A Study of Iron Alloys

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Electrical Engineering

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A STUDY OF IRON ALLOYS

BY

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

TRYGVE D. YENSEN

ENTITLED A STUDY OF IRON ALLOYS

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DEGREE OF MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

[Signatures]

Recommendation concurred in:

[Signatures]

Committee on Final Examination
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A STUDY OF IRON ALLOYS

1. INTRODUCTION

1. Scope. Conservation of natural resources in one of the great problems of modern times, and the problem of economy in the use of materials is one of the most important in this connection. The experiments recorded in this thesis were undertaken with the view to improve the economy in the use of materials for electromagnetic machinery by increasing the magnetic permeability of the iron.

The experiments treat the effect upon the magnetic qualities of nearly chemically pure iron by adding to it an oxide of Boron. This oxide is commercially known as Boron Suboxide and has an approximate composition $B_7O$. It was originally intended to take up various heat treatments of the alloys as well as a certain amount of metallography, but on account of serious delays in receiving the apparatus needed, the thesis is limited to a comparison of the permeability of the alloys, firstly as forged and secondly after annealing at $900^\circ C$. The permeability thus obtained must not be taken as a final value, as it is well known that further annealing has a marked beneficial effect upon permeability. It is also believed that the iron has been very slightly oxidized in melting—a point which will be taken up later—and this would naturally have a disadvantageous effect upon the permeability. However, the results may be looked upon as an indication of what may be expected of the final product after proper treatment.

As a confirmation of the permeability tests the tensile strength, together with the elongation and reduction
of area was measured for most of the alloys, as it is generally accepted that ductility and high permeability go together.

Finally in order to get an indication of the eddy current losses the electrical resistance of the alloys was measured.

2. Historical Review.

On account of the relatively small importance attached to the magnetic qualities of iron previous to the appearance of electrical machinery, it is only comparatively recently that serious efforts have been made to improve these qualities, and the published literature upon the subject is rather scant.

Two very important researches have been published during the last ten years, and will be reviewed briefly.

(1) Barrett, Brown, and Hadfield: "Researches on different alloys of iron", Journal of the Institution of Electrical Engineers, Vol. 31, page 674, February 13, 1902. The electrical and magnetic qualities are recorded of some 100 alloys of iron with carbon, manganese, nickel, tungsten, aluminium, silicon, cromium and copper. Swedish charcoal iron of a purity of 98.97 per cent iron was used as a basis.

As to the electrical resistance the results show that the increase in specific resistance by adding 1% of one of the above metals is about proportional to the specific heat of the alloying metal, or inversely proportional to its atomic weight. Fig. 1 shows the permeability of the various alloys for H = 8 c.g.s. units. Fig. 2 gives the saturation curves for Swedish charcoal iron and the 2 1/4% aluminium and the 2 1/2% silicon
Fig. 1.
Permeability of alloys of iron for $H = 8$ c.g.s units.
(Barrett, Brown, & Hadfield)
Fig. 2
Permeability Curves
from rods = 256 diameters.

(Barrett, Brown & Hadfield.)
TABLE I

Hysteresis Loss

(Barrett, Brown & Hadfield)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Hyst. Const.:</th>
<th>Hysteresis Loss (Watts per cu. inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max. Ind.=5000:</td>
<td>Max. Ind.= 9000</td>
</tr>
<tr>
<td>S. C. I. (Sw. Charcoal Iron)</td>
<td>.0011</td>
<td>.149</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.382</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.695</td>
</tr>
<tr>
<td>S.C.I. with $\frac{1}{2}$ % Si.</td>
<td>.00073</td>
<td>.123</td>
</tr>
<tr>
<td>&quot; &quot; $\frac{3}{4}$ % Al.</td>
<td>.00068</td>
<td>.254</td>
</tr>
<tr>
<td>&quot; &quot; $\frac{3}{4}$ % Al.</td>
<td>.00068</td>
<td>.236</td>
</tr>
</tbody>
</table>
Alloys. Table 1 gives the hysteresis loss for these same alloys. It is seen that out of the eight metals investigated only silicon and aluminium have a beneficial effect upon the magnetic qualities of the iron, while carbon has the most detrimental influence.

C. F. Burgess and James Aston of the University of Wisconsin thru grants from the Carnegie Institution of Washington have carried on for a number of years researches on iron alloys, using electrolytically refined iron of a purity of 99.97% iron as the basis. These researches have been published chiefly in the Electro-chemical and Metallurgical Industry for 1909 and Metallurgical and Chemical Engineering for 1910 * and partly in the Transactions of the American Electro-Chemical Society for 1909 and 1910.

The investigations cover alloys of copper, arsenic, tin, bismuth, antimony, manganese, nickel, silicon and various others. They probably form the most important series of researches upon the magnetic and electrical, as well as physical properties in general of iron alloys, as the purity of iron gives the assurance that the effect is caused by the allowing metal and not by a combination of this metal with the impurities of the iron.

As far as magnetic qualities are concerned the only metals that prove to be of any special interest are arsenic,

* The name of the former was changed to the latter in 1910. As a matter of fact it is the same journal.
bismuth, silicon and tin. The permeability is increased slightly with these metals over that of the electrolytic iron, for small percentages of alloying metal. The hysteresis loss is decreased in some case to less than one half, and the resistance is materially increased over that of the electrolytic iron. The best results are obtained with 3.86% arsenic, 2.06% tin, 2.00% bismuth and 4.66% silicon.

As a summary of the results thus far obtained by different investigators is given in Table II the permeability for $H = 20$ c.g.s. units.


