishes to express his gratitude to a large number of persons connected with the University of Illinois, who have rendered very valuable assistance in carrying on this investigation.

Among these he wishes particularly to mention Prof. E. J. Berg and Prof. E. B. Paine for their interest in the work as heads of the Electrical Engineering Department, Dr. Grinnell Jones, now of Harvard, for assistance in the production of the electrolytic iron, Prof. S. W. Parr for opening his laboratory for the chemical determinations, and Mr. J. M. Lindgren for making the determinations, Dr. O. F. McFarland for the metallurgical part of the investigation, Mr. Rudolph McDermott for the critical temperature determinations and for assistance in general, and Mr. J. H. Belt for electrical resistance determinations.

The Ceramics Department has been of valuable assistance in connection with making the crucibles in which to melt the iron. Finally, a number of electrical manufacturing companies have shown their willingness to co-operate in the investigation by going to great trouble and expense in preparing rods from various grades of iron for the purpose of comparison.

II. Material and Apparatus.

5. *Electrolytic Iron.*—The electrolytic iron used in this investigation was obtained by methods developed by Burgess[301]. As a considerable amount of work has been done recently by Watts and Li[302] to improve upon the methods originally used by Burgess, the details of the refining plant constructed by the author will be omitted, and only the chief features will be mentioned. The electrolyte used consisted of ferrous sulphate and ammonium chloride. Swedish charcoal iron was used as anodes, having the following impurities:

Si	—.032%
S	—.0002%
C	—.163%
P	—none
Mn	—none

The Swedish iron was first deposited upon lead cathodes, and these were used as anodes in the second refining. The chemical analysis of the doubly refined iron shows that it contains C —.006 per cent, Si —.01 per cent. This iron, of a purity of 99.97 to 99.98 per cent, is the material that has been used as the basis for the present investigation. The iron, as deposited, was very rough and nodular, but for the purpose intended this condition was of no importance as the iron had to be broken into small pieces.

6. *Crucibles.*—The crucibles for melting the electrolytic iron were made from electrically fused magnesia, practically free from iron but containing about 2 per cent silica. They measure 3¼ in. (8.3 cm.) outside diameter and 4 in. (10 cm.) in height, holding 500 to 600 grams of crushed electrolytic iron. The arc furnace for producing the magnesia and the method of making the crucibles are described in Appendix I.

7. *Vacuum Furnace.*—As already mentioned in the introduction, a Hoskins resistance furnace was at first employed for melting the iron, but on account of the contamination of the iron with oxygen and carbon, this was superseded by a vacuum furnace. The details of this furnace are given in Appendix II. Suffice it to say here that it is of the Arsem type and was constructed in the shop of the Electrical Engineering Department. It is capable of melting 500 to 600 grams of pure iron in half an hour with a vacuum of less than 0.5 cm. of mercury.

8. *Reheating Furnace.*—The reheating furnace employed for annealing the test-pieces is described in detail in Appendix III. It was modeled after the Hoskins carbon plate resistance type furnace and was

constructed in the department shop. For the critical temperature investigation of the iron a small Hoskins muffle furnace was employed.

9. *Pyrometer.*—All temperature determinations were made with a standard platinum-platinum + 10 per cent rhodium pyrometer. This was calibrated at intervals by means of the melting points of copper (1,083° C.), aluminum (658° C.), and tin (232° C.) in a reducing atmosphere and the boiling points of sulphur (444.7° C.) and water (100° C.), all of standard purity. The calibration curve was found to be practically constant, uniformly low by 6 to 8° C. In the early part of the investigation the cold junction was kept at room temperature and the galvanometer readings corrected by adding one-half of this, but later a vacuum bottle was provided for keeping this junction at 0° C. Electroquartz protecting and insulating tubes were used throughout.

10. *Permeameter.*—A number of different instruments for the magnetic measurements were tried and discarded. As it was desirable to make a large number of test pieces, Rowland's ring method was impracticable, both on account of the difficulty of construction and because of the difficulty of electrical resistance measurements. An instrument was needed that could measure accurately the magnetic properties of relatively short rods. The one finally decided upon was constructed by the author in accordance with recommendations made by the Bureau of Standards[402]. While this instrument requires considerable time for the actual measurements, no corrections need ordinarily to be made, and the meters read directly in B and H. The apparatus with all its accessories is fully described in Appendix IV. Briefly stated, it consists of a double bar and yoke, with one main and one auxiliary solenoid, separately operated, and four compensating coils in series, next to the yokes. By means of three secondary, or search coils, next to the bars, the magnetic flux can be investigated at different points of the magnetic circuit and can be equalized by adjusting the currents in the various magnetizing coils. With no leakage the magnetizing force for the rod measured is

$$H_T = .4\pi n_T I_T$$

where n_T = number of turns per cm. length of the main solenoid, and I_T = current in amperes of the main solenoid.

It is shown in Appendix IV that the correction to H_T on account of the end effects of the various magnetizing coils is within + 1 per cent of H_T for ordinary iron, and is within + 4 per cent for the highest permeability found for electrolytic iron melted in vacuo. These corrections

have not been made in the results reported in this bulletin for reasons to be shown below.

For the determination of "B" a Leeds and Northrup ballistic galvanometer was used in the early part of the work. The period of this galvanometer was adjusted to 15 seconds, and its resistance was 1,800 ohms. It could be calibrated without changing the galvanometer circuits by means of a mutual inductance (also described in Appendix IV) consisting of a primary coil 90 cm. long by 10 cm. diameter and a secondary coil about 8 cm. long, wound over the middle portion of the primary. This galvanometer served the purpose very well, until the vacuum iron was to be measured. This iron was found to have such high permeability, particularly after being annealed, and such low electrical resistance that the eddy currents produced in the rod as well as the high inductance of the coils made the change of magnetism too sluggish for accurate determinations. This was particularly true for hysteresis measurements. in changing from B_{max} to some point on the descending part of the loop, such as $B = -\frac{1}{2} B_{max}$, the change would require as much as five or six seconds before being completed. To remedy this difficulty a Grassot fluxmeter was obtained for the final measurements. In this instrument the suspension effect has been practically eliminated, and the deflection is independent of the time required by the flux to complete the change. All the different connections for operating the permeameter are made through rocking mercury switches operated by means of keys similar to piano keys. In this manner any number of switches up to ten may be operated simultaneously, and comparatively little time is occupied in making the adjustments.

In Fig. 2 is shown the magnetization curves for the standard rod No. 3-33B, as obtained, first, by the Bureau of Standards, second, by means of the author's permeameter using the Leeds and Northrup galvanometer, and third, by using the Grassot fluxmeter. The second curve was obtained by first making adjustments by means of the fluxmeter and then by making the final measurement with the galvanometer. The discrepancy between the first and third curves at low and medium densities may be partly explained in this way: The rod as measured by the Bureau of Standards was covered with a thin film of oxide, preventing perfect contact between the rod and the yokes. On this account a comparatively large compensating current was necessary to obtain equality of flux for low values of H. The author tested the bar upon its return from the Bureau of Standards and obtained figures somewhat lower than but

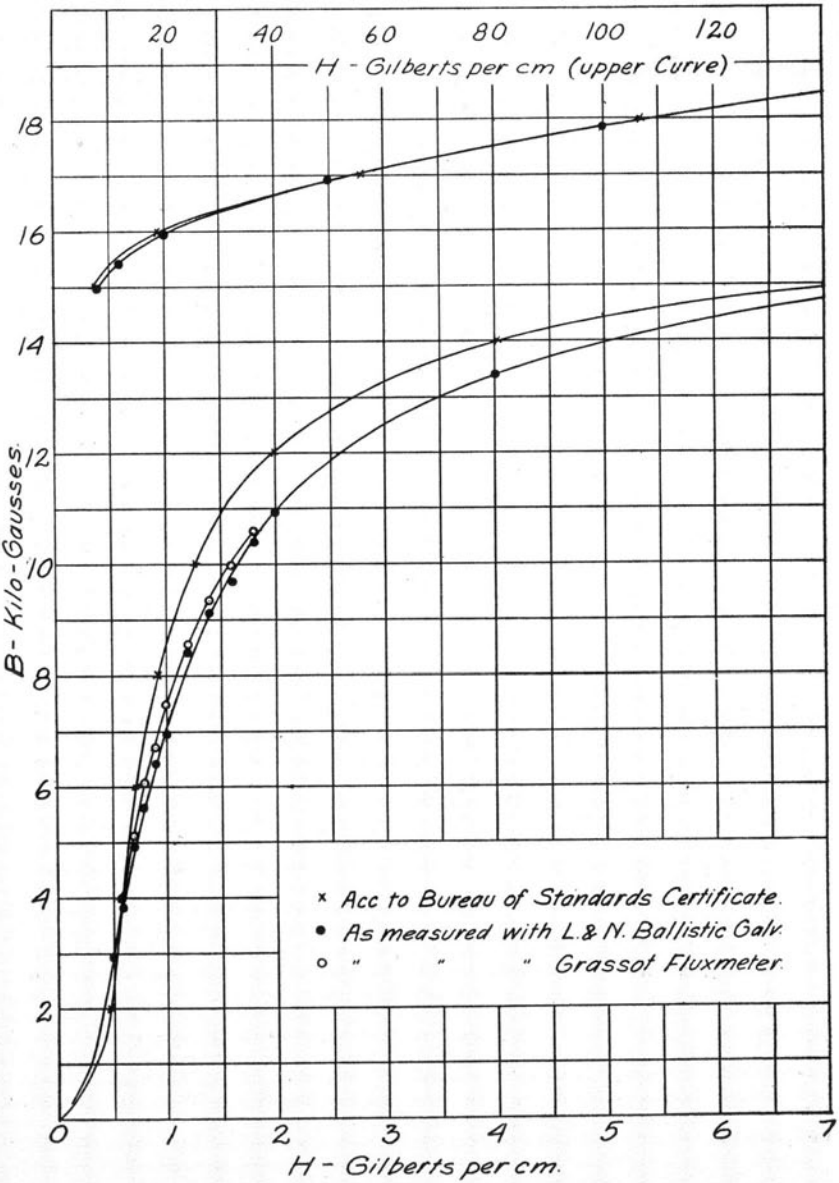

FIG. 2. MAGNETIZATION CURVES FOR STANDARD ROD. NO. 3-33B.

quite close to those submitted by the Bureau. However, when it later on was found necessary to clean the contacts of the rods in order to keep the compensating currents within proper limits, the standard rod was also cleaned and remeasured. The curves shown in Fig. 2 are the results of this final test. It may be that these results are due to the effect of the cleaning process upon the magnetic properties of the iron. But this is doubtful, as the cleaning was done by means of light hand rubbing with rather fine emery cloth. Again it may be, as will be discussed later, that the discrepancy is due to some slight straining of the rod as clamped between the yokes. At any rate the author's curve, for low and medium densities, is below that of the Bureau of Standards, and he feels, therefore, that the results given in this bulletin, if they be slightly in error, are on the safe side. For this reason no corrections of H_T due to the end effects, referred to above, have been made.

11. *Conductivity Bridge.*—The electrical resistance was measured on a Thompson double bridge using 13 cm. of the rods between the contacts. The bridge was checked by means of a potentiometer and standard cell and the discrepancy found to be less than 1 per cent.

III. Details of the Experiments.

12. *Cleaning the Iron.*—The electrolytic iron before being placed in the crucible to be melted was thoroughly cleaned as follows: The iron was crushed into small pieces and the requisite amount for one melt, from 500 to 600 grams, weighed out and placed in a bath of 1:3 hydrochloric acid solution until all rust had disappeared. The acid was then removed by introducing boiling distilled water through a glass tube that at the same time served as a stirrer. This process was continued until the solution was perfectly clear and free from acid. The water was then poured off and any water adhering to the iron dissolved by means of two baths of denatured alcohol from which the moisture had been removed by quicklime. After such a treatment the iron might be left exposed to the air for a day or more without rusting. However, during these experiments it was immediately transferred to a crucible, covered by means of a magnesia cover, and placed in the furnace.

13. *Melting the Iron.*—As mentioned in the introduction, an ordinary resistance furnace was used in the early part of the investigation. The covered magnesia crucible was placed inside a covered graphite crucible and buried in crushed graphite. The melting was completed in about three hours, the current was then cut off and the furnace left to cool.

In the vacuum furnace the magnesia crucible was placed in a low graphite receiver as shown in Appendix II. The furnace was exhausted, first by means of a water aspirator capable of reducing the pressure to 4 or 5 cm. of mercury, and then by means of a Geryck double cylinder pump. A vacuum of 0.5 cm. was deemed sufficient for this work, although it was less at times. As soon as this vacuum was reached the furnace was heated up, slowly at first, so as to give the absorbed gases time to get away without too much loss of vacuum. When vacuum was regained and the resistor had become dull red, requiring about one hour, full load was put on and left on for the length of time required to thoroughly melt the charge. The time required was ascertained by means of a preliminary test, in which a cover with a small hole in the center was used on the crucible. The condition of the iron could then be watched through the window in the top of the furnace. About 15 kw. for 30 minutes was usually sufficient to melt the charge, but in order to insure homogeneity about 12 kw. was left on for another 15 minutes. The furnace was then left to cool.

14. *Forging the Ingots into Rods.*—When removed from the furnace the ingots were as bright as silver and so soft that they could be cut with a knife. They were reheated in a coke forge and forged under a steam or trip hammer. No difficulty was experienced in the process, but care had to be used not to heat the ingots too hot, as the iron burned very readily, and after overheating it was liable to go to pieces under the hammer. An ordinary forging temperature, dull to bright orange, has been found the most suitable. In order to reduce the size of the crystals the forging was continued until the rods were black. The dimensions of the finished rods were about $\frac{1}{2}'' \times 20''$ ($= 1.25$ cm. $\times$ 50 cm.).

With regard to the safety of reheating this pure iron in an ordinary forge without contamination the chemical analysis has shown that the carbon content of the iron was practically the same before and after forging, in this respect confirming the conclusions of Professor Burgess.

15. *Preparing the Test-pieces.*—From the forged rods the following test-pieces were made:

1. One magnetic test-piece, serving also for the electrical tests, $0.392''$ ($= .996$ cm.) in diameter and $14''$ ($= 35.5$ cm.) long. The earlier rods were only $12''$ ($= 30.5$ cm.) long.

2. Two test-pieces for the mechanical tests, having a middle section $0.3''$ ($= .76$ cm.) in diameter and $1\frac{1}{2}''$ ($= 3.8$ cm.) long, with threaded ends $\frac{1}{2}''$ by $\frac{1}{2}''$ ($= 1.25$ cm.). (See Fig. 11.)

3. One test-piece for the metallurgical investigation ½″ by ½″ (= 1.25 cm.).

4. One test-piece for the critical temperature investigation ½″ (= 1.25 cm.) by 1″ (= 2.5 cm.), with a hole ¼″ (= .6 cm.) by ½″ (= 1.25 cm.) drilled in one end.

The shavings obtained by the process of preparing these test-pieces were collected after first removing the exposed parts of the rods and used for the chemical analysis. No oil was used during the collection of these shavings.

16. *Annealing and Quenching.*—After the test-pieces (1 and 3 above) had been tested as forged, they were sent through different heat treatments, either alone or together with other test-pieces. If they were to be annealed they were packed in pulverized sintered magnesia in an iron container, A, Fig. 62. In order to minimize the formation of oxide on the surface of the rods, it was found expedient to moisten the magnesia with alcohol. The alcohol in evaporating presumably expelled the air surrounding the rods, leaving them in a reducing atmosphere. The film of oxide formed on the rods under these conditions was very thin and could be removed with fine emery cloth, except after severe treatment, such as cooling from 900° C. to 200° C. in 48 hours. Even then no difficulty was had in removing the film. With the exception of the preliminary tests of rods No. 3-39 and No. 3-31, definite cooling curves were followed. In a few cases this was the logarithmic curve $T = 900\epsilon^{-.00105t}$, where T = temperature and t = time in minutes. In all other cases the cooling curve was a straight line, connecting 900° and 200° C. The time was 12, 24 or 48 hours. While it was impossible to follow the curve exactly, the deviation from it was slight. The temperature was measured by placing the pyrometer tube in direct contact with the rods about 2″ (= 5 cm.) from one end. The uniformity of temperature in the container was tested once for all by means of Seger cones placed at regular intervals along the rod with their apexes touching the rod. No marked difference could be detected. Below 200° C. the rods were allowed to cool without supervision, but they were not removed from the container until cool enough to handle with the hands.

The quenching was done by placing the test-pieces in a container, Q, Fig. 62. This was filled with magnesia and moistened with alcohol. A loose fitting iron stopper was placed at one end. At the desired temperature the container was removed from the furnace, tipped up and the contents plunged into the quenching bath by means of a sharp blow

from a hammer on the top of the container. The quenching bath used consisted of iced brine at —21° C. In one case liquid air was used, but then the magnesia was omitted.

17. *Magnetic Tests.*—After each heat treatment the rods were tested magnetically and electrically. The magnetic test consisted in determining the magnetization curve up to $H = 150$ or 200 gilberts per cm. and the hysteresis loops for $B_{max} = 10{,}000$ and usually for $B_{max} = 15{,}000$. Points on the magnetization curve were determined by the method of reversal, the details of which are given in Appendix IV. The hysteresis loop was determined by changing from H_{max} to the particular value of H wanted, and noting the deflection of the flux-meter corresponding to this change. Thus, by using the maximum values of H and B as the basis, the magnetic viscosity does not affect the results. Unless very high values of H are used, this method appears to the author to be preferable to the one suggested by Taylor*, in which the retentivity point is used as the basis. For further details the reader is referred to Appendix IV.

18. *Metallurgical Analyses.*—As mentioned above, a small specimen for studying the microstructure was prepared from each rod as forged, and these specimens accompanied the magnetic rods wherever they went. Photomicrographs were obtained after the various treatments for nearly all the different rods. For this work an inverted metallurgical microscope was used, constructed by Ernst Leitz of Wetzlar. Great care had to be used in polishing the specimens on account of their softness. The etching was done altogether by picric acid.

The second metallurgical specimen was used for the critical temperature determinations. This was done by placing the specimen in a ½″ (1.25 cm.) "Electroquartz" pyrometer tube with the hot junction of the pyrometer inserted in the small hole made in one end of the specimen. The tube was partly filled with fused magnesia and placed in the Hoskins muffle furnace with the end at the middle of the furnace. The temperature was gradually raised to about 1,000° C., the current cut off, and the furnace allowed to cool naturally, while the time interval for each 10° C. was obtained by means of two stop-watches. From the data thus obtained three different curves were plotted for each specimen, namely:

1. The temperature-time curve, using temperature as abscissa and time as ordinate.

*Phys. Review XXIII, p. 95, 1906.

2. The temperature-rate curve, using temperature as abscissa and number of degrees fall in temperature per minute as ordinate.

3. The inverse rate curve, using temperature as abscissa and number of seconds per degree fall in temperature as ordinate.

From these curves the critical temperatures can readily be located.

While this method is not as accurate as the differential method by means of three thermocouples, it serves as a check upon the other determinations made in the course of the investigation.

19. *Mechanical Tests.*—As only two mechanical test-pieces could be obtained from each rod it was possible to use only a few different treatments in order to secure data that could be compared. The following treatments were used:

1. As forged.
2. Annealed at 900° C. and cooled in 12 or 24 hours.
3. Quenched in brine from 1,000° C.
4. One test-piece was quenched in liquid air from 1,000° C.

The tests were made on an Olsen 10,000-pound testing machine. The load was applied very slowly and uniformly by means of an electric motor. In most cases the elastic limit was very definite, and the stress for this point was obtained whenever it was sufficiently pronounced. The elongation was also measured in a large number of cases as soon as the ultimate stress had been reached.

20. *Chemical Analyses.*—From the chemical analysis of the Swedish charcoal iron and the doubly refined electrolytic iron it is seen that the only measurable impurities in the latter are carbon and silicon. As these are the only impurities that are liable to be affected during the processes described, it seemed superfluous to analyze for anything except carbon and silicon. A few analyses were made for sulphur, but only traces could be found. A large number of carbon analyses were made. Considerable difficulty was had at first in making these analyses on account of the small quantities present. Finally a direct combustion furnace was purchased for these tests, and consistent results have since been obtained. It was found necessary with this method to clean the samples thoroughly with ether before making the analyses in order to remove any trace of oil with which they might have become contaminated in the process of preparation. Although special precautions were taken to prevent such contamination, the analyses showed that as much as 0.02 per cent carbon was removed by cleaning the shavings with ether.

IV. Results.

In presenting the results of the investigation it has seemed desirable to divide the rods into a number of natural groups.

Group 1 includes the rods obtained from electrolytic iron melted in the resistance furnace under atmospheric pressure and is represented by rods Nos. 3-13, 3-15, 3-17, 3-18, 3-19, 3-20 and 3-25.

Group 2 includes rods obtained from electrolytic iron melted in vacuo and is represented by rods Nos. 3-34, 3-36, 3-37 and 3-38. After being forged these rods were reheated to forging temperature and cooled in air. The temperature was not measured with a pyrometer but estimated from the color to be between 1,000 and 1,100° C.

Group 3 includes rods obtained from electrolytic iron melted in vacuo and is represented by rods Nos. 3-40, 3-41, 3-43, 3-45 and 3-47. These rods were not at any time after being forged heated to a higher temperature than about 900° C. They were annealed three times at 900° C. with different cooling rates, in company with the three rods from Group 5 containing various percentages of carbon. The results show possible contamination from contact with these rods.

Group 4 includes rods obtained from electrolytic iron melted in vacuo and is represented by rods No. 3-48, 3-49 and 3-50. These rods were first annealed twice at slightly above 900° C., then annealed at 1,080° C. and cooled in about 6 hours, and finally annealed at 900° C. and cooled in 24 hours.

Group 5 includes the rods obtained from electrolytic iron melted in vacuo with different percentages of carbon added and is represented by rods Nos. 3C01, 3C02, 3C03, the amount of carbon added being 0.05 per cent, 0.10 per cent and 0.50 per cent, respectively. The rods were annealed together with the rods representing Group 3, as mentioned above.

Besides the rods included in the above five groups the following single rods were tested: Rods Nos. 3-39 and 3-31 were used separately for the preliminary test in the attempts to ascertain the most favorable annealing temperature. Rods SWI-4 and No. 1-21 were used to ascertain the effect of remelting Swedish charcoal iron in vacuo. SWI-4 was cut from a plate of Swedish iron ½″×6″×12″ (1.25×15×30 cm.) and machined into a magnetic test rod directly. The iron for No. 1-21 was cut from the same plate as SWI-4 and directly next to it and was melted in the vacuum furnace. After forging and turning, the two

TABLE 4.

GROUP 1: ELECTROLYTIC IRON MELTED IN RESISTANCE FURNACE UNDER ATMOSPHERIC PRESSURE. CRUCIBLES BURIED IN CRUSHED GRAPHITE.

Rod No.	% Carbon as per Chem. Analysis	Heat Treatment: Annealing Temp. °C.	Heat Treatment: Cooling Curve	Heat Treatment: Hours Cooling	Values of B in Gausses for: H=.5	H=1	H=2	H=8	H=20	H=100	Spec. Elect. Resist. at 20° C. microhms
3-17	.10	As	Forged			300	800	10,200	14,400	17,500	12.60
3-19	.05					200	450	9,100	14,600	17,600	13.20
3-23	.107					350	1,000	10,200	13,700	16,800	14.88
3-25						100	300	8,200	14,100	17,500	14.70
Avg.						250	640	9,425	14,200	17,350	13.85
3-13	.105*	1000	Log.	About 6		1,200	6,300	13,700	15,250	17,450	13.77
3-15						100	300	10,800	14,500	17,600	14.63
3-18						200	700	11,250	14,700	17,500	12.50
3-20	.14*					1,900	6,250	12,700	14,700	17,300	12.80
Avg.						825	3,387	12,125	14,788	17,462	13.43
3-13	.105*	934	Straight Line	24	600	2,700	7,900	14,000	15,400	17,450	13.70
3-15					250	550	1,900	12,500	15,100	17,600	14.52
3-17	.100*				500	1,750	6,450	13,600	15,200	17,500	12.55
3-18					50	100	400	11,500	15,000	17,400	12.40
3-19	.050*				50	125	400	10,500	14,700	17,300	13.20
3-20	.140*				700	3,150	8,000	13,650	15,100	17,300	12.53
3-23	.107*				400	1,500	6,000	13,000	14,700	17,100	14.65
3-25					50	125	400	11,500	15,000	17,400	14.62
Avg.	.100				325	1,250	3,930	12,530	15,025	17,380	13.52

* Analyzed as forged

NOTE: Magnetic measurements made with L. & N. galvanometer.

TABLE 5.

SUMMARY OF MAGNETIC AND ELECTRIC TESTS FOR ROD NO. 3-31.

Ref. No.	Heat Treatment: Annealing Temp. °C.	Heat Treatment: Cooling Curve	Heat Treatment: Hours Cooling from Max. to 200 °C.	Values of B in Gausses for: H=1	H=2	H=8	H=20	H=100	Spec. Elect. Resist. at 20°C. microhms
A	As Forged				4,250	11,500	14,850	17,500	9.98
B	532	Natural	ab't 3	1,750	5,100	12,700	15,300	17,500	9.96
C	700	"	" 4	3,300	8,250	14,200	15,500	17,500	9.96
D	800	"	" 5	4,900	10,400	14,600	15,600	17,600	9.90
E	900	"	" 6	6,100	10,600	14,800	15,600	17,600	9.93
F	950	"	" 6½	7,800	12,350	15,000	15,700	17,600	10.04
G	1,000	"	" 7	7,000	10,900	15,000	15,800	17,600	
H	900	"	" 6	7,600	11,500	15,200	15,750	17,750	
J	900	Logarith.	24	9,000	12,900	15,250	16,000	17,800	
K1	900	Str. Line	48	10,100	13,000	15,400	16,000	17,800	10.03
K2	900	Str. Line	48	9,770*	12,400*	15,600*	16,200*	17,900*	10.03

* As measured with Grassot fluxmeter

TABLE 6.

SUMMARY OF MAGNETIC AND ELECTRIC TESTS FOR ROD NO. 3-39.

Heat Treatment				Values of B in Gausses for					Spec. Elect. Resist. at 20°C. microhms
Ref. No.	Annealing Temp. °C.	Cooling Curve	Hours Cooling from Max. to 200°C.	H=1	H=2	H=8	H=20	H=100	
A	As Forged			550	2,300	10,000	14,500	18,100	9.78
B	680	Natural	ab't 4	3,700	9,900	15,600	16,300	18,100	9.85
C	800	"	" 5	8,800	14,400	15,900	16,400	18,100	9.95
D	900	"	" 6	9,400	14,500	15,900	16,400	18,100	
E	950	"	" 6½	8,100	11,900	15,800	16,400	18,100	
F	1,000	"	" 7	10,500	14,500	15,600	16,200	18,000	
G	1,060	"	" 7	9,650	14,500	15,500	16,100	17,900	10.00
H	912	"	" 6	10,650	14,600	15,500	16,100	18,000	9.83
J	800	"	" 5	8,600	12,400	15,500	16,100	17,900	9.87
K	700	"	" 4	9,900	14,200	15,500	16,100	17,700	9.87
L	616	"	" 3½	11,000	14,500	15,500	16,100	17,800	
M	500	"	" 3	10,800	14,500	15,500	16,100	17,800	9.87
N	1,000	Cooled in brine	ab't 1 min.	6,400	10,200	15,100	15,800	17,900	10.10
O	1,000	Q'nch'd in brine		1,000	2,600	7,900	12,200	17,500	10.15
P	644	Natural	ab't 4	2,000	7,600	14,700	15,950	17,900	
Q	900	"	" 6	7,500	13,000	15,200	15,900	17,700	
R	900	Logarith.	24	9,900	13,800	15,400	16,000	17,800	
S_1	900	Straight Line	48	10,500	13,600	15,400	16,000	17,900	9.95
S_2				12,100*	14,400*	15,500*	16,200*	17,900*	

*As measured with Grassot fluxmeter.

TABLE 7.

GROUP 2: ELECTROLYTIC IRON MELTED IN VACUO.

	Rod No.	% Carbon as per Chem. Analysis	Heat Treatment			Values of B in Gausses for						Hysteresis Loss. Ergs per c.c. per cycle		Coercive Force for B max =15,000	Retentivity for B max =15,000	Spec. Elect. Resist. at 20° C. microhms.	Critical Temp. Ar_3 °C
			Annealing Temp. °C.	Cooling Curve	Hrs. Cooling from 900 to 200 °C.	H=.5	H=1	H=2	H=8	H=20	H =100	B max =10,000	B max =15,000				
I.	3-34	.009	Forging temp.	Cooled in air													895
	3-36	.015						6,200	14,000	15,650	17,800	3,360		1.40	9,500	10.33	875
	3-37	.045					1,900	6,550	14,000	15,600	17,800	3,710		1.70	10,000	10.39	885
	3-38	.010						10,000	15,000	15,900	17,800	2,000		.90	10,100	10.00	905
	Avg.	.0198						7,600	14,330	15,716	17,800	3,020		1.33	9,900	10.24	890
II.	3-34		902	Log.	24	3,600	9,400	12,700	15,200	16,100	17,800					10.28	
	3-36					2,600	6,900	10,500	14,800	15,850	17,700	1,560				10.28	
	3-37					1,850	6,000	9,900	14,900	15,900	17,800	1,530				10.38	
	3-38					4,000	9,100	12,300	15,500	16,050	17,700					9.99	
	Avg.					3,010	7,850	11,230	15,100	15,980	17,750					10.23	
III	3-34		914	Straight Line	48	7,800	11,400	13,900	15,700	16,100	18,000	895	1,600	.30	10,600	10.20	
	3-36					5,960	9,640	12,500	15,500	16,100	18,000	953	1,830	.33	9,000	10.16	
	3-37					4,000	7,400	10,300	14,800	15,750	17,700	1,255	2,000*	.40*	9,500*	10.30	
	3-38					9,400	12,500	14,400	15,700	16,100	17,700	813	1,640	.29	12,100	10.00	
	Avg.					6,800	10,235	12,750	15,425	16,010	17,850	979	1,770	.33	10,300	10.16	

NOTE—Magnetic measurements for I and II were made with L. & N. galvanometer.
Magnetic measurements for III were made with Grassot fluxmeter.
*Estimated by comparison with 3-36.

rods were treated exactly alike. Rod No. 3-30 was made from electrolytic iron and melted in vacuo. It was given only one heat treatment, namely, annealed at 900° C. and cooled from 900 to 200° C. in 48 hours.

For the sake of comparison the results obtained with two sets of rods made from commercial iron are included in the final summary. One set of rods was made from a bar of silicon alloy steel, containing about 4 per cent silicon, while the other set of rods was made from bars such as are usually rolled into standard electrical sheets. The latter is material of commercially high permeability and is practically free from silicon. Both sets were prepared by the manufacturer and given their standard anneal.

TABLE 8.

GROUP 3: ELECTROLYTIC IRON MELTED IN VACUO.
ANNEALED WITH GROUP 5.

	Rod No.	% Carbon as per Chem. Analysis	Heat Treatment: Annealing Temp. °C.	Heat Treatment: Cooling Curve	Heat Treatment: Hrs. Cooling from 900 to 200 °C.	Values of B in Gausses for H=.5	H=1	H=2	H=8	H=20	H=100	Hysteresis Loss. Ergs per c. c. per cycle: B max =10,000	B max =15,000	Coercive Force for B max =15,000	Retentivity for B max =15,000	Spec. Elect. Resist. at 20° C. microhms	Critical Temp. Ar 3 °C.
I.	3-40	.0110	As	forged			900	4,400	11,000	14,900	17,900	4,500				9.78	895
	3-41	.0095					900	3,900	11,500	15,100	18,200	4,520				10.00	895
	3-43	.0096					550	2,800	9,750	14,200	17,900	5,620				9.90	895
	3-45	.0080					2,000	5,600	12,400	15,900	18,100	1,830				9.86	895
	3-47	.0080					1,900	5,200	12,300	15,700	18,200	1,570				10.10	900
	Avg.	.0092					1,250	4,380	11,400	15,150	18,050	3,690				9.93	896
II.	3-40		902	Straight Line	12	4,000	11,500	14,100	15,400	16,000	17,900	1,080				9.70	
	3-41					3,550	8,300	12,200	15,600	16,200	18,000	1,490				9.93	
	3-43					3,100	8,100	12,300	15,750	16,500	18,100					9.77	
	3-45					2,900	10,500	14,000	16,100	16,650	18,500	1,250				9.76	
	3-47					2,950	8,300	11,900	15,700	16,550	18,200					9.96	
	Avg.					3,300	9,350	12,900	15,710	16,380	18,100					9.82	
III.	3-40		909	Straight Line	24	4,000	10,500	14,000	15,400	16,000	17,800					9.64	
	3-41					4,400	8,900	11,950	15,600	16,300	18,000	1,300				10.01	
	3-43					4,800	8,900	13,100	15,850	16,500	18,100					9.86	
	3-45					2,950	8,600	13,600	16,100	16,700	18,500					9.86	
	3-47					5,000	11,100	14,350	15,750	16,550	18,200	990	1,930			10.02	
	Avg.					4,030	9,600	13,400	15,740	16,410	18,120					9.88	
IV.	3-40		903	Straight Line	48	4,800	8,850	11,700	15,300	16,000	17,700	1,240	2,500	.36	10,100	9.70	
	3-41					5,560	8,620	11,300	15,500	16,200	18,000	1,155	2,180*	.40*	10,000*	10.00	
	3-43					6,330	9,850	13,000	16,000	16,500	18,150	1,165	2,180	.40	10,200	9.85	
	3-45					4,300	8,200	12,000	16,250	16,800	18,450	1,470	2,640	.40	10,600	9.87	
	3-47					4,600	8,450	11,900	15,800	16,500	18,100	1,190	2,120	.35	9,000	10.05	
	Avg.					5,120	8,790	11,980	15,770	16,400	18,080	1,242	2,324	.38	9,980	9.89	

NOTE—Magnetic measurements for I, II and III made with L. & N. galvanometer.
Magnetic measurements for IV were made with Grassot fluxmeter.
*Estimated by comparison with 3-43.

The results of the tests are shown in the tables and curves. Tables 4, 7, 8, 9 and 10 give the results for the five groups of rods mentioned above. Table 5 gives a summary of the results for rod No. 3-31 after the various heat treatments. Table 6 gives the same for rod No. 3-39, but the heat treatments have been carried further for this rod than for No. 3-31. The results for No. 3-39 are also shown graphically in Fig. 3. Table 11 is a summary of the results for all the electrolytic iron rods melted in vacuo. Table 12 gives the final summary for all rods tested. Finally, Table 13 gives a summary of the results of the mechanical tests. Due to an oversight the rods of Groups 3 and 5 were annealed together. The results obtained were rather unusual and are, therefore, shown graphically in Fig. 4 for H=1.

TABLE 9.

GROUP 4: ELECTROLYTIC IRON MELTED IN VACUO.

	Rod No.	% Carbon as per Chem. Analysis	Heat Treatment: Annealing Temp. °C.	Heat Treatment: Cooling Curve	Heat Treatment: Hrs. Cooling from 900 to 200 °C.	Values of B in Gausses for H=.5	H=1	H=2	H=8	H=20	H=100	Hysteresis Loss. Ergs per c.c. per cycle: B max =10,000	B max =15,000	Coercive Force for B max =15,000	Retentivity for B max =15,000	Spec. Elect. Resist. at 20° C. microhms	Critical Temp. Ar_3 °C.
I.	3-48	.0080	As	forged			650	3,400	10,500	15,000	18,500	4,550					
	3-49	.0120					650	3,050	10,300	14,950	18,500	4,550					
	3-50	.0099					1,400	4,600	11,400	15,200	18,100	3,380					
	Avg.	.0099					900	3,680	10,730	15,050	18,370	4,160					
II.	3-48		925	Str'ght Line	24	6,070	9,750	12,650	16,100	16,600	18,300	970	1,915	.35	10,400		
	3-49					6,500	8,950	11,500	15,950	16,450	18,100	994	1,830	.31	8,200		
	3-50					5,100	9,200	12,500	15,900	16,400	18,200	1,195	2,060	.37	9,300		
	Avg.					5,890	9,300	12,220	15,980	16,480	18,200	1,053	1,935	.34	9,300		
III.	3-48		930	Str'ght Line	48	6,400	9,200	11,800	15,600	16,300	18,150	955	1,850	.29	9,300	9.70	
	3-49					6,100	8,700	11,200	15,800	16,500	18,200	902	1,710	.31	8,100	9.90	
	3-50					5,920	8,830	11,500	15,600	16,250	18,050	995	1,940	.30	9,000	9.70?	
	Avg.					6,140	8,910	11,500	15,670	16,350	18,130	951	1,830	.30	8,800	9.77	
IV.	3-48		1080	Log.	6	5,200	8,500	11,500	15,100	15,850	17,600					10.20	
	3-49					5,500	8,800	11,700	15,100	15,850	17,600					10.05	
	3-50					5,250	8,500	11,700	15,100	15,700	17,400					10.20	
	Avg.					5,320	8,600	11,630	15,100	15,800	17,530					10.15	
V.	3-48		918	Str'ght Line	24	5,760	8,620	11,100	15,200	15,900	17,600					9.95	
	3-49					5,810	9,200	11,600	15,150	15,700	17,600					10.00	
	3-50					5,400	8,830	11,500	15,150	15,900	17,600					10.15	
	Avg.					5,660	8,870	11,400	15,170	15,830	17,600					10.03	

NOTE—Magnetic measurements for I, II, III and V were made with Grassot fluxmeter.
Magnetic measurements for IV were made with L. & N. galvanometer.

TABLE 10.

GROUP 5: ELECTROLYTIC IRON WITH CARBON ADDED, MELTED IN VACUO. ANNEALED WITH GROUP 3.

	Rod No.	% Carbon as per Chem. Analysis	Heat Treatment: Annealing Temp. °C.	Heat Treatment: Cooling Curve	Heat Treatment: Hrs. Cooling from 900 to 200 °C.	Values of B in Gausses for H=.5	H=1	H=2	H=8	H=20	H=100	Hysteresis Loss. Ergs per c. c. per cycle: B max =10,000	B max =15,000	Coercive Force for B max =15,000	Retentivity for B max =15,000	Spec. Elect. Resist. at 20° C. microhms	Critical Temp. Ar_3 °C.
I.	3C01	.013	As forged			400	1,000	2,900	10,900	15,000	18,400	5,380				10.2	895
	3C02	.012				100	300	1,000	8,700	13,800	18,500	8,600				10.66	895
	3C03	.181				25	200	400	7,500	13,100	17,200	11,880				12.74	?
II.	3C01		902	Str'ght Line	12	1,450	5,600	9,600	15,650	16,450	18,350					10.25	
	3C02					750	5,100	10,000	15,300	16,100	18,100					10.67	
	3C03					750	2,000	6,300	12,900	14,700	17,100					12.6	
III.	3C01		909	Str'ght Line	24	3,000	7,000	10,500	15,900	16,600	18,500					10.25	
	3C02					1,600	6,800	11,600	15,500	16,300	18,100					10.7	
	3C03					900	3,150	7,100	12,900	14,800	17,100					12.65	
IV.	3C01		903	Str'ght Line	48	3,625	8,000	11,800	16,100	16,900	18,500	1,405	2,300	.40	10,000	10.24	
	3C02					1,840	7,750	11,600	15,500	16,200	18,000	1,710	3,190	.50	10,700	10.64	
	3C03					870	4,140	7,800	13,550	15,100	17,200	1,910				12.4	

NOTE—1. Magnetic measurements for I, II, and III were made with L. & N. galvanometer.
Magnetic measurements for IV were made with Grassot fluxmeter.
2. Carbon added as follows: 3C01—.05% added.
3C02—.10% added.
3C03—.50% added.

TABLE 11.

ELECTROLYTIC IRON MELTED IN VACUO. SUMMARY OF GROUPS 2, 3 AND 4 AND RODS 3-30, 3-31 AND 3-39.

No. of Rods Represented	Group or Rod No.	% Carbon as per Chem. Analysis	Heat Treatment: Annealing Temp. °C.	Heat Treatment: Cooling Curve	Heat Treatment: Hrs. Cooling from 900 to 200° C.	Values of B in Gausses for H=.5	H=1	H=2	H=8	H=20	H=100	Hysteresis Loss. Ergs per c. c. per cycle: B max =10,000	B max =15,000	Coercive Force for B max =15,000	Retentivity for B max =15,000	Spec. Elect. Resist. at 20° C. microhms	Critical Temp. Ar_3 °C.
4	Gr.2		As forged														890
5	Gr.3	.0092					1,250	4,380	11,400	15,150	18,050	3,690				9.93	896
3	Gr.4	.0099					900	3,680	10,730	15,050	18,370	4,160				9.80	
1	3-31	.0120					1,200?	4,250	11,500	14,850	17,500	4,600		1.80	7,700	9.98	885
1	3-39	.0110					550	2,300	10,000	14,400	18,100	5,460		1.80	7,000	9.78	905
Avg. for 10 rds.		.0100					1,070	3,950	11,070	15,015	18,100	4,090				9.88	894
4	Gr.2	.0198*	914	Str. Line	48	6,800	10,230	12,750	15,425	16,010	17,850	978	1,770	.33	10,300	10.16	
5	Gr.3	.0092	903	"	48	5,120	8,790	11,900	15,770	16,400	18,080	1,242	2,324	.38	9,980	9.89	
3	Gr.4	.0099	930	"	48	6,140	8,910	11,500	15,670	16,350	18,130	951	1,830	.30	8,800	9.77	
1	3-30	.0090	914	"	48	5,500	8,880	11,600	15,200	15,800	17,700					9.94	
1	3-31	.0120	900	"	48	6,580	9,770	12,400	15,600	16,200	17,900	980	1,760	.32	9,100	10.03	
1	3-39	.0110	900	"	48	8,050	12,100	14,400	15,500	16,200	17,900	880	1,860	.32	12,600	9.95	
Avg. for 15 rds.		.0125				6,090	9,500	12,350	15,590	16,200	17,950	1,060	1,990	.34	9,940	9.96	

*Analyzed as forged.

Fig. 5 shows the magnetization curves for the iron-carbon alloys melted in vacuo, while Fig. 6 gives the average magnetization curves for the rest of the rods. Fig. 7 shows the magnetization curves for the average and best electrolytic iron rods melted in vacuo, and Fig. 8 the hysteresis loops and permeability curve for the best rod obtained, namely, No. 3-38. Fig. 9 shows the corresponding curves for No. 3-34. While cooling curves were obtained for all the rods, only the one for No. 3-43 is included here; this is shown in Fig. 10. It was thought that it might be of interest to see some of the mechanical test-pieces after being tested; consequently, a few of these are exhibited in Fig. 11 together with a sample test-piece that has not been broken. In this figure the distance between the vertical lines is 1 in. (2.54 cm).

TABLE 12.

SUMMARY OF RESULTS

Rods thoroughly annealed at 900°C.

Rod No.	Description of Iron	Furnace Used for Melting	Carbon as per Chemical Analysis %	Max. Permeability	Flux Density for Max. Permeability.	Hysteresis Loss. Ergs per c.c. per cycle		Coercive Force for	Retentivity for	Spec. Elect. Resist. at 20°C. microhms	Critical Temp. Ar_3 °C.
						B max =10,000	B max =15,000	B max =15,000	B max =15,000		
3–38	Electrolytic	Vacuum	.0104	19,000	9,500	813	1,640	.29	12,100	10.00	905
3–39	"	"	.0110	16,500	8,500	880	1,860	.32	12,600	9.95	905
3–34	"	"	.0090	16,000	6,500	895	1,600	.30	10,600	10.20	895
3–49	"	"	.0120	15,400	5,000	902	1,710	.31	8,100	9.90	
3–31	"	"	.0120	13,100	6,200	980	1,760	.32	9,100	10.03	885
3–43	"	"	.0196	12,900	5,500	1,165	2,180	.40	10,200	9.85	895
3–48	"	"	.0080	12,600	5,500	955	1,850	.29	9,300	9.70	
3–36	"	"	.0150	12,250	6,000	953	1,830	.33	9,000	10.16	875
3–40	"	"	.0110	12,000	9,000	1,240	2,500	.36	10,100	9.70	895
3–47	"	"	.0080	11,900	8,000	1,190	2,120	.35	9,000	10.05	900
3–50	"	"	.0099	11,600	5,000	995	1,940	.30	9,000	9.70	
3–41	"	"	.0095	11,250	4,500	1,155	2,180	.40	10,000	10.00	895
3–30	"	"	.0090	11,050	5,500					9.94	
3–45	"	"	.0080	10,500	9,000	1,470	2,640	.40	10,600	9.87	895
3–37	"	"	.0450	8,050	4,500	1,255	2,000	.40	9,500	10.30	885
Avg.	"	"	.0125	12,950	6,550	1,060	1,990	.34	9,940	9.96	894
Avg. for Resist.	Iron melted in Furnace		.1000	1,965	3,930					13.53	
3C01	.05% C.ad'd	Vacuum	.0130	8,600	6,000	1,405	2,300	.40	10,000	10.24	895
3C02	.10% C. "	"	.0120	7,600	7,000	1,710	3,190	.50	10,700	10.64	895
3C03	.50% C. "	"	.1810	4,400	5,500	1,910				12.40	
1–21	Sw. Charc. Iron remlt'd in Vacuo		.0080	10,350	7,000	1,290	2,640	.48	11,200	10.30	
	Commercial Grades										
SwI-4	Sw. Charc. Iron cut from Plate		.1630	4,870	6,600	2,490	4,530	.95	8,000	10.57	
G 1 & 2	Standard Transformer Steel*			3,850	7,000	3,320	5,910	1.33	9,900	11.09	
H1 & 2	4% Silicon Steel*			3,400	4,300	2,260	3,030	.88	5,400	51.15	

* Received manufacturer's standard anneal.

TABLE 13.

SUMMARY OF RESULT OF MECHANICAL TESTS.

Specimen No.	Carbon Content. %	A — AS FORGED: Stress at Yield Pt. lb. per sq. in.	A: Ultimate Strength lb. per sq. in.	A: Elong. % 1	A: Elong. % 2	A: Reduc'n of Area %	B — Annealed at 900° C. Cooled in 12 hrs. acc'd. to Straight Line.: Stress at Yield Pt. lb. per sq. in.	B: Ultimate Strength lb. per sq. in.	B: Elong. % 1	B: Elong. % 2	B: Reduc'n of Area %	C — Annealed at 900° C. Cooled in 24 hrs. acc'd. to log. curve exc. as noted.: Stress at Yield Pt. lb. per sq. in.	C: Ultimate Strength lb. per sq. in.	C: Elong. % 1	C: Elong. % 2	C: Reduc'n of Area %	D — Quenched in Brine from 1000° C. except as noted.: Stress of Yield Pt. lb. per sq. in.	D: Ultimate Strength lb. per sq. in.	D: Elong. % 1	D: Elong. % 2	D: Reduc'n of Area %	REMARKS
3-30	.0090	36,600	44,800		41	87.7																
3-31	.0120	69,100	70,500		20	82.8	20,700	35,500	30	60	89.5											
3-33		64,000	68,000		22	81.5												40,500	24	53	84.5	
3-34	.0090												34,300		47	61.1		55,500	14	32	83.1	
3-35												14,400	34,500		54	87.3		44,900	22	44	86.0	
3-36	.0150											20,100	37,500		52	77.0						
3-37	.0450																41,250	64,600	15	37	73.7	
3-38	.0104												35,150		56	85.5	37,400	45,500	17	42	86.1	
3-39	.0110	35,800	44,700		39	80.4						16,400	36,100		61	80.9						Column C: cooled in 48 hrs. acc'd. to straight line.
3-40	.0110	39,600	43,500		38	82.3		41,600		42	85.7											
3-41	.0095	62,200	65,500		26	83.8		40,200	18	53	85.1											
3-43	.0096						18,750	35,800	31	59	84.5											
3-45	.0080	51,400	55,500		32	85.8	15,000	39,400	27	40	88.0											
3-47	.0080						17,400	36,100	31	57	91.3						30,200	40,000	20	47	80.8	
																	15,500	35,400	27	45	36.6	← Quenched in liq. air.
3-48	.0080	45,600	51,800	12.0	36	86.4						15,300	35,800	23	42	73.2						Column C: cooled 900° to 200° C. in 24 hrs. acc'd. to str. line.
3-49	.0120	41,400	48,700	12.0	44	76.2						11,100	34,900	23	32	75.7						
3-50	.0099	38,200		12.5	35							19,300	35,800	28	45	86.5						
Avg.	.0125	48,390	54,800	12.2	33.3	83.0	17,960	38,100	27.4	51.8	87.4	16,100	35,500	24.7	48.6	78.4	36,280	50,170	18.6	42.5	82.4	
3 CO1	.0130						21,000	51,100	27	41	72.5						33,200	53,000	20	65	86.2	%Carbon added=.05
3 CO2	.0120						19,400	38,900	29	60	73.5						67,700	76,900	7	25	79.7	%Carbon added=.10
3 CO3	.1810						22,100	51,000	24	50	64.5											%Carbon added=.50
Sw.I-4	.1630		40,000		36	57.0																As cut from plate

1. Elongation before specimen has commenced to "neck." 2. Ultimate elongation.

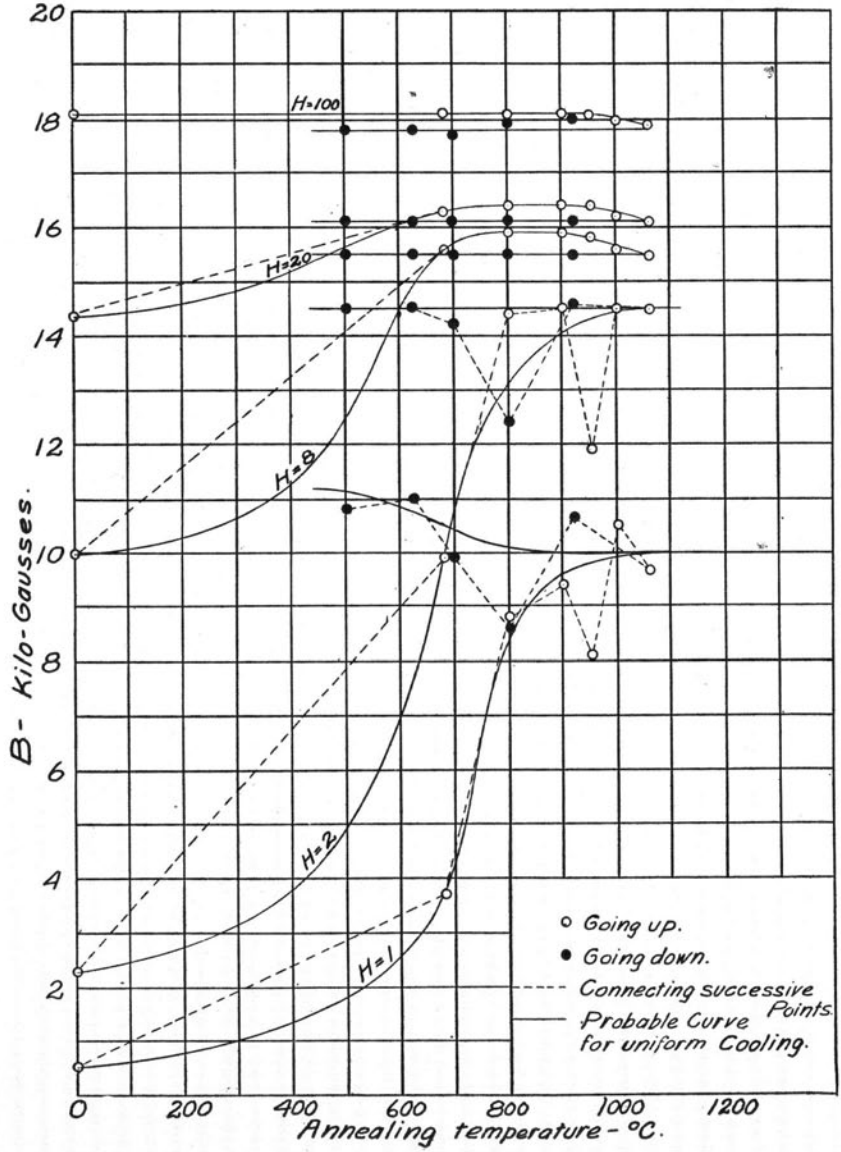

FIG. 3. ELECTROLYTIC IRON MELTED IN VACUO. EFFECT OF ANNEALING TEMPERATURE. ROD NO. 3-39.

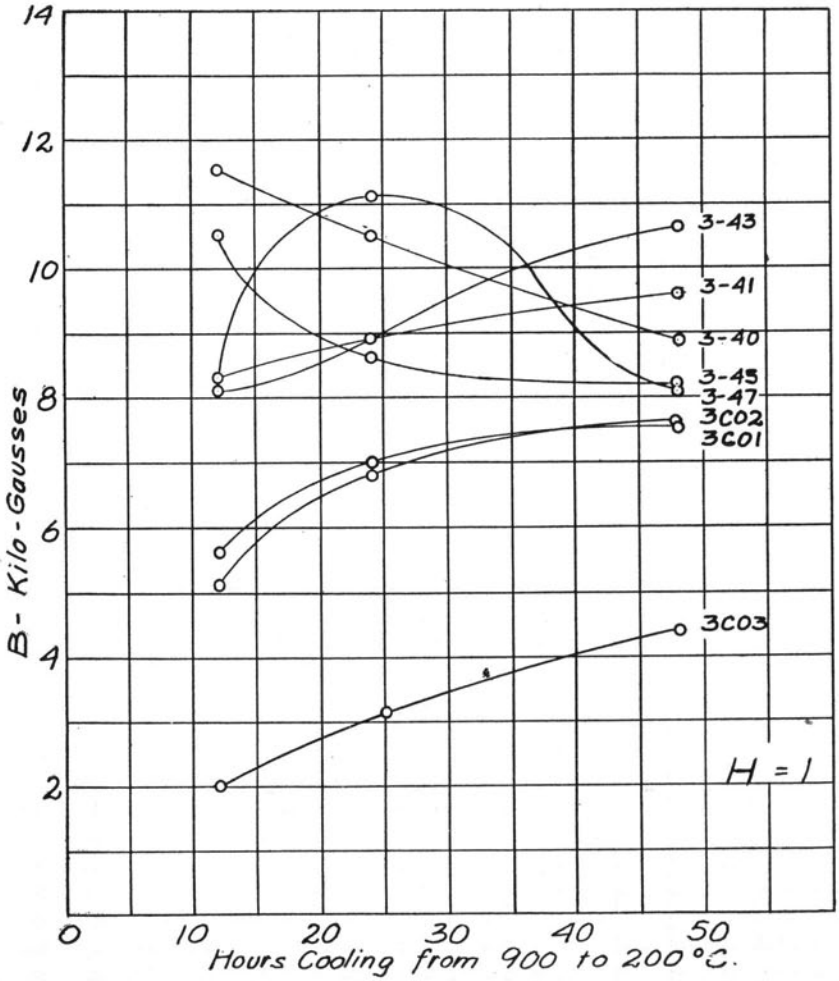

FIG. 4. ELECTROLYTIC IRON ANNEALED AT 900° C. IN CONTACT WITH RODS CONTAINING CARBON.

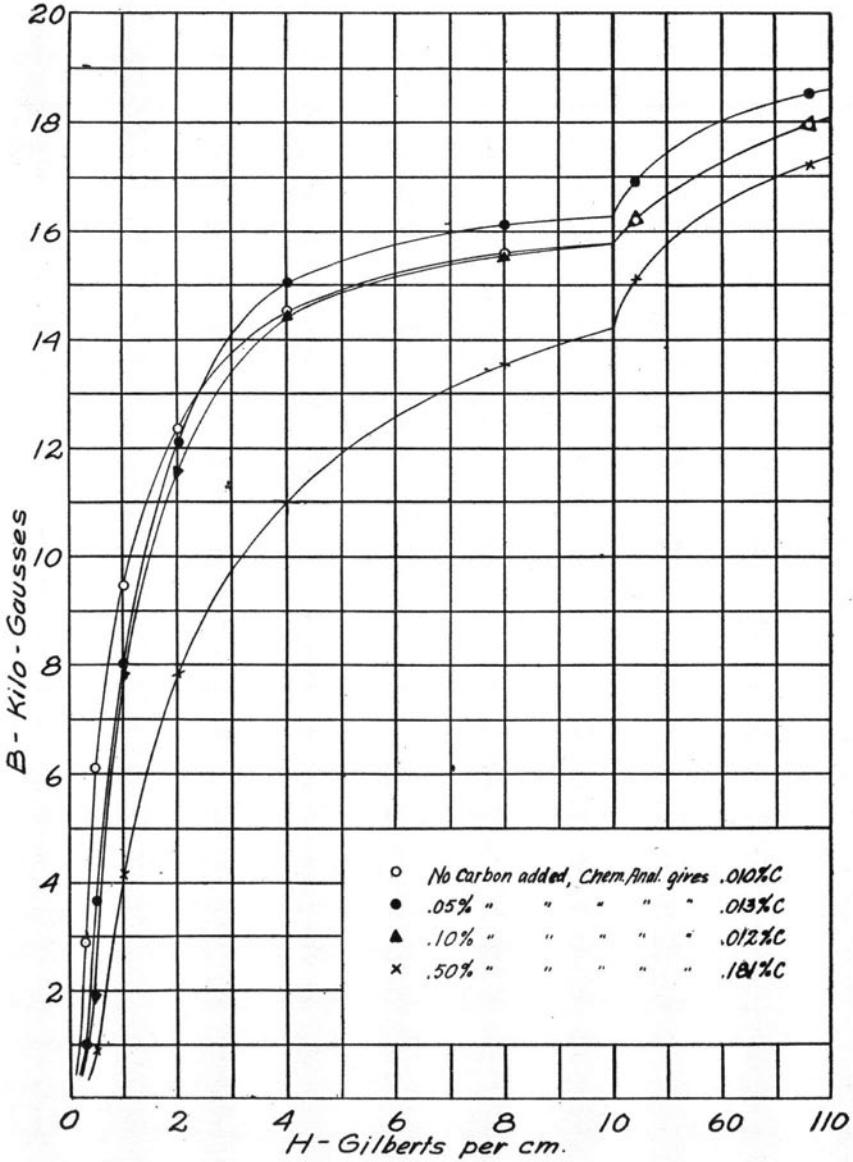

FIG. 5. ELECTROLYTIC IRON MELTED IN VACUO. EFFECT OF CARBON. ANNEALED AT 900° C.

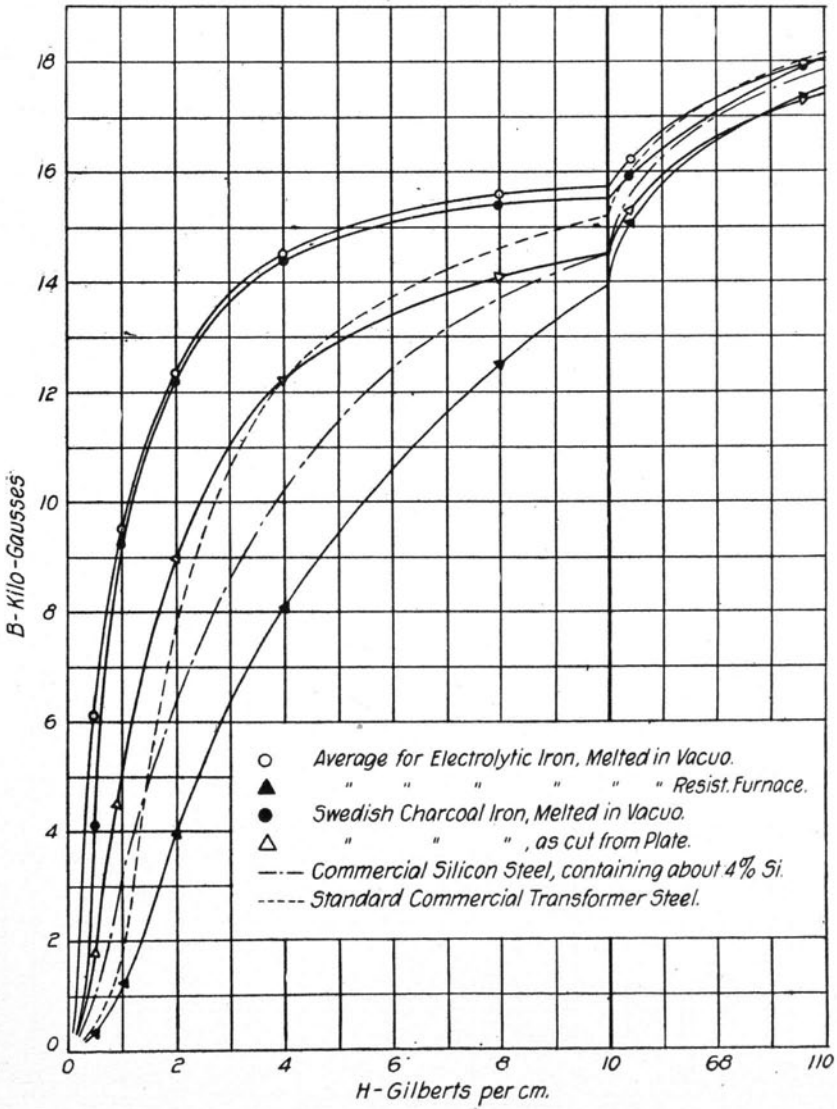

FIG. 6. MAGNETIZATION CURVES FOR DIFFERENT GRADES OF IRON.

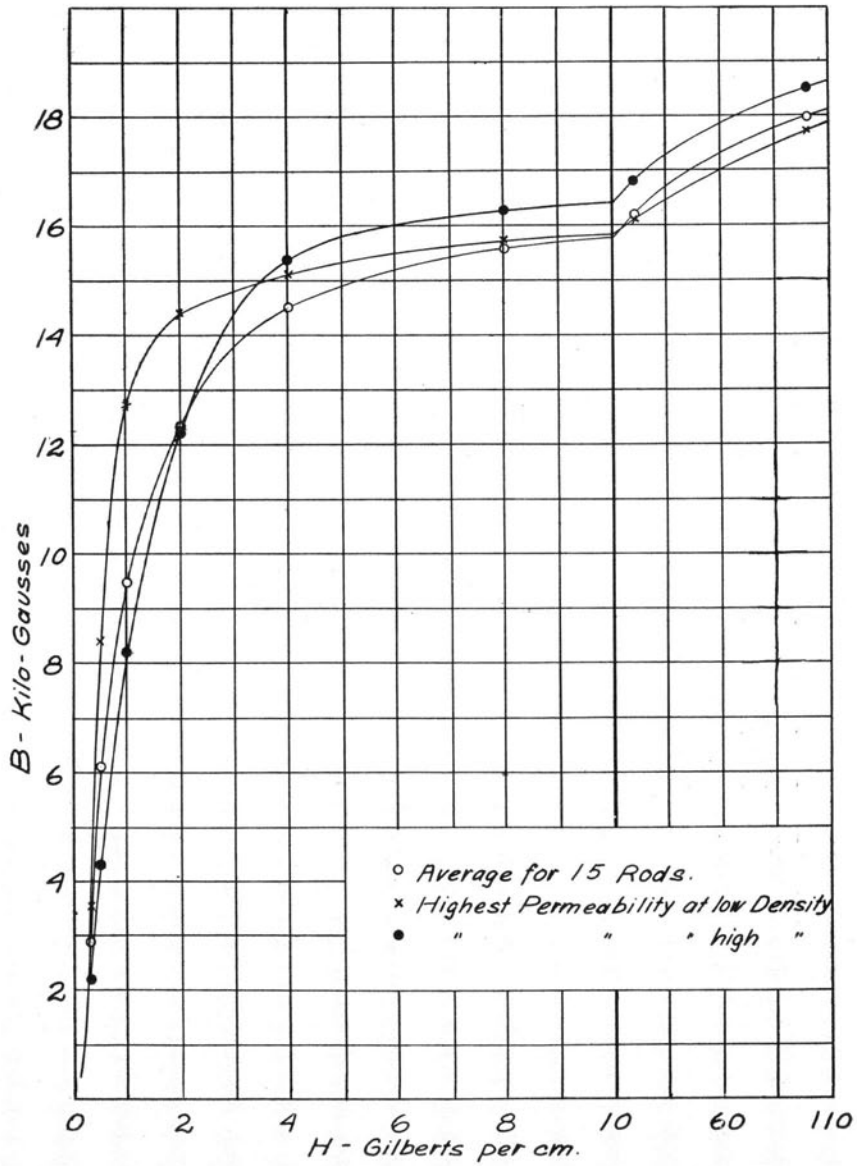

FIG. 7. ELECTROLYTIC IRON MELTED IN VACUO. ANNEALED AT 900° C. COOLED IN 48 HOURS.

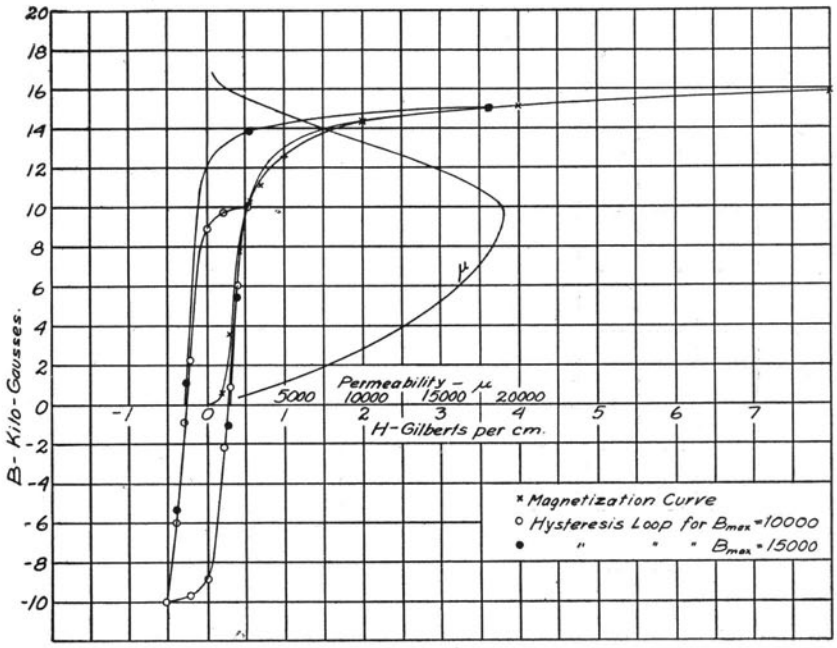

FIG. 8. ELECTROLYTIC IRON MELTED IN VACUO. ANNEALED AT 900° C. COOLED IN 48 HOURS. ROD NO. 3-38.

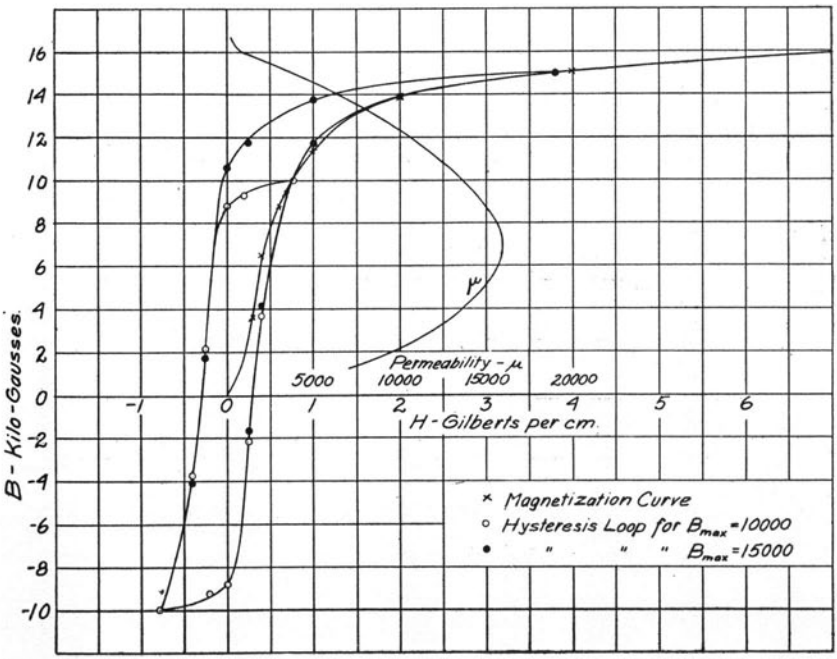

FIG. 9. ELECTROLYTIC IRON MELTED IN VACUO. ANNEALED AT 900° C. COOLED IN 48 HOURS. ROD NO. 3-34.

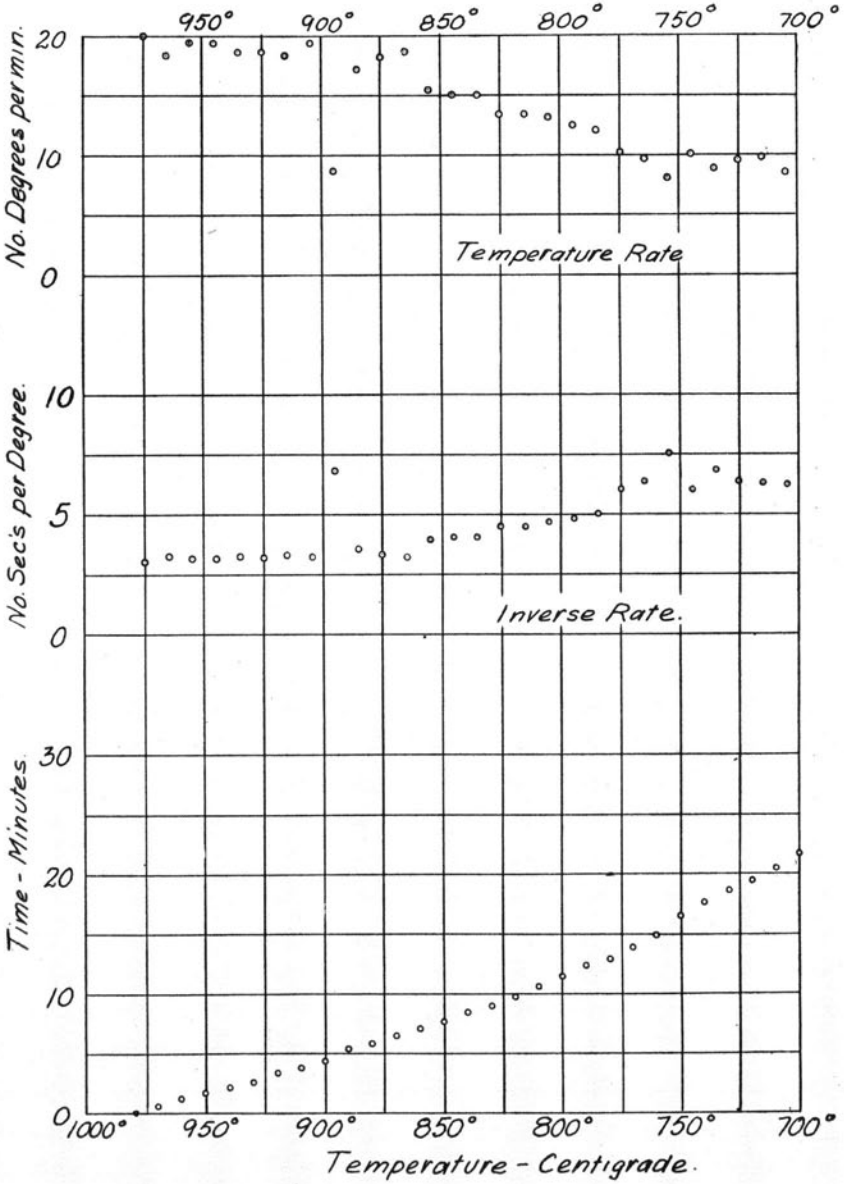

FIG. 10. COOLING CURVES FOR ELECTROLYTIC IRON MELTED IN VACUO. ROD NO. 3-43.

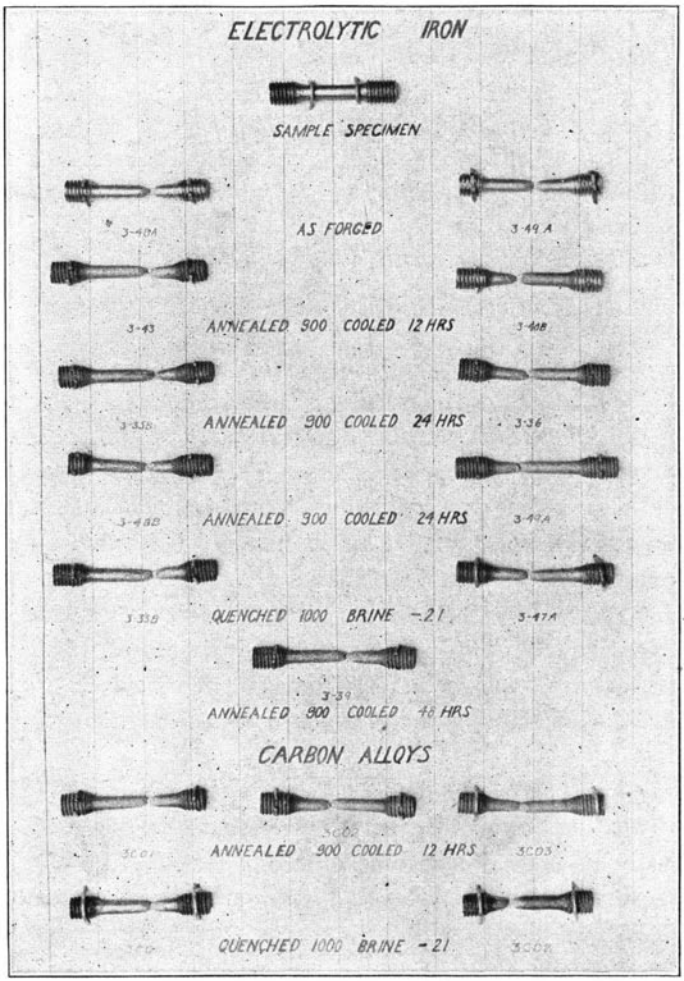

FIG. 11. A FEW MECHANICAL TEST PIECES.

As already mentioned, photomicrographs were obtained for nearly all rods after each heat treatment. Only a few of these will be exhibited here. Figs. 19-30 show the complete series for rod No. 3-39, as this rod was given a larger variety of heat treatments than any other rod. This series may be studied to advantage together with Table 6 and Fig. 3. Besides these photomicrographs for No. 3-39 a few for some of the other electrolytic iron rods melted in vacuo are shown. To show the effect of carbon there has been included an exhibit of the three iron-carbon alloys No. 3C01, No. 3C02, and No. 3C03. The difference between SWI-4 and No. 1-21, one being Swedish iron cut from the plate and the other after being melted in vacuo, is clearly shown in Figs. 43-45. Fig. 46 shows the structure of the electrolytic iron melted in the resistance furnace under atmospheric pressure.

V. Discussion of Results.

The results obtained may perhaps best be discussed by considering first the equilibrium diagram for iron-carbon alloys. Fig. 12 shows this diagram as represented by Rozenhain. This diagram should probably be modified somewhat in view of the recent researches upon the critical temperatures for pure iron. It has been shown for instance by Burgess and Crowe[501] in a bulletin just issued by the Bureau of Standards that the point F, usually called Ar_2, for pure iron is 768° C. Furthermore, it has been shown conclusively that the temperature at which pure iron changes from a ferromagnetic to a paramagnetic substance, or vice versa, is 785° C., thus showing that these two transformation points do not coincide.

Only that part of the diagram lying to the left of "I" will be considered here. From this diagram it is seen that after the iron has passed from the liquid state it exists in the form of a solid solution of iron and carbon, called austenite. When this solution cools it eventually reaches the line E-G-I, where ferrite crystals begin to be precipitated. Upon further cooling the solution, now enriched in carbon, passes downwards towards the right following E-G-I, more and more ferrite being precipitated. Finally, upon reaching the point I, the part of the solution still remaining, containing now 0.9 per cent carbon, is decomposed into cementite (Fe_3C) and ferrite, and the resulting mixture is called pearlite. At this temperature the iron consequently consists of pure ferrite crystals

with the spaces between the crystals filled up with a mixture of ferrite and cementite. One generally accepted theory states that iron has three different allotropic modifications, Alpha, Beta, and Gamma. Gamma iron is stable above the line E-G-I, Beta iron between E-G and G-F, and Alpha iron below G-F. It has been shown that iron in the Beta and Gamma modifications is weakly paramagnetic,* while Alpha iron

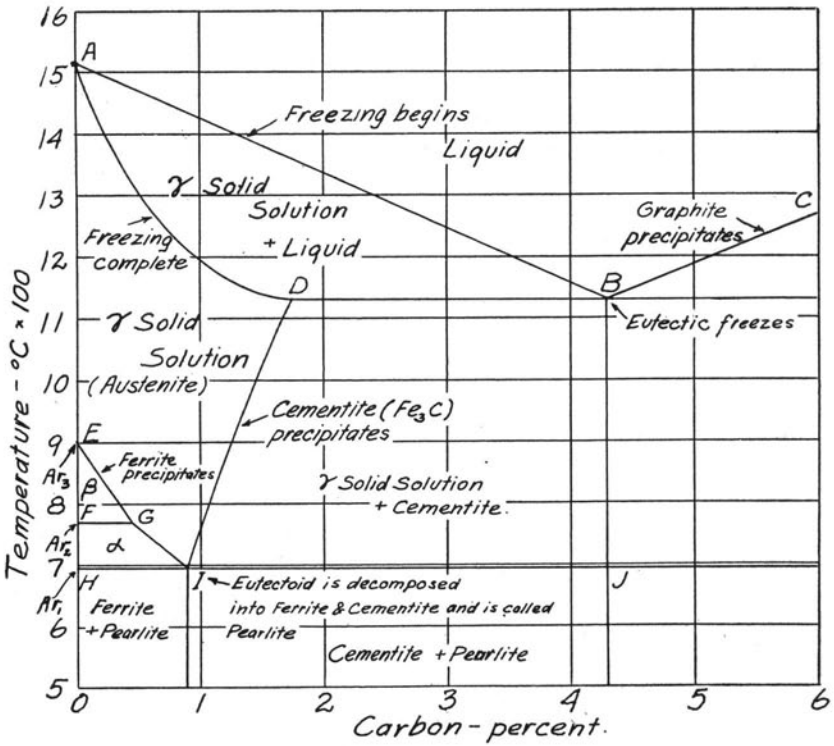

FIG. 12. IRON-CARBON EQUILIBRIUM DIAGRAM ACCORDING TO ROZENHAIN.

is ferromagnetic. Under certain conditions Beta and Gamma iron may exist to some extent below the boundaries given above. It is supposed, for instance, that if iron be cooled rapidly from a high temperature, Gamma and Beta iron may not have sufficient time to change into Alpha

*A paramagnetic substance is a substance capable of being magnetized in the same direction as that of the magnetizing force applied to it, in contradistinction to a diamagnetic substance, which, when placed in a magnetic field, is magnetized in the opposite direction to that of the field. A ferromagnetic substance is a paramagnetic substance whose permeability is of the same order as that of iron under ordinary conditions.

iron. If, however, such iron be reheated to above the line E-G-I and slowly cooled, the iron may ultimately all be obtained in the ferromagnetic Alpha modification. This theory is confirmed by the results obtained by Hadfield and Hopkinson[105], who found that the "specific magnetism" of iron-carbon alloys is decreased to a large but uncertain extent by quenching from a high temperature. Certain elements, carbon and manganese for example, when added to the iron assist in retaining the iron in the Gamma form. Thus Hadfield obtained an iron-manganese alloy whose permeability is nearly unity at ordinary temperatures.

Another factor which may influence the magnetic properties of iron is mechanical strain, due either to outside influence or to rapid cooling. It is not definitely known which is the more important, removing mechanical strain, or changing all the iron into Alpha iron, but it is certain that both are important and that both may be accomplished by proper annealing. It is well known that if subsequent to annealing the iron be mechanically strained, its magnetic quality is depreciated. The author noticed this while measuring a rod that had been slightly bent during the annealing process. Its permeability seemed, compared with previous measurements, to be unusually low. It was noticed that in clamping it in the permeameter it had been strained to some extent. It was then adjusted, so as to lessen the strain as far as possible, and the permeability was found to have increased materially. This fact helped to explain some rather puzzling results obtained in the course of the investigation. It also showed that, if the iron has not been strained beyond a certain point the effect of the strain is only temporary.

With the above explanations and facts in mind the results given in the previous part of the bulletin will now be considered.

It is at once apparent from Table 12 and Fig. 6 that melting electrolytic iron, or low carbon iron in general, in an atmosphere of carbon monoxide gases under atmospheric pressure gives the iron an opportunity to absorb carbon, the amount absorbed varying from 0.05 to 0.15 per cent. This result is in agreement with the experiments of Burgess and Aston referred to in the introduction. It is furthermore seen that carbon is not the only factor that affects the magnetic properties of iron. Swedish charcoal iron SWI-4 with a carbon content of 0.163 per cent and No. 3C03, an electrolytic iron-carbon alloy melted in vacuo, with a carbon content of 0.181 per cent, both have a decidedly higher permeability than the electrolytic iron melted in the resistance furnace, although the latter has an average carbon content of only 0.10 per cent. Again, the

electrical resistance of the resistance furnace iron is 13.52 microhms, while that of SWI-4 and No. 3C03 is 10.57 and 12.40 microhms respectively. The carbon content of 0.1 per cent does not by itself account for a resistance of 13.52 microhms. According to Barrett[19] this resistance corresponds to a carbon content of 0.6 per cent. As carbon is probably absorbed from CO by the reversible reaction

$$Fe + CO \rightleftarrows C + FeO$$

it seems natural to assume that not only carbon, but also iron oxide has been absorbed by the iron. In that case the result would be an alloy of ferrite, cementite (Fe_3C) and iron oxide (FeO). For a carbon content of 0.1 per cent, the alloy would contain 1.5 per cent Fe_3C, and 0.59 per cent FeO. While cementite is slightly ferromagnetic as shown by Hadfield and Hopkinson[105], FeO is weakly paramagnetic, and a very poor conductor of electricity. With these two substances interspersed among the ferrite crystals the low permeability and high resistance can be satisfactorily explained. From a further study of Fig. 6 and Table 12 it is seen that the Swedish charcoal iron has lost nearly all of its carbon by being melted in vacuo, the carbon content of the final iron being only .008 per cent. At the same time its electrical resistance has been lowered and its magnetic permeability considerably increased. Similarly, the three iron-carbon alloys melted in vacuo have lost the larger portion of the carbon added to them. While the additions amounted to .05, .10 and .50 per cent, respectively, the chemical analysis of the final iron shows a carbon content of .013, .012 and .181 per cent. If to the former figures is added the carbon content of the electrolytic iron as deposited, namely, .006 per cent, the loss of carbon is found to be 76.8, 88.5 and 64.4 per cent respectively. The corresponding loss for the Swedish iron was 95 per cent. It has been demonstrated by the Bureau of Standards[501] that such a loss occurs by melting electrolytic iron in vacuo, the loss found being in one case 67 per cent, in another case 87.5 per cent.

In the present case the electrolytic iron melted in vacuo not only did not lose any carbon, but actually gained a slight amount. In order to explain this apparent discrepancy it should be mentioned that the pressure used by the Bureau of Standards in their vacuum furnace was .01 mm. of mercury, while the pressure used by the author was from 2 to 5 mm. Based upon the facts above enumerated the following explanation is now offered: Any oxygen left in the furnace combines with the carbon of the heating element and forms carbon monoxide (CO). This gas, as already stated in connection with the results obtained

with the resistance furnace, reacts with the iron according to the reversible equation

$$Fe + CO \rightleftarrows FeO + C,$$

until equilibrium is established. If now the pressure in the furnace be lowered the reaction will take place from right to left; that is, any FeO that may be present will be reduced by the carbon in the iron with the result that the carbon content will be decreased, until equilibrium is restored. Conversely, with an increase of pressure due to an admission of oxygen, the reaction will take place from left to right, and the carbon content, as well as the FeO, of the iron will be increased. Upon this hypothesis the difference between the carbon content obtained by the Bureau of Standards and that obtained by the author is immediately explained. The final carbon content in any particular case, besides depending upon the pressure, will, according to this hypothesis, depend upon the relative amounts of carbon and iron oxide present; it will probably also depend upon the length of time the iron is kept in the molten state.

The changes in the structure of the Swedish iron are very well illustrated by the photomicrographs shown in Figs. 43-45. Fig. 43 shows the nonhomogeneous Swedish iron as rolled. The dark spots are probably partly slag and partly pearlite, shown to a higher magnification in Fig. 44. Fig. 45 shows the iron after being melted in vacuo, being perfectly homogeneous and without any sign of pearlite. Figs. 37 to 42 show the structures of the iron-carbon alloys No. 3C01, No. 3C02 and No. 3C03, verifying in general the chemical analysis as to carbon content. However, Fig. 5 and Table 10 show that the electrical resistance and magnetic permeability for No. 3C01 and No. 3C02 are not strictly in accordance with the chemical analysis. From the latter, No. 3C01 and No. 3C02 are approximately alike, while the electrical and magnetic tests indicate that No. 3C02 should have a higher carbon content than No. 3C01. It is difficult to explain why this discrepancy should exist, as the analysis for No. 3C02 was repeated four times, each giving results that agree quite closely.

The effect of annealing at different temperatures is shown in Tables 5 and 6 and graphically in Fig. 3. From the figure it is seen that the permeability increases as the annealing temperature is raised, at first slowly, and then very rapidly as the temperatures are raised from 700° to 800° C. Above 900° C. some uncertainty appears. The permeability

is decreased for 950° and again increased for 1,000° C. Whether this result is due to mechanical strain in clamping the rod in the permeameter or whether it is due to different rates of cooling or to some other cause, the author is not prepared to say. From the experience previously related it seems most probable that the drop for 950° is due to mechanical straining, as it occurs for low values of H only. The experiments of Terry[226] show that 1,100° is the most favorable annealing temperature for pure iron. While the results shown in Fig. 3 are not conclusive in themselves, they help to confirm the results obtained by Terry. Another interesting point is shown in Fig. 3. For values of $H = 8$ or above, the permeability is decreased by annealing at temperatures above 900° C. and does not return to the higher value by further annealing at lower temperatures. Furthermore, upon annealing successively at decreasingly lower temperatures the permeability is increased for low values of H. Such a process is, of course, equivalent to annealing at the highest temperature and cooling at a slower rate than was used for each of the successive annealings. This assumption was verified by annealing at 900° C. and cooling, first in 24 hours, according to a logarithmic time-temperature curve, and finally in 48 hours according to a straight line connecting 900° and 200° C. As seen from Table 6 these treatments increased the permeability considerably for low values of H, but did not alter it for high values of H. Quenching from 1,000° C. in iced brine produced a decided magnetic hardening, but this hardening was again removed by reheating to 900° C. followed by slow cooling.

The results obtained with rod No. 3-39 are confirmed by those obtained with the three groups of rods made from electrolytic iron melted in vacuo. Thus, the rods of Group 2 (see Table 7) that were reheated to forging temperature, between 1,000° C. and 1,100° C., gave a decidedly lower permeability for high values of H than rods that had not been heated above 900° C. The same is shown by the results obtained for the rods of Group 4 after these rods had been annealed at 1,080° C., as seen in Table 9. While this table shows that the permeabiltiy for low values of H were not altered materially by such annealing, the rods of Group 2 as well as rod No. 3-39, that had been annealed above 1,000° C., include the best rods, magnetically, of the entire series.*

*Rod No. 3-37 belonging to Group 2 has an exceptionally low permeability, probably due to an accident somewhere in the process, as the chemical analysis shows that it contains .045 per cent carbon.

The results shown in Fig. 4, taken from Tables 8 and 10, appear somewhat puzzling. The rods represented in Fig. 4 were all annealed together in such a way as to come in intimate contact with each other, but no record was kept as to the relative location of each rod. However, it is not probable that they occupied the same relative position each time. It will be seen that after each heat-treatment the permeability of two or three rods is decidedly lower than it was previous to that heat-treatment, and while the permeability for two of the pure iron rods is constantly increasing and that for two others is constantly decreasing, the permeability for No. 3-47 is at first increased and then decreased. No such variation occurs for any other group of rods, and the only explanation that can be offered is that the only rod containing any appreciable amount of carbon, namely No. 3C03, which contains .181 per cent, has contaminated the two or three rods with which it came in contact during each heat-treatment.

Various other inconsistencies appear upon a close scrutiny of the tables and figures, but they are of less importance and do not affect the general results. These inconsistencies show, however, how difficult it is, even by using great care, to obtain uniform results with pure iron.

The summary for all the rods made from electrolytic iron melted in vacuo, as given in Table 11, includes the results as forged and after the 48-hour cooling from 900° C., whether this last heat-treatment gave the best result with regard to magnetic quality or not. The average values obtained from this table for all the 15 rods, including rod No. 3-37, which perhaps should have been thrown out, are therefore somewhat lower than may be expected for 15 rods treated under more favorable conditions. However, the magnetization curve plotted from these average values, as shown in Fig. 6, serves to indicate the place occupied by electrolytic vacuum iron in relation to other grades of iron. While the average curve for the electrolytic vacuum iron is the highest of those shown in Fig. 6, the curve for the Swedish charcoal iron remelted in vacuo is a close second, and these two curves are far above the curves for commercial iron used at present for magnetic purposes.

The maximum permeability for the average magnetization curve as obtained from Table 12 is 12,950 occurring at a flux density of 6,550 gausses, while the maximum obtained for the best rod of the series, No. 3-38, is 19,000 occurring at a flux density of 9,500 gausses. Terry gives 11,000 as the maximum permeability obtained for electro-

lytic iron as deposited, but it is not perfectly clear whether this permeability occurred at ordinary temperatures or in the neighborhood of 760° C., as he compares this maximum value obtained with those obtained by Morris and Wells, which occurred near the critical temperature, 785° C. However, it is believed that Terry's maximum occurred at room temperature after annealing at 1,100° C.

While high permeability is of interest for certain purposes, the characteristics of iron that are of special interest to the manufacturer and user of electrical machinery are hysteresis and eddy current losses, the latter depending, to a large extent, upon the electrical resistance of the iron. (See ref. 32 in Bibliography.)

From Table 12 the hysteresis loss for $B_{max} = 10{,}000$ is seen to be less than one-half as high for the average electrolytic vacuum iron as it is for the commercial silicon steel, while for $B_{max} = 15{,}000$, the corresponding figure is about two-thirds. The reason why the hysteresis loss for the vacuum iron is not even still lower compared with commercial iron is readily seen by looking at the figures for retentivity. (See also Figs. 8 and 9.) While the retentivity for $B_{max} = 15{,}000$ is 9,940 for the average electrolytic vacuum iron, it is only 5,400 for silicon steel. The hysteresis loss for Hadfield's best magnetic steels, the 2½ per cent silicon alloy and the 2¼ per cent aluminum alloy, as reported by Barrett, Brown and Hadfield[15-18], is 1,550 and 1,440 ergs per c.c. per cycle for $B_{max} = 9{,}000$. Comparing these results, it is seen that in spite of the high retentivity, the hysteresis loss for the electrolytic vacuum iron is much lower than for any material thus far produced of which the literature gives information. This is due to the low coercive force, namely, .34 gilberts per cm. being the average value for the 15 rods.

The specific electrical resistance for the average vacuum iron is 9.96 microhms. The resistance for the standard transformer steel is 11.09 microhms, while that for the silicon steel is 51.15 microhms. Thus the eddy current losses per unit volume, for the same thickness of sheet and for the same maximum flux density, would be much in favor of the silicon steel. However, it is definitely known that the resistance of the electrolytic vacuum iron can be raised by the addition of silicon or aluminum. What the effect of such additions upon the magnetic quality of the iron will be remains to be seen, but, judging from the effect they have upon commercial grades of iron, it seems probable that it will not be harmful.

While the photomicrographs are of interest primarily to show the structure of the electrolytic vacuum iron in general, and in what respect it differs from other grades of iron, certain conclusions as to the relation between the microstructures and the magnetic quality of the iron may be drawn. Considering the series for rod No. 3-39 it appears that there is no general growth in the size of the crystals. Annealing at 900° C. or above with subsequent slow cooling breaks the crystals up into smaller parts. Quenching from 1,000° C., this fine structure again gives way for larger crystals with indefinite boundaries, but the fine structure reappears upon subsequent annealing and slow cooling. The structure that seems to give the best magnetic quality is that shown in Figs. 27 and 30 for rod No. 3-39. This same structure is obtained for the best rod of the series, No. 3-38, and appears in Fig. 18, also for rod No. 3-43 in Fig. 35 and for No. 3-31 in Fig. 15.

The photomicrographs of the quenched specimens, Figs. 47 to 56, show that the structure of pure iron is not changed materially by quenching either in iced brine or in liquid air. The only specimen that has undergone a decided change is No. 3C03 that contains .181 per cent C. As quenched in iced brine, Figs. 50 and 51, this specimen exhibits a structure suggesting that some of the iron has been retained in the Beta and Gamma modifications. The dark crystals are probably martensite, the first transition stage in the decomposition of austenite. Fig. 55 shows the structure of No. 3C03 after quenching in liquid air. This structure is quite different from the one shown in Figs. 50 and 51, and the substance represented is probably austenite.

These results show that the changes in the properties of pure iron resulting from rapid cooling are not so much due to changes in the structure of the iron as to mechanical strains caused by such cooling. With a small carbon content, however, the changes in the properties of the iron due to rapid cooling may be partly attributed to the retention of the iron in the Beta and Gamma modifications, as shown by Figs. 50, 51 and 55.

The results of the critical temperature determinations show that the point Ar_3 (see Fig. 12) for the average electrolytic vacuum iron is 894°C, agreeing with the value found by the Bureau of Standards for pure iron.

Table 13 shows that magnetic and mechanical hardness go together and confirms further the results obtained by previous writers. It emphasizes the extreme mechanical softness of the electrolytic iron melted

in vacuo, particularly after annealing at 900° C. In comparing No. 3C01, No. 3C02, and No. 3C03 with the rest of the rods, it should be remembered that the actual carbon content of the former is .013, .012 and .181 per cent respectively.

While the results show some inconsistencies that cannot at present be satisfactorily explained, it should be borne in mind that the experiments have necessarily been made upon relatively small samples, that the processes involved in order to obtain the test pieces in the final condition are numerous, and that the magnetic properties are very readily affected by outside influences.

It is hoped that employing a vacuum furnace for annealing as well as for melting the iron will help to remove some of these inconsistencies.

VI. Summary and Conclusion.

The results recorded in the previous pages may be summarized as follows:

1. Pure iron melted in an atmosphere of carbon monoxide under atmospheric pressure will absorb both carbon and oxygen with the result that the iron thus produced is of an inferior magnetic quality.

2. Low carbon iron melted in vacuo will lose 50 to 90 per cent of its original carbon content.

3. The magnetic quality of electrolytic iron melted in vacuo is decidedly superior to any grade of iron thus far produced, the maximum permeability obtained being 19,000 at a flux density of 9,500 gausses. The average hysteresis loss obtained is less than 50 per cent of that found in the best grades of commercial transformer iron.

4. The specific electrical resistance of pure iron melted in vacuo is 9.96 microhms.

5. Swedish charcoal iron melted in vacuo has a magnetic quality approximating that of electrolytic iron melted in vacuo, chiefly due to the reduction of the carbon content.

From these facts it appears that a superior quality of iron for magnetic purposes may be obtained by melting electrolytic iron in vacuo. While the electrical resistance of the iron thus obtained is very low, this defect may be remedied by the addition of such alloying elements as silicon or aluminum, elements that are known to increase the electrical resistance very materially without affecting the magnetic quality to any

large extent. Experiments are now under way for determining the effect of such alloying elements, and the results will be published at some later date.

Whether iron melted in vacuo will ever become a commercial product depends, of course, upon whether any apparatus can be devised for producing such iron on a commercial scale at a cost that will not be prohibitive.

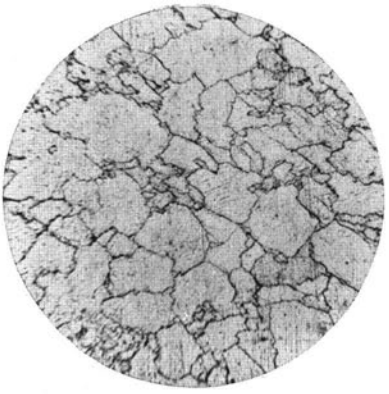

Fig. 13. 3-31A x 40.
As forged.

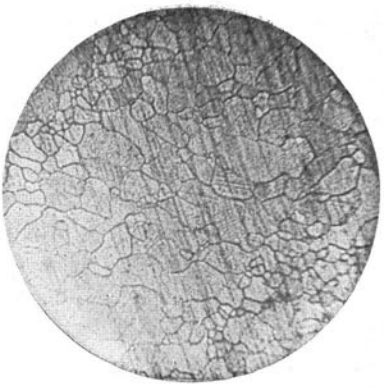

Fig. 14. 3-31F x 40.
Annealed at 950° C.

Fig. 15. 3-31K x 40.
Annealed at 900° C. Cooled in 48 hours.

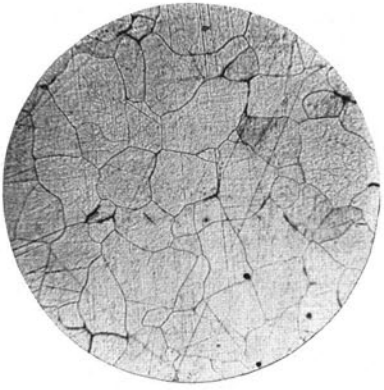

Fig. 16. 3-36 x 40.
Annealed at 900° C.

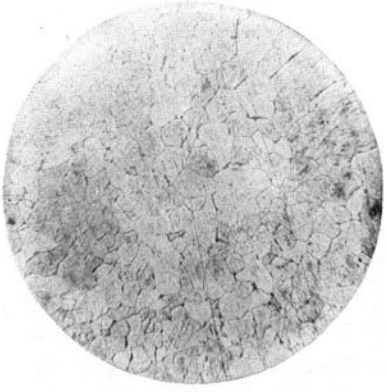

Fig. 17. 3-37 x 40.
Forged and reheated to 1,050° C.

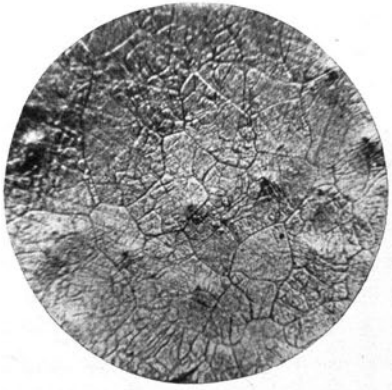

Fig. 18. 3-38 x 40.
Annealed at 900° C.

ELECTROLYTIC IRON, MELTED IN VACUO. SEE TABLES 5 AND 7.

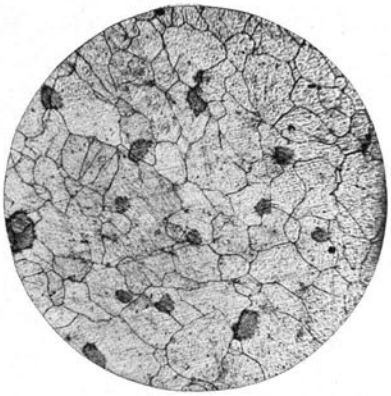

Fig. 19. 3-39A x 40.
As forged.

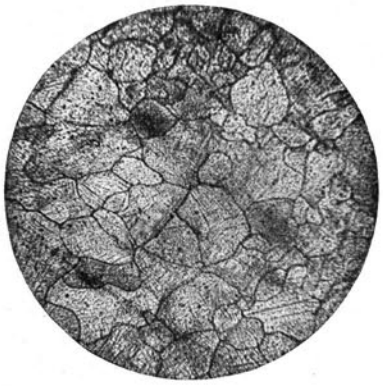

Fig. 20. 3-39B x 40.
Annealed at 680° C. Going up.

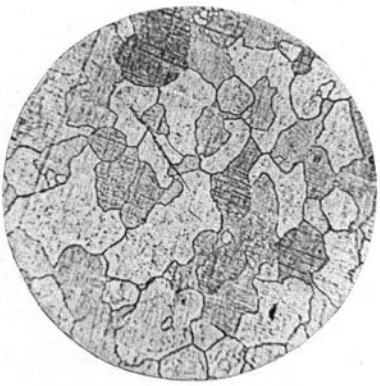

Fig. 21. 3-39D and E x 40.
Annealed at 900 and 950° C. Going up.

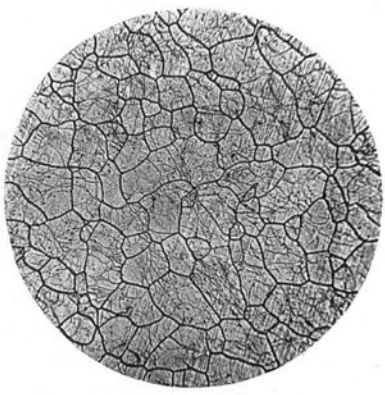

Fig. 22. 3-39F x 40.
Annealed at 1,000° C. Going up.

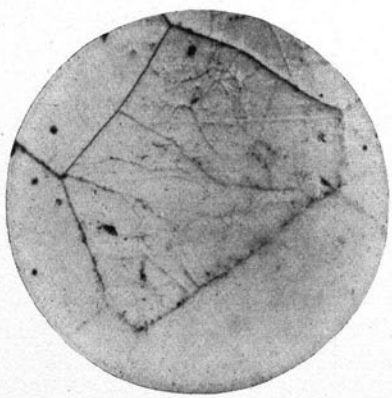

Fig. 23. 3-39F x 240.
Same as Fig. 22.

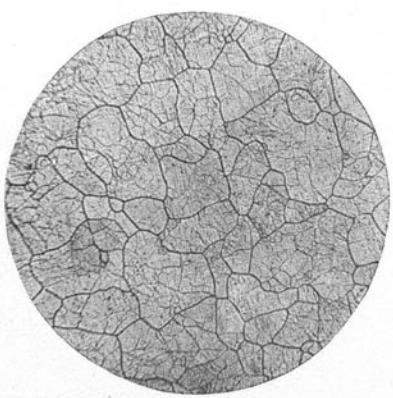

Fig. 24. 3-39G x 40.
Annealed at 1,060° C.

ELECTROLYTIC IRON, MELTED IN VACUO. SERIES FOR ROD NO. 3-39. SEE TABLE 6.

Fig. 25. 3-39H x 40.
Annealed at 912° C. Going down.

Fig. 26. 3-39J x 40.
Annealed at 800° C. Going down.

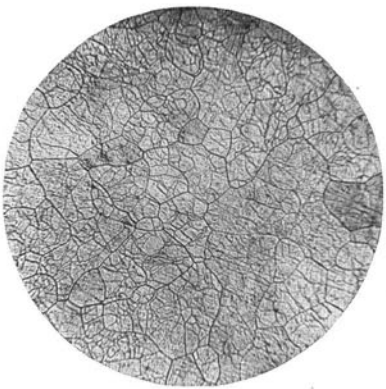

Fig. 27. 3-39L x 40.
Annealed at 616° C. Going down.

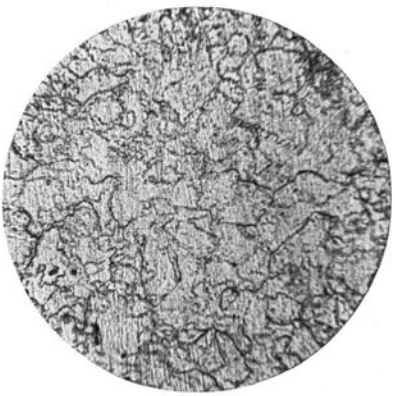

Fig. 28. 3-39O x 40.
Quenched in brine from 1,000° C.

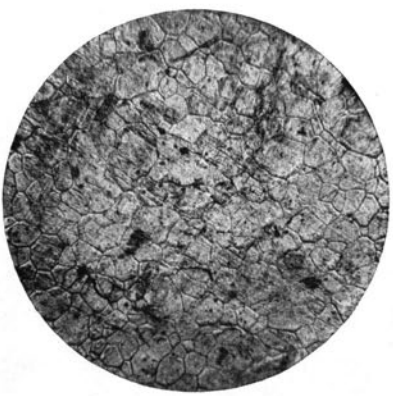

Fig. 29. 3-39Q x 40.
Annealed at 99° C. Cooled in 24 hours.

Fig. 30. 3-39S x 40.
Annealed at 900° C. Cooled in 48 hours.

ELECTROLYTIC IRON, MELTED IN VACUO. SERIES FOR ROD NO. 3-39. SEE TABLE 6.

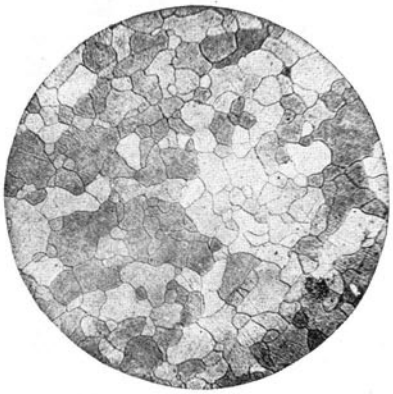

Fig. 31. 3-41 x 40.
Annealed at 900° C. Cooled in 12 hours.

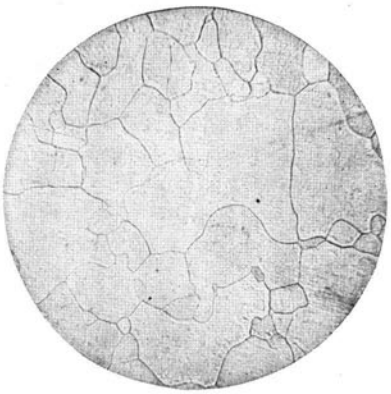

Fig. 32. 3-43 x 40.
Same treatment as Fig. 31.

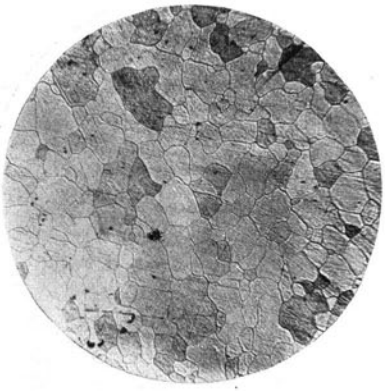

Fig. 33. 3-45 x 40.
Same treatment as Fig. 31.

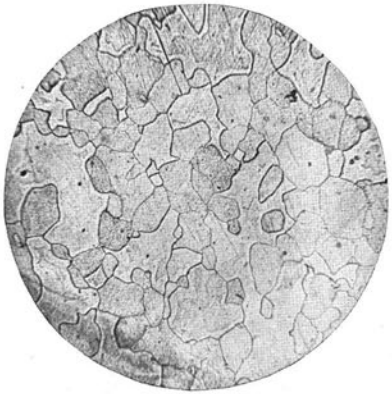

Fig. 34. 3-47 x 40.
Same treatment as Fig. 31.

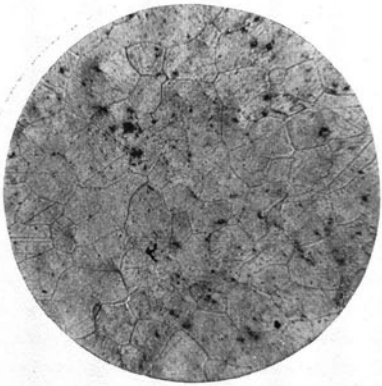

Fig. 35. 3-43 x 40.
Annealed at 900° C. Cooled in 48 hours.

Fig. 36. 3-45 x 40.
Same treatment as Fig. 35.

ELECTROLYTIC IRON MELTED IN VACUO. SEE TABLE 8.

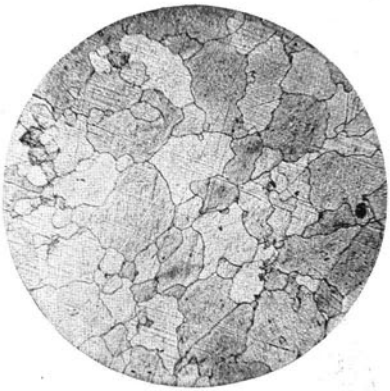

Fig. 37. 3C01 x 40.
As forged.

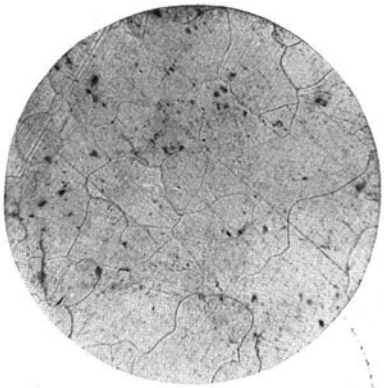

Fig. 38. 3C01 x 40.
Annealed at 900° C. Cooled in 48 hours.

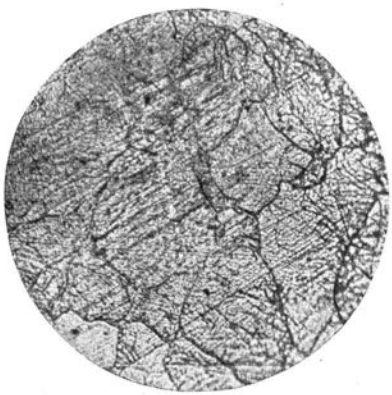

Fig. 39. 3C02 x 240.
As forged.

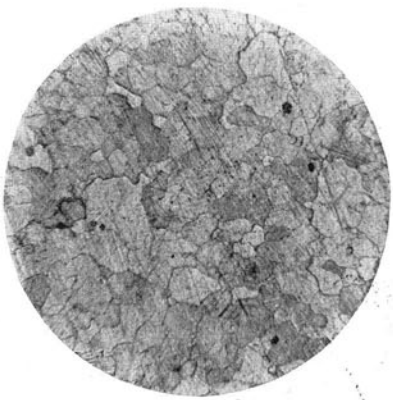

Fig. 40. 3C02 x 40.
Same treatment as Fig. 38.

Fig. 41. 3C03 x 240.
As forged.

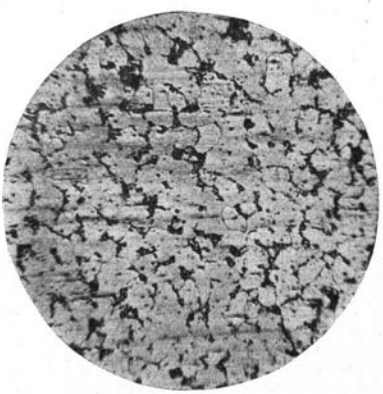

Fig. 42. 3C03 x 40.
Same treatment as Fig. 38.

ELECTROLYTIC IRON WITH CARBON ADDED, MELTED IN VACUO. SEE TABLE 10.
Carbon added: 3C01—.05%, 3C02—.10%, 3C03—.50%.
Carbon as per chemical analysis: 3C01—.013%, 3C02—.012%, 3C03—.181%.

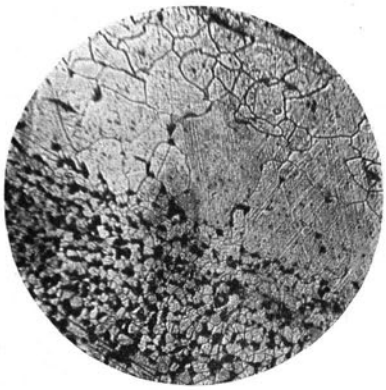

Fig. 43. SwI-4 x 40.
Annealed at 945° C.

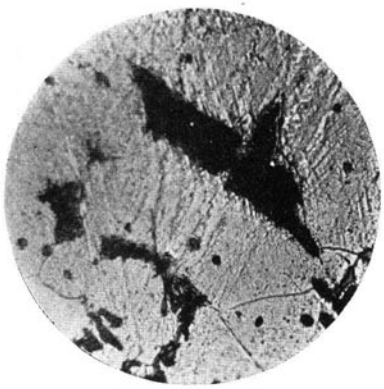

Fig. 44. SwI-4 x 240.
Same treatment as Fig. 43.

Swedish charcoal iron as cut from plate. Carbon content .163%.

Fig. 45. 1-21 x 40.
As forged.

Swedish charcoal iron remelted in vacuo. Carbon content .008%.

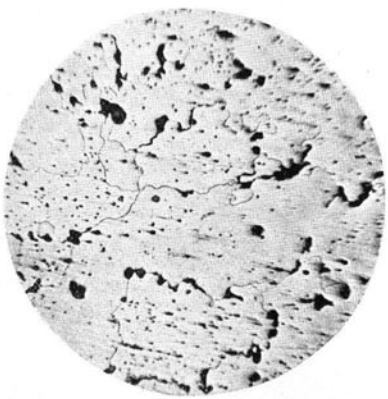

Fig. 46. 3-13 x 40.
Annealed at 900° C.

Electrolytic Iron melted in resistance furnace under atmospheric pressure. Carbon content .105%.

Fig. 47. 3-34 x 40.
Carbon content .009%.

Fig. 48. 3C01 x 40.
Carbon content .013%.

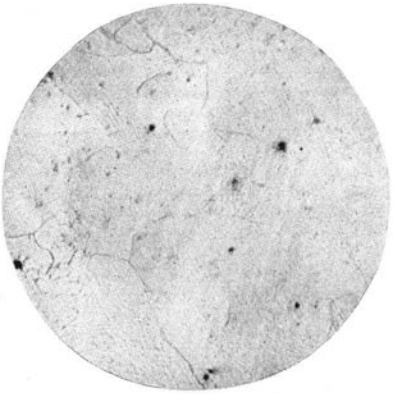

Fig. 49. 3C02 x 240.
Carbon content .012%.

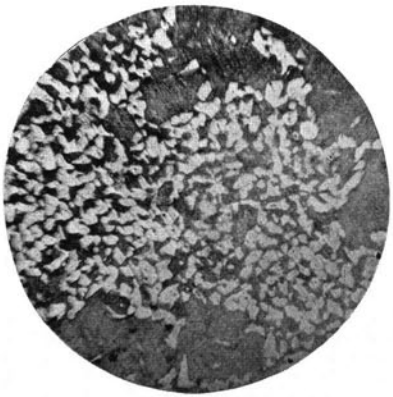

Fig. 50. 3C03 x 40.
Carbon content .181%.

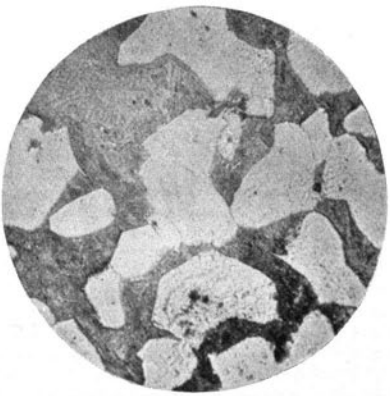

Fig. 51. 3C03 x 240.
Same as Fig. 49.

ELECTROLYTIC IRON WITH AND WITHOUT CARBON ADDED, MELTED IN VACUO.
QUENCHED FROM 1000° C. IN BRINE AT —21° C.

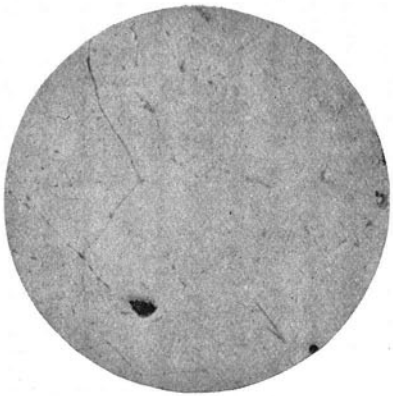

Fig. 52. 3-36 x 40.
Carbon content .015%.

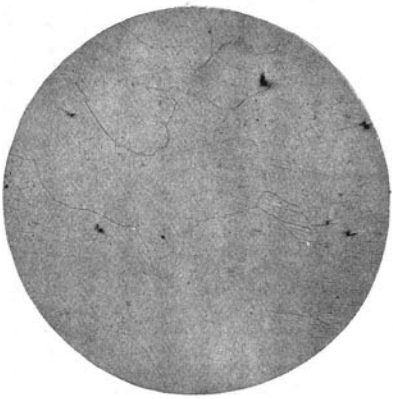

Fig. 53. 3-47 x 40.
Carbon content .008%.

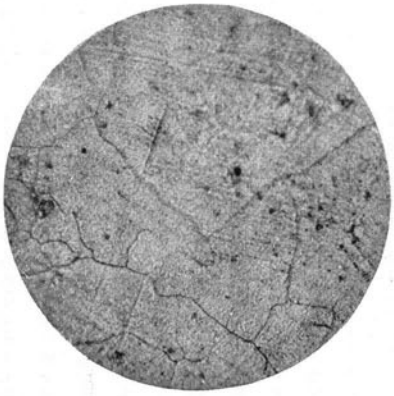

Fig. 54. 3C02 x 40.
Carbon content .012%.

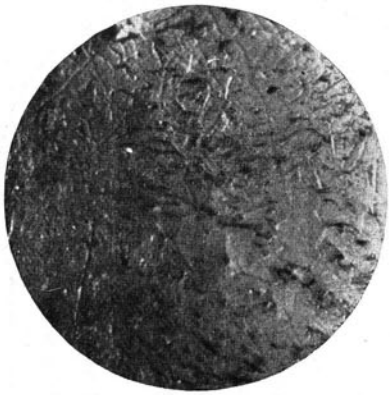

Fig. 55. 3-C03 x 240.
Carbon content .181%.

Fig. 56. 1-21 x 40.
Swedish charcoal iron, remelted in vacuo.
Carbon content .008%.

ALL SPECIMENS QUENCHED FROM 1000° C. IN LIQUID AIR.

APPENDIX I.

Crucibles and Arc Furnace.

The crucibles in which the electrolytic iron was melted were made from electrically fused magnesia, made in the arc furnace shown in Fig. 57. This furnace was the outcome of a series of experiments with different furnaces. It consists essentially of an iron shell 28″ (71 cm.) in diameter and 48″ (122 cm.) in height, placed upon an iron tray 60″ (152 cm.) in diameter. The top is provided with four 6″ (15 cm.) openings with iron covers. The lower electrode consists of an 8″ (20 cm.) round carbon block, hollowed out on the top and placed upon a layer of magnesia bricks. Into this block is screwed a 3″ (7.6 cm.) carbon rod that extends through the iron shell. The upper electrode consists or a 3″ (7.6 cm.) carbon rod capable of being raised or lowered by means of a rope and counterweight. The guides for the electrodes consist of iron pipes fastened to the iron shell by locknuts and insulated from the shell by asbestos washers.

The raw material used at first consisted of a product known as "native powdered magnesite," calcined at about 1000° C. Chemical analysis showed that it contains 4 per cent SiO_2 and 2 per cent Fe. The fused material contains 2 per cent SiO_2. Later, a purer product was used, obtained by precipitation. This product had not been calcined and was found upon analysis to contain .4 per cent SiO_2, 3 per cent Fe_2O_3 and Al_2O_3, and .179 per cent CaO. The fused magnesia from this product contains 1.0 per cent SiO_2.

The operation of the furnace was as follows: The shell was completely filled with the raw material. On account of its consistency it served as an excellent heat insulator, so that no other lining of the shell was needed. The arc was started by lowering the upper electrode until it touched the carbon block, the current being limited by means of a water rheostat. The electrode was then raised until the voltage across the arc was about 50 volts. As the magnesia fused it filled the hollow in the carbon block, and, being a good conductor of electricity in the fused state, the arc formed between it and the upper electrode. The latter consequently had to be raised gradually as more and more magnesia fused in order to maintain the voltage. As the arc was raised the magnesia gradually solidified but continued to act as a conductor.

During this operation fresh magnesite had to be supplied on account of the shrinkage. The "native powdered magnesite" shrank to about one-fourth, while the precipitated magnesite shrank to about one-tenth of the original volume. At the end of 10 to 12 hours the operation was completed, and the result was a core of fused magnesia, weighing 75 to 100 pounds (35 to 45 kg.), surrounded by sintered magnesia weighing 100 pounds or more.

Attending this furnace was by no means a pleasure. As fresh magnesite fell down into the arc an explosion would take place, forcing steam, CO_2, and other gases out of the furnace, accompanied by a cloud

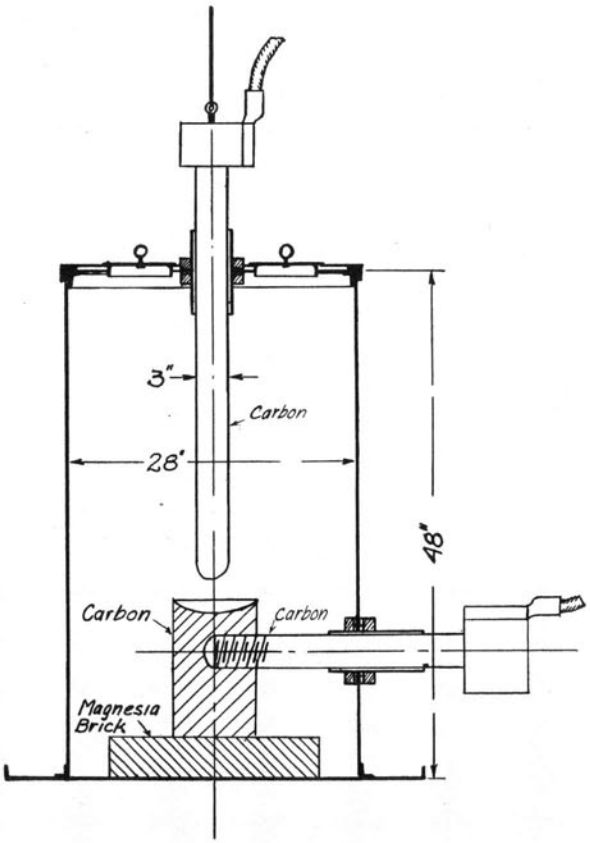

FIG. 57. ARC FURNACE FOR PRODUCING FUSED MAGNESIA.

of fine particles of magnesite. This was particularly true of the precipitated magnesite, and it would probably have been cheaper and easier to have calcined this material in some other way previous to fusing it in the arc furnace.

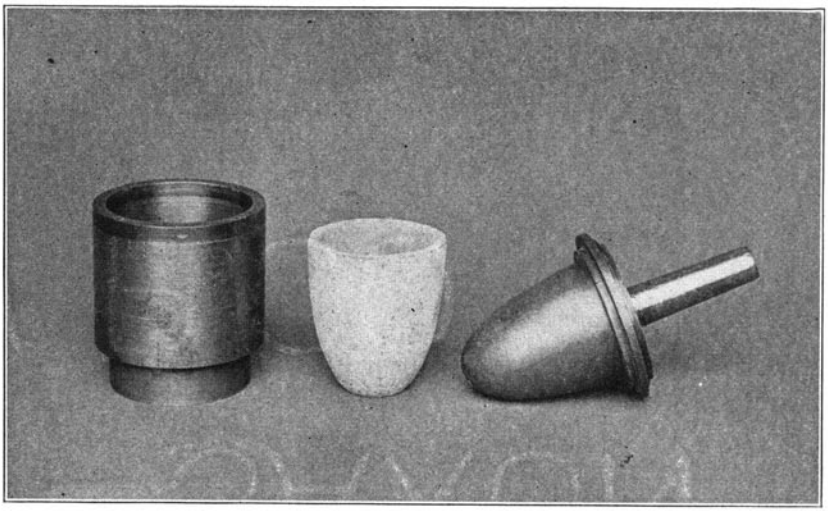

FIG. 58. FORM FOR MAKING CRUCIBLE AND FINISHED PRODUCT.

For making the crucibles the fused magnesia thus obtained was ground to go through a 40 mesh sieve. The binder used consisted of hydrated magnesia, made by mixing 600 grams "native powdered magnesite" with 1,000 c.c. water. This was placed in a stone mill that was kept going for twenty-four hours. Just a sufficient amount of this binder was used with the fused magnesia to make the mass moist. The crucibles were pressed in a steel form, shown in Fig 58, fitting into a hand operated press capable of exerting a pressure of 4,000 pounds. After being formed the crucibles were left to dry over steam pipes for a couple of days and were then baked in the electric furnace, shown in Fig. 62, at a temperature of 1,600 to 1,800° C. The finished product is shown in Fig. 58. If burned in a slightly oxidizing atmosphere the crucibles will come out perfectly white. They are strong mechanically and do not begin to show signs of softening below 1,800° C.

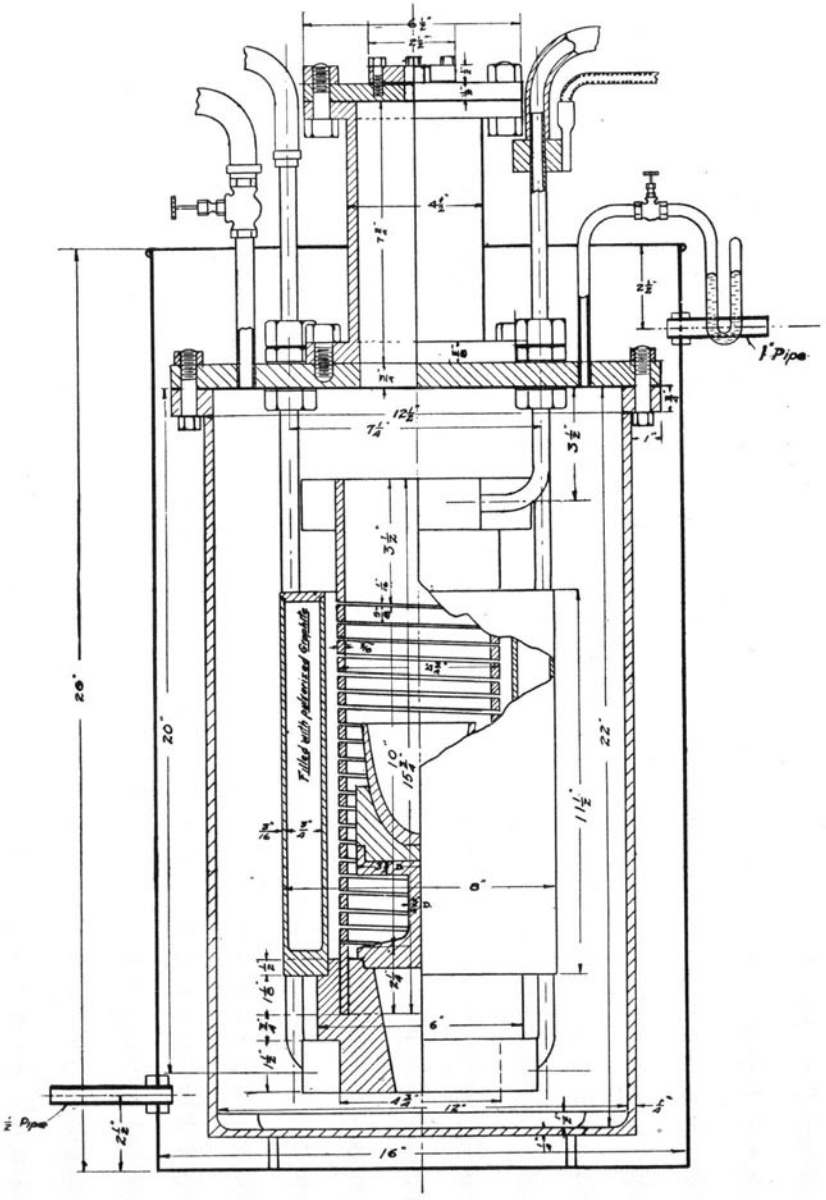

FIG. 59. VACUUM FURNACE.

APPENDIX II.

Vacuum Furnace.

The furnace described here was modeled after the vacuum furnace developed by W. C. Arsem, who presented a paper descriptive of this type of furnace before the American Electrochemical Society in 1906. The furnace as constructed by the author is illustrated in Figs. 59, 60 and 61. The vacuum tank was made from a 12″ (30 cm.) wrought iron pipe, with a ¼″ (.64 cm.) steel plate welded on at one end. A steel ring was shrunk around the top and the joint made airtight by means of a groove filled with molten lead. The cover was made from a ¾″ (1.9 cm.) steel plate and the dome from a 4″ (10 cm.) wrought iron pipe provided with flanges at each end. A mica window was placed in the top of the dome for the inspection of the charge during operation. As the furnace is submerged in water, all the joints were made airtight by means of rubber gaskets.

The heating element was cut from a solid 4¾″ (12 cm.) carbon electrode by first cutting a helical groove of the desired pitch and depth and then cutting out the core by means of a pipe provided with teeth on one end. Care had to be exercised to obtain a perfectly uniform cross-section. The radiation screen surrounding the helix was made from an 8″ (20 cm.) carbon electrode and filled with crushed graphite. Both the helix and the screen are supported at the lower end by a carbon base which in turn is supported by a water cooled copper tubing. This tubing is connected to the base by means of a cast iron clamp, and it serves both as a support for the heating part of the furnace and as a conductor for the current. It is clamped in place by two airtight insulating bushings in the cover. The upper end of the helix is similarly supported by another water cooled copper tubing connected to the helix through a cast iron clamp.

An ordinary mercury manometer was used to measure the pressure, as it was deemed unnecessary to reduce the pressure below .5 cm.

At first the furnace was submerged in ordinary water, but as direct current was used it was found that under these conditions the bushings were very badly attacked by electrolysis. Consequently, the furnace was placed in a tank filled with distilled water and this was kept cool by circulating water in the outside tank and also by means of cooling coils

placed on the top of the cover. With this arrangement the temperature of the distilled water seldom rose above 60° C.

The furnace was exhausted down to a pressure of 2 to 3 cm. by means of a water aspirator. The Geryck pump was then started and this reduced the pressure to .5 cm. or below.

With an input of 15 kw. the temperature in the crucible was raised to 1,600° C. in half an hour and could be maintained at that temperature with 12 kw. No instrument was used for measuring the temperature, as the melting of the iron could be observed through the window in the top of the dome.

The life of the helix heating element has been about 50 melts, each melt lasting approximately one hour with a temperature of 1,500° to 1,600° C. in the crucible. The temperature of the helix itself was, of course, much higher, possibly 2,000° C.

It was found that the helix gradually sagged and after a certain length of time the lower turns came close enough together to allow an arc to form. This arc increased the current so as to raise the drop between the next two turns sufficiently to cause an arc, and so on. In this way a dead short circuit took place. As after this length of time the helix had become partly disintegrated, any attempt to increase the distance between the turns resulted in a broken helix, and a new one had to be substituted. For this reason a different shaped heating element might be preferable, although the helix can be made quite cheaply for this size furnace. For larger sizes the helix form would probably be out of the question.

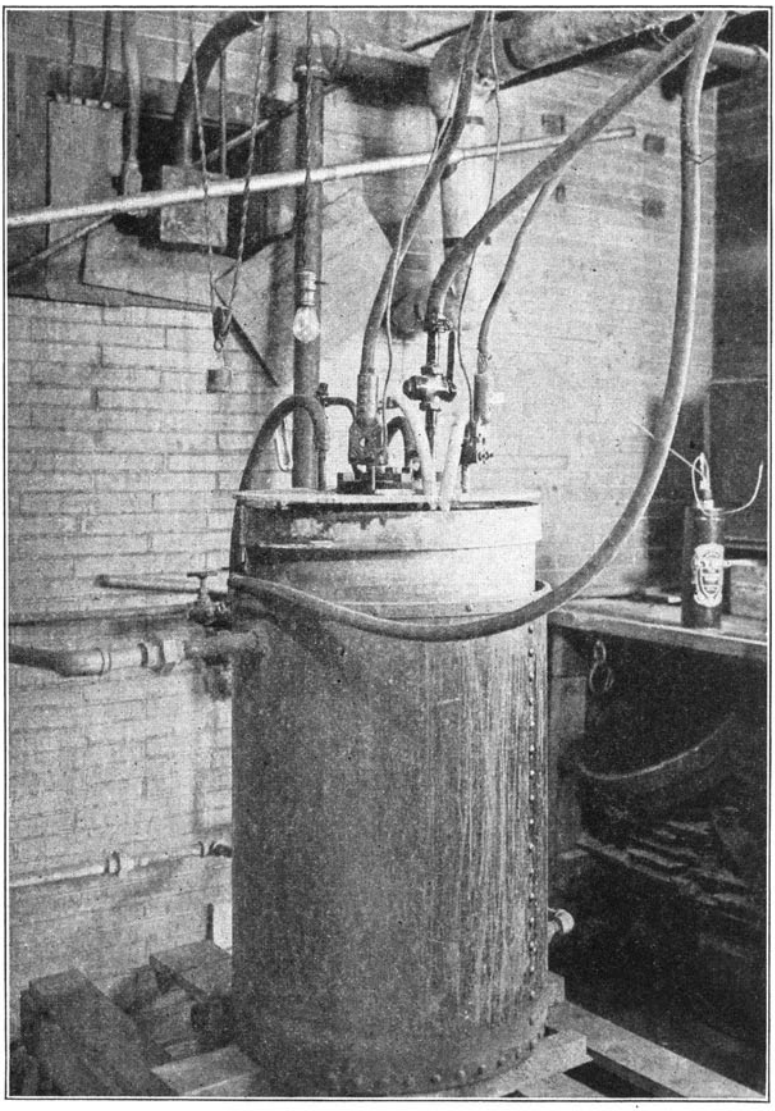

FIG. 60. VACUUM FURNACE.

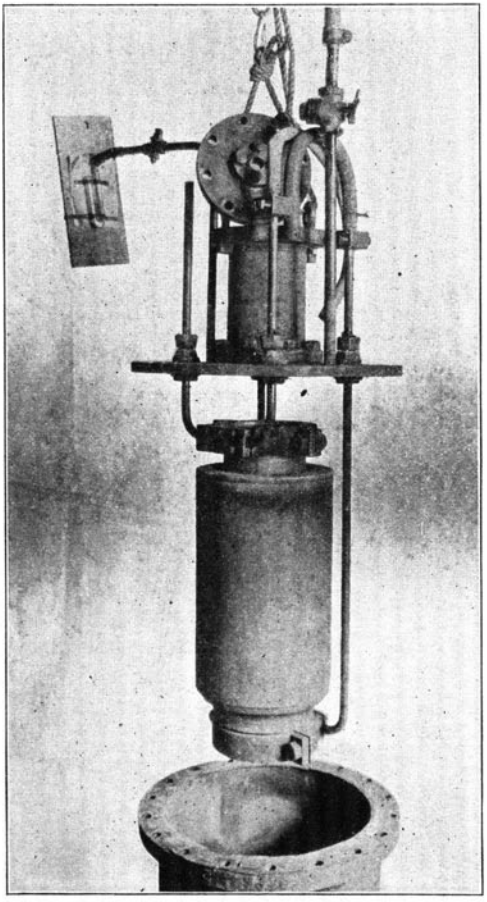

FIG. 61. CONSTRUCTION OF VACUUM FURNACE.

APPENDIX III.

Reheating Furnace.

For the annealing and quenching of the iron rods a resistance type furnace was used, modeled after the Hoskins carbon plate furnace. A photograph of the furnace is shown in Fig. 62. The lining of the furnace consists of one layer of magnesia brick next to the heating chamber and another layer of firebrick next to the iron shell. The heating element consists of carbon plates, ¼″ (.63 cm.) × 1⅝″ (4.13 cm.) × 8″ (20 cm.) arranged along the sides of the heating chamber. The two rows of plates are connected in parallel by means of 2″ (5 cm.) carbon plates, and 3″ (7.6 cm.) carbon electrodes are screwed into these end plates. The connections to the transformer consist of water cooled cast iron clamps and heavy copper cables. The pressure on the carbon plates can be varied by means of screws at each end. The furnace requires for its operation about 1,500 amperes at 25 volts. With this input the temperature will rise to 1,000° C. in 1½ hours. If the current is cut off at this temperature, the furnace will cool along a logarithmic temperature-time curve to 200° C. in about seven hours, depending somewhat upon the previous rate of heating. In most cases, however, slower cooling along definite temperature-time curves was necessary, and for this purpose the energy input was regulated either by varying the primary voltage of the transformer, or by varying the pressure on the carbon plates, or by varying both.

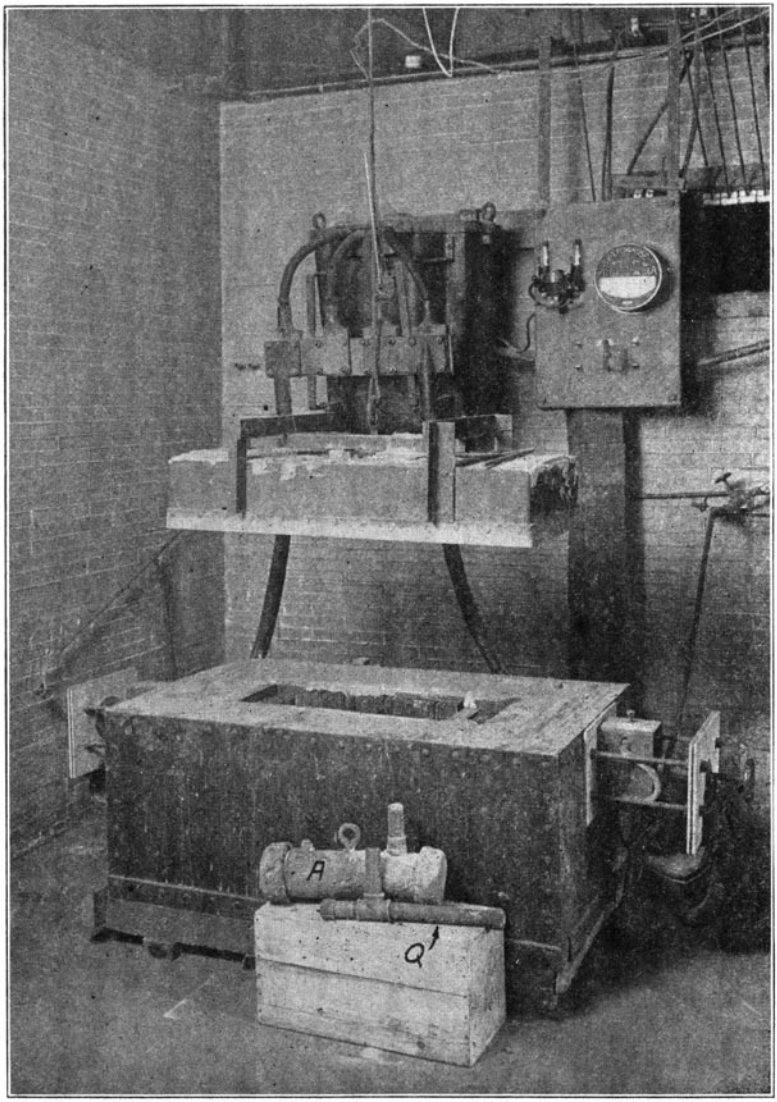

FIG. 62. ANNEALING FURNACE.

APPENDIX IV.

PERMEAMETER.

As the apparatus for measuring the magnetic properties is the one upon which the numerical accuracy of the results depend, this apparatus will be described in detail and the probable error in each measurement calculated. The method used is known as the compensated double bar and yoke method and is based upon the results obtained by the Bureau of Standards and described by Charles W. Burrows in Reprint No. 117. The apparatus as constructed by the author is shown in Fig. 63 drawn to scale. Two rods are used, of approximately the same magnetic and electrical quality, one of which is the rod to be measured and the other to be referred to as the auxiliary rod. The two rods are clamped together by means of split yokes made from Swedish charcoal iron, thoroughly annealed. Thus a complete magnetic circuit is established. The magnetizing coils T and A are wound on red fibre tubing and consist of No. 18 B. & S. double cotton covered copper wire, wound 20 turns per inch (7.875 turns per cm.) in 10 layers. The first layer was wound on a screw thread cut in the tube so as to make exactly 20 turns per inch, the next layer wound in the grooves of the first layer, and so on for all 10 layers. After completion the separate layers were connected in series. Four compensating coils, C, serve to overcome the demagnetizing effect of the yokes and the joints, and these coils were wound in the same manner as the two long coils. The secondary coils, *t*, *a* and *c* are also wound on fibre tubes, and each consists of 126 turns of No. 30 B. & S. double silk covered copper wire; *t* is the secondary of the main magnetizing coil T, *a* that of the auxiliary coil A, and *c* is divided into two halves, one at each end of T, directly under the compensating coils. After being wound these secondary coils were boiled in paraffin so as to insure perfect insulation.

For calibration purposes a mutual inductance M was constructed as shown in Fig. 67. It is wound on a cylinder of seasoned wood. The primary consists of No. 18 B. & S. double cotton covered copper wire and in order to insure uniformity the wire was laid in a screwthread of 20 threads per inch (7.875 threads per cm.). The secondary, *m*, consists of 1,260 turns of No. 30 double silk covered copper wire wound in 10 layers of 126 turns each, the layers being separated by layers of paraffin poured on in a molten state and turned down smooth.

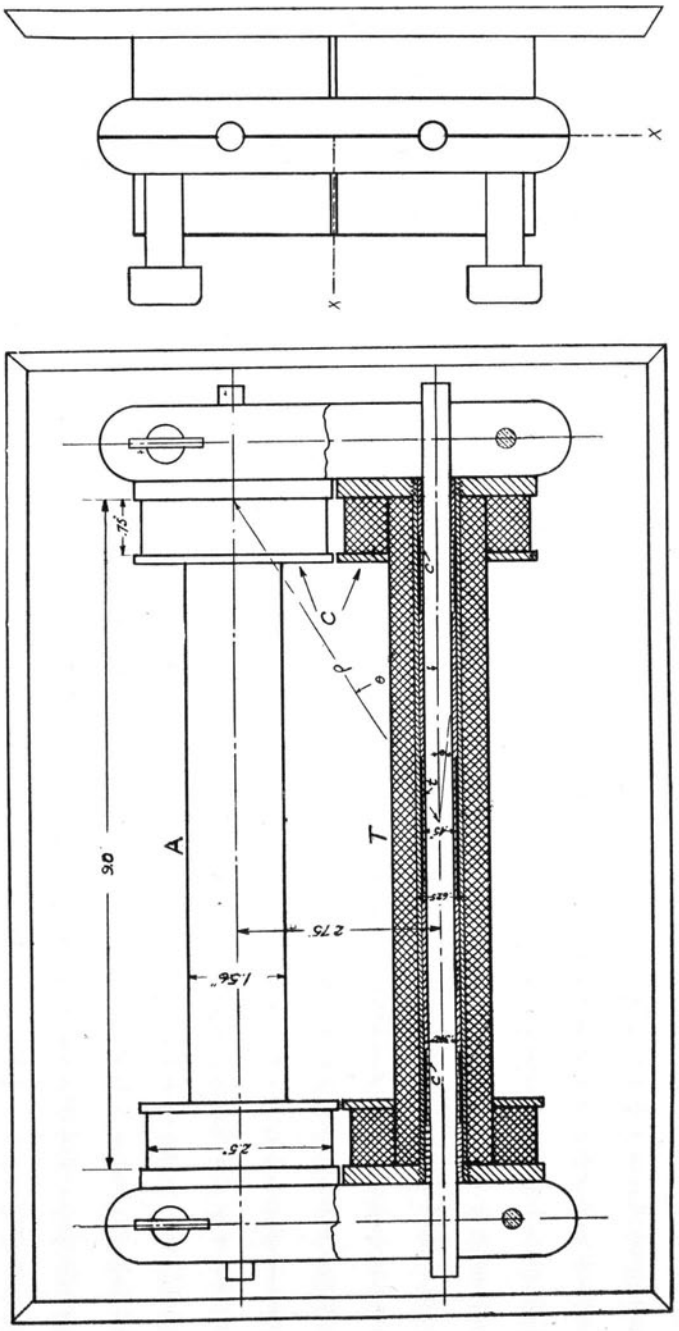

FIG. 63. PERMEAMETER.

The following notation will be used.

I_T, H_T = magnetizing current and magnetizing force for coil T.
I_A, H_A = magnetizing current and magnetizing force for coil A.
I_C, H_C = magnetizing current and magnetizing force for coil C.
I_M, H_M = magnetizing current and magnetizing force for coil M.
n_T = number of turns per cm. of coil T.
n_M = number of turns per cm. of coil M.
n_t = number of turns of coil *t*.
n_m = number of turns of coil *m*.
Φ_t = total flux threading coil *t*.
Φ_m = total flux threading coil *m*.

The principle upon which this method depends is that the true value of H for a certain section of the magnetic path can be obtained from the value of the magnetizing current in the coil for that section, provided, first, that this coil is wound with absolute uniformity, second, that the flux is absolutely uniform throughout that section, and third, that the end effects of the magnetizing coils are small. In that case

$$H = .4\pi\, n\, I.$$

The uniformity of the flux can be investigated by means of the three secondary coils, *t*, *a*, and *c*, see Fig. 64. With a fixed magnetizing current in T and the galvanometer switch connected at *ta*, the current in A can be adjusted until the galvanometer shows no deflection upon reversal of the currents. Since *t* and *a* are connected in opposition and contain the same number of turns, they must be threaded by the same flux. The sensitivity of the galvanometer, for this purpose, may be made a maximum by short-circuiting the resistence ω. In the same way the flux may be adjusted to equality at *t* and *c* by means of the current in the compensating coils C.

With the flux the same at *t*, *a*, and *c*, it is justifiable to assume that, for all practical purposes, it is the same throughout the magnetic path and in particular that it is the same throughout the rod to be measured. Then, with a magnetizing current of I_T amperes in T, the magnetizing force is

$$H_T = .4\pi n_T I_T \text{ gilberts per cm.}$$

provided the end effects of the coils may be neglected. These end effects will now be investigated with reference to the particular apparatus used.

The correction due to one end of the solenoid T, to be applied at the middle of the same, is*

$$\frac{1}{2} k_T = -\frac{1}{2} (1 - \cos \alpha) H_o \qquad (1)$$

*Burrows: Bull. Bur. of Stand., Vol. 6, No. 1, reprint 117.

where H_o is the magnetizing force due to an infinite solenoid and $\tan \alpha = \frac{2r}{l}$, r being the mean radius of the coil and l the length of the coil. Expanded (1) becomes

$$\frac{1}{2} k_T = -\frac{H_o}{2}\left[\frac{1}{2}\left(\frac{2r}{l}\right)^2 - \frac{3}{8}\left(\frac{2r}{l}\right)^4 + \frac{5}{16}\left(\frac{2r}{l}\right)^6 - \ldots\right] \quad (2)$$

Similarly the correction due to one end of solenoid A, to be applied along the axis of T at its center, for the same magnetizing force H_o, but opposite in direction, is

$$\frac{1}{2} k_A = +\frac{H_o}{2}\left[\frac{1}{2}\left(\frac{r}{\rho}\right)^2 P_1 - \frac{3}{8}\left(\frac{r}{\rho}\right)^4 P_3 + \frac{5}{16}\left(\frac{r}{\rho}\right)^6 P_5 \ldots\right] \quad (3)$$

where d = distance between the axis of the two coils, and P_1, P_3, P_5, etc., are the zonal harmonics of cos θ (see Fig. 63). The corrections to be applied at the center of T due to the compensating coils may be obtained from (2) and (3) by substituting the appropriate constants.

For the particular case under consideration the following constants apply:

For solenoids T and A.	For the compensating solenoids C. For the outer end	For the inner end
$r = 1.39$ cm.	$r_c = 2.62$ cm.	$r_c = 2.62$ cm.
$l = 22.8$ cm.	$l = 22.8$ cm.	$l_c = 18.6$ cm.
$d = 7.0$ cm.	$d = 7.0$ cm.	$d = 7.0$ cm.
$\theta = 31°.5$	$\theta = 31°.5$	$\theta_c = 37°.0$
$\rho = 13.4$ cm.	$\rho = 13.4$ cm.	$\rho_c = 11.65$ cm.

Substituting in (2) and (3), the correction due to the four ends of solenoids T and A is

$$2\left(\frac{1}{2}k_T + \frac{1}{2}k_A\right) = -H_o\left\{\left[\frac{1}{2}\left(\frac{1.39}{11.4}\right)^2 - \frac{3}{8}\left(\frac{1.39}{11.4}\right)^4 + \frac{5}{16}\left(\frac{1.39}{11.4}\right)^6 - \ldots\right]\right.$$
$$\left. -\left[\frac{1}{2}\left(\frac{1.39}{13.4}\right)^2 \cos\theta - \frac{3}{8}\left(\frac{1.39}{13.4}\right)^4\left(\frac{5}{2}\cos^3\theta - \frac{3}{2}\cos\theta\right) + \ldots\right]\right\}$$
$$= -H_o\left[.00365 - .0023\right]$$
$$= -.0027\, H_o$$

Substituting in (2) and (3), the correction due to the eight ends of the compensating coils, C, for the same current as in the main coil, T, is

$$2\left(\frac{1}{2}k_{c_1}+\frac{1}{2}k_{c_2}+\frac{1}{2}k_{c_3}+\frac{1}{2}k_{c_4}\right)=$$

$$+H_o\left\{\left[\frac{1}{2}\left(\frac{2.62}{9.3}\right)^2-\frac{3}{8}\left(\frac{2.62}{9.3}\right)^4+\cdots\right]-\left[\frac{1}{2}\left(\frac{2.62}{11.4}\right)^2-\frac{3}{8}\left(\frac{2.62}{11.4}\right)^4+..\right]\right.$$

$$-\left[\frac{1}{2}\left(\frac{2.62}{11.65}\right)^2\cos\theta_c-\frac{3}{8}\left(\frac{2.62}{11.65}\right)^4\left(\frac{5}{2}\cos^3\theta_c-\frac{3}{2}\cos\theta_c\right)+\cdots\right]$$

$$\left.+\left[\frac{1}{2}\left(\frac{2.62}{13.4}\right)^2\cos\theta-\frac{3}{8}\left(\frac{2.62}{13.4}\right)^4\left(\frac{5}{2}\cos^3\theta-\frac{3}{2}\cos\theta\right)+\cdots\right]\right\}$$

$$=+H_o\left[.03754-.02550+.01614-.02014\right]$$

$$=+.00804\,H_o$$

Consequently, the total correction due to the ends of all the coils, for the same current in all of them, is

$$k=(-.00270+.00804)\,H_o=+.00534\,H_o.$$

As it has been found by experience that for the highest permeabilities the compensating current may be 5 times as large as the main magnetizing current, the maximum correction to be applied is

$$k_{max}=(-.0027+.0402)\,H_o+.0377\,H_o.$$

From this result it is seen that for ordinary iron the values of H as obtained by the expression $H=.4\pi n_T I_T$ are correct within 1 per cent for all values of H, while for the highest permeability iron the errors in the values thus obtained vary from 4 per cent for low values of H to less than 1 per cent for values of H above 20 gilberts per cm. These corrections have not been applied to the values of H as given in the preceding account. From the data given for the magnetizing coils,

$$H=.4\pi\,n\,I$$
$$=.4\pi\times 78.75\,I$$
$$=99\,I$$

Thus H might be measured by means of an ordinary milliammeter by dividing the readings by 10 and deducting 1 per cent from the result. In order to avoid this correction and at the same time to yield greater accuracy for the main solenoid the following scheme was adopted:

The magnetizing force H_T for the rod to be tested was measured by the drop of potential across the shunt shown in Fig. 64. This shunt has three contacts so adjusted that if the first switch is closed the millivoltmeter reads 10 H_T, if switch No. 2 is closed it reads H_T directly, and if switch No. 3 is closed it reads $\frac{1}{4}$ H_T. Thus the error in reading H for $H_T=.5$ is $\pm .005$ or ± 1 per cent. The magnetizing force in coils A and

C are measured by milliammeters, as the accuracy of these readings are of less importance. All these meters have been calibrated against a Weston standard and corrections applied.

The flux density in the rod under test was at first measured by means of a Leeds and Northrup ballistic galvanometer whose period was adjusted to 15 seconds. This galvanometer was calibrated before every test by the mutual inductance previously referred to and shown in Fig. 67.

The inside diameter of the primary is 3.9″ (9.9 cm.) and the mean diameter $D_{av.} = 4.0''$ (10.025 cm.). In order to include the total flux inside of the secondary coil, the equivalent value of the diameter at which the magnetizing current may be considered concentrated is found to be

$$D_{eq.} = \sqrt{D_{av.}^{2} - \left(\frac{d}{2}\right)^{2}}$$

where d = radius of the primary wire = .127 cm. Substituting numerical values, $D_{eq.} = \sqrt{10.025^{2} - .064^{2}} = 10.025$ —. Thus the error in using $D_{av.}$ as the effective diameter is negligible. The effective area is then

$$A = \pi \frac{D_{av.}^{2}}{4} = 78.6 \text{ cm.}^{2}$$

With a current of I_M flowing in the primary, the total flux threading the secondary for an infinitely long solenoid is

$$\Phi'_m = .4\pi n_M I_M \times A$$
$$= 782\ I_M.$$

The correction to be applied at the center due to the effect of the ends is

$$k_M = -H_o\left[\frac{1}{2}\left(\frac{10}{90}\right)^2 - \frac{3}{8}\left(\frac{10}{90}\right)^4 + \frac{5}{16}\left(\frac{10}{90}\right)^6 - \cdots\right]$$
$$= -.0061\ H_o.$$

Thus the flux as corrected is

$$\Phi_m = (1 - .006)\ 782\ I_m$$
$$= 777\ I_M$$

With 1260 turns on the secondary, the total flux turns are

$$\Phi_m n_m = 1260 \times 777\ I_M.$$

The test rods have a diameter of .392″ (.995 cm) and the area is thus .779 cm.^{2} With an induction of B gausses the total flux in the rod is

$$\Phi_t = B_t \times .779,$$

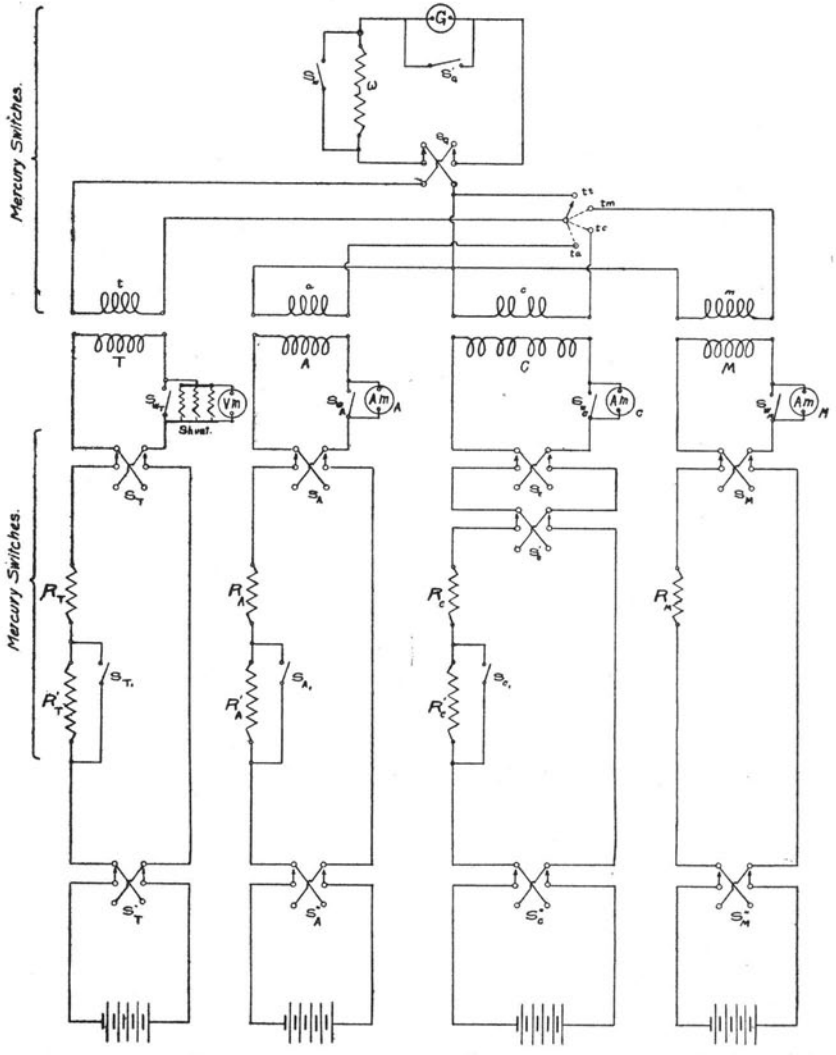

FIG. 64. ELECTRICAL CONNECTIONS.

and as the number of secondary turns are 126, the flux turns are

$$\Phi_t n_t = 126 \times .779 \times B_t.$$

If now the secondary coil, *t*, be connected in opposition to the coil, *m*, in series with the galvanometer and the latter shows no deflection upon reversing all the magnetizing currents, including I_M, then

$$\Phi_m n_m = \Phi_t n_t,$$

or

$$1260 \times 777\, I_M = 126 \times .779 \times B_t,$$

$$B_t = .997 \times 10{,}000\, I_M.$$

As it has been assumed that $B_t = 10{,}000\, I_M$, the correction to be applied is — .3 per cent.

On account of the difference in the time required to establish the flux in M and T it was found impracticable to apply this zero method. Instead, the resistance, ω, was so adjusted that the deflection of the galvanometer upon reversal of I_M was

$$D = 20\, I_M.$$

Thus with the coil *t* connected to the galvanometer, the value of B_t corresponding to a deflection D, upon reversal of the magnetizing currents, is

$$B_{t\,max} = \frac{1{,}000\ D}{2}$$

and the total change of B_t is

$$\triangle B_t = 1{,}000\ D,$$

as B_t passes from $+ B_{t_{max}}$ to $- B_{t_{max}}$ upon reversal.

All the different switching operations are accomplished by means of rocking mercury switches, as shown in Figs. 65 and 66. With this arrangement any number of switches may be operated simultaneously. As a matter of fact, the three switches, S_T, S_A, and S_C, and also S_{T_1}, S_{A_1}, and S_{C_1}, are connected together so that they operate in unison.

The magnetization curves are obtained by the method of reversals. Preliminary to each measurement the flux is adjusted to equality around the magnetic path as already described.

Hysteresis loops are traced by a similar method. All values are referred to the maximum. After having made the adjustments for equality for the maximum value to be used, the resistances R_T, R_A, and R_C are not changed. If H_2 be the desired value of H_T on the loop, this is obtained by opening the switches S_{T_1}, S_{A_1}, and S_{C_1}, and adjusting the resistances R'_T, R'_A, and R'_C. The latter are then short-circuited and the flux reversed a few times so as to follow the loop. These operations have taken place with the galvanometer short-circuited. Adjustments for

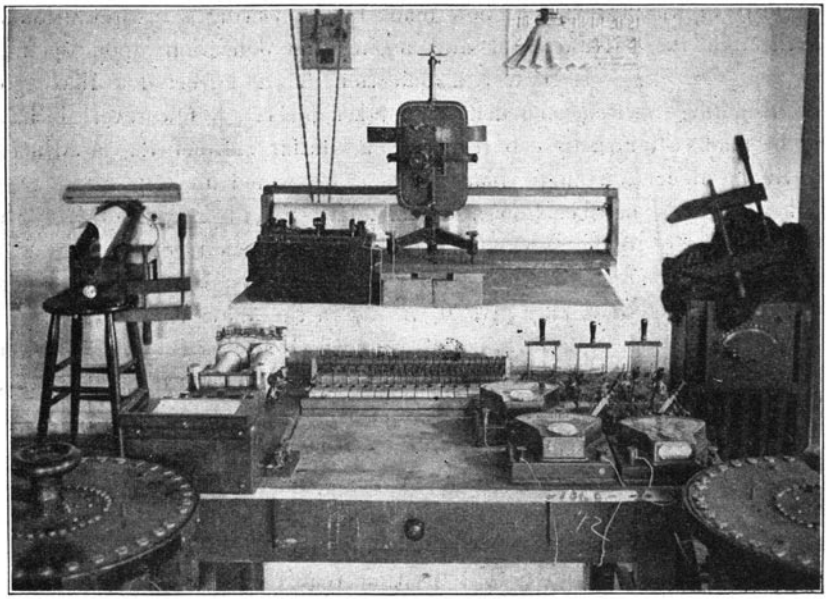

FIG. 65. PERMEAMETER. OPERATING TABLE.

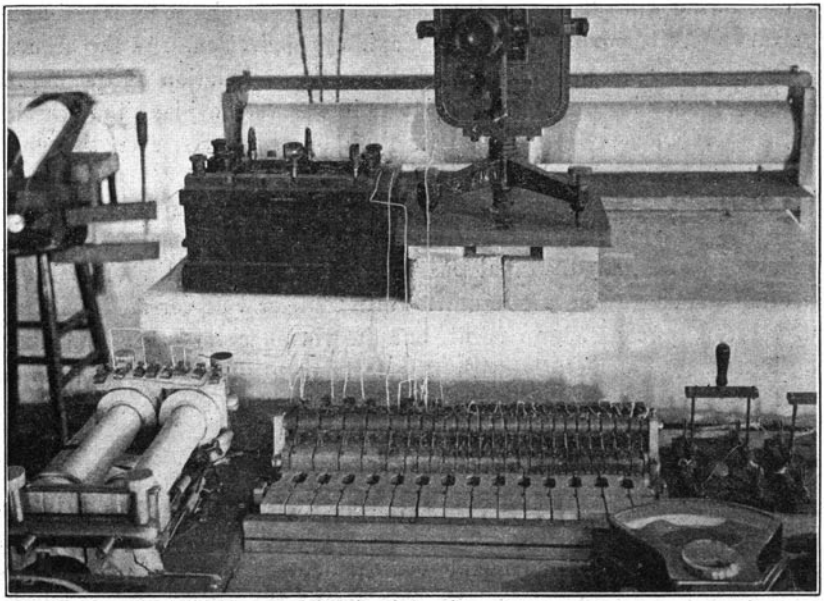

FIG. 66. PERMEAMETER. OPERATING TABLE.

equality of flux for H_2 are now made by connecting a in opposition to t through the galvanometer and noting the deflection upon opening S_{T_1}, S_{A_1}, and S_{C_1}. If there is a deflection, R'_A is adjusted so that upon opening these switches no deflection takes place. A few reversals have to be made after each such trial. In a similar manner R'_C is adjusted until no deflection takes place with c connected in opposition to t. When equality has been obtained all along the line, the coil t is connected directly to the galvanometer and the deflection noted upon opening S_{T_1}, etc. This operation gives a point between B_{max} and the retentivity point B_r, or it may give B_r if R'_T in the above case is infinity, i. e., open-circuited. For values of B_2 between B_r and $-B_{max}$ the reversing switches S_T, S_A and S_C are operated at the same time as S'_T, etc. Otherwise the procedure is exactly the same.

The Leeds and Northrup galvanometer was sufficiently accurate for iron of low permeability, but when attempts were made to use it for vacuum iron the errors introduced on account of the viscosity of the iron were too large. This was particularly true in measuring hysteresis. It was found, for instance, that the time required for a complete change of flux in a particular case was 5 to 6 seconds. As the period of the galvanometer was 15 seconds for a complete swing, or about 4 seconds for ¼ swing, the change of flux had not been completed by the time the galvanometer coil had reached its maximum deflection. As the accuracy of a ballistic galvanometer depends upon the completion of the impulse before the coil has moved appreciably, it was very evident that the ballistic galvanometer had reached its limit of usefulness, even though its period had been doubled.

For all the final measurements of the vacuum iron a Grassot fluxmeter was therefore used. In this meter the suspension effect has been practically eliminated, so that the same result is obtained whether the deflection is made from maximum towards zero or vice versa. The needle does creep towards a zero point, but the travel is very slow and hardly noticeable. Consequently with this instrument it makes no difference how quickly or how slowly the change of flux takes place. It can be shown that in any case

$$\Delta\Phi = K\Theta$$

where K is a constant and Θ is the deflection. The time element does not enter. The meter, besides being provided with a needle, is also equipped with a mirror, so that measurements may be taken in connection with a lamp and scale. By this means the sensitivity may be increased 20 times. For the present purpose the lamp and scale were used

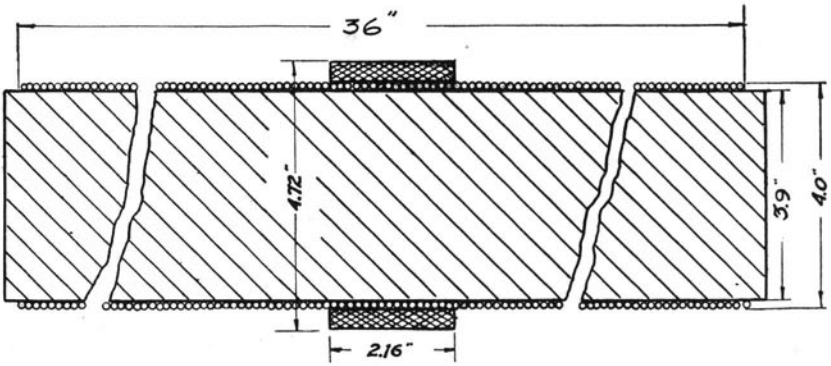

FIG. 67. MUTUAL INDUCTANCE FOR CALIBRATION OF GALVANOMETER OR FLUXMETER.

for the preliminary adjustments for equality of flux, while the final measurement was obtained from the deflection of the needle. The meter was calibrated to read in 10,000 maxwells per scale division per turn of the search coil. As the secondary coil, t, contains 126 turns and the cross-section of the rod is .779 sq. cm. the deflections of the fluxmeter were multiplied by

$$\frac{10{,}000}{126 \times .779} = 102$$

in order to give ΔB_t.

By comparing the results obtained with the fluxmeter with those obtained with the galvanometer, it was found that the results are identical for permeabilities up to 4,000 or 5,000. For permeabilities of 10,000 the results obtained by the fluxmeter are 10 to 15 per cent higher, while for values of $\frac{\Delta B}{\Delta H}$ of 20,000 or above, such as may occur on the steepest part of the hysteresis loop, the fluxmeter gives results 50 to 100 per cent higher than the galvanometer. The values of the standard rod as obtained by the two meters are shown in Fig. 2.

The preliminary adjustments for equality of flux are made very readily and accurately with the fluxmeter. If the two rods are not just alike the change of flux may occur at a different rate in one than in the other with the result that, if the initial and final flux values are nearly the same, the needle will deflect first in one direction and then in the other. While these two kicks caused considerable trouble with the galvanometer, no uncertainty exists with the fluxmeter. If the spot of light on the scale returns to the same spot from which it started it makes no difference what happens to it in the meantime. In that case it is definitely known that the fluxes threading the two opposing coils are equal.

APPENDIX V.

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