From the above table it is seen that all the elements used to improve the magnetic permeability of iron are strong deoxidizing agents, especially aluminium and silicon, whose oxides are among the most stable known to chemistry. Again, very small quantities of these elements have to be added to produce the beneficial results; if more is added, the permeability is decreased.

These facts seem to point to the probability that the function of these elements is to completely deoxidize the iron, and the more pure iron there is in the resulting alloy the better. On this assumption, if chemically pure iron could be obtained and melted down without being contaminated by oxygen or other elements, this would be the ideal iron for magnetic purposes. As this is practically impossible, at present at least, the best that can be done is to use as pure iron as possible and employ as deoxidizing agents elements that,
TABLE II


<table>
<thead>
<tr>
<th>Investigators</th>
<th>Alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Barrett, Brown &amp; Hadfield</td>
<td>2 1/4% Al. for H=20 B = 17000</td>
</tr>
<tr>
<td>2. Burgess and Aston</td>
<td>3.86% As.</td>
</tr>
<tr>
<td>3. &quot; &quot; &quot;</td>
<td>2.00% Bi.</td>
</tr>
<tr>
<td>4. &quot; &quot; &quot;</td>
<td>3.56% As.</td>
</tr>
<tr>
<td>5. Sankey's Lohy's Sheet</td>
<td></td>
</tr>
<tr>
<td>6. Electrolytic Iron Forged</td>
<td></td>
</tr>
<tr>
<td>7. Burgess and Aston</td>
<td>4.14% As.</td>
</tr>
<tr>
<td>8. Hadfields Magn. Steel</td>
<td></td>
</tr>
<tr>
<td>9. Barretts pure Iron</td>
<td></td>
</tr>
<tr>
<td>10. Burgess and Aston</td>
<td>1.81% As.</td>
</tr>
<tr>
<td>11. &quot; &quot; &quot;</td>
<td>0.29% As.</td>
</tr>
<tr>
<td>12. Allens C. I.</td>
<td></td>
</tr>
<tr>
<td>13. Barrett, Brown &amp; Hadfield</td>
<td>2 1/2% Si.</td>
</tr>
<tr>
<td>14. High Grade Sheet</td>
<td></td>
</tr>
<tr>
<td>15. Transformer Iron + 5% As.</td>
<td></td>
</tr>
</tbody>
</table>
when oxidized, will form a slag on the top of the iron and not be dissolved by it. This is known to be true of silicon and alumina.

However, the analysis of the alloys prepared by Prof. Burgess show that the amount of element added to the iron before melting is practically equal to the amount of element in the resulting alloy, which seems to indicate that none of it is oxidized, unless the oxide is dissolved in the iron. According to the present knowledge of the action of these oxides, they do form a slag on the top of the iron and are not dissolved. Consequently the conclusion may be drawn that, while these agents may protect the iron from being oxidized and deoxidize it if necessary, their main function in improving the magnetic quality of the iron must be sought in the alloys which they form with the iron. That elements which by themselves are non-magnetic should be able to improve the magnetic quality of a strongly magnetic element like iron does not seem impossible after the discovery of alloys like the Heusler alloys, composed of the three apparently non-magnetic elements: copper, manganese and aluminium. If in the first place the saturation value of an iron alloy is higher than that for pure iron it is evident that either the number of elementary magnets or the magnetic moment of each of these, or both, have been increased, since

$$B_s = K \times N \times m$$

where
\[ B_s = \text{saturation value} \]
\[ K = \text{constant} \]
\[ N = \text{number of elementary magnets for unit vol.} \]
\[ m = \text{magnetic moment of each elementary magnet.} \]

If, in the second place, the saturation value is constant, but the permeability has been increased below saturation, this shows that the mobility only of the elementary magnets has been increased.

The first change involves an atomic or ionic change in the material, while the second change involves more of a molecular change in the structure of the iron. For practical purposes the saturation value is of little importance if the permeability is high below saturation. Consequently, if an iron is obtained with fairly high saturation value and the mobility of the elementary magnets can be improved the solution of the problem will have been approached. The saturation value of pure iron is very high, it can probably not be increased, so that the problem consists in alloying pure iron with some element that will bring about this mobility. Boron has been shown to have a marked beneficial effect upon the conductivity of cast copper, and it has been suggested that it might have a beneficial effect also upon the magnetic quality of iron.

The experiments, therefore, consist in producing as pure iron as possible, by electrolytic deposition, melting this down with certain percentages of boron, forging the resulting ingots into rods and test their magnetic, electrical and mechanical properties.
II MATERIAL AND APPARATUS

1. Electrolytic Iron.

The composition of the electrolyte employed for the preparation of electrolytic iron is due to Prof. Burgess and is made up as follows:

Electrolyte per liter: 400 grams of ferrous sulphate crystals
50 grams of ammonium chloride

Anodes: These consist of 3/8" or 1/2" wrought iron plates placed far enough apart to allow about 2 inches between the anode and the cathode. Swedish charcoal iron has been used altogether, of the following composition:

Silicon .032 %
Sulphur .0002%
Phosphorus None
Manganese None
Carbon .259%
Iron (by diff) 99.71%

Cathodes: As it was desirable to refine the iron twice, lead cathodes 1/16" thick were employed in the first set of tanks and after these had been covered by iron about 1/4" thick, they were used as anodes in the second set of tanks. As cathodes in these latter tanks were used Swedish wrought iron plates 1/16" thick. The deposited iron was stripped off of these plates without trouble.

Current Density: This was kept at about 5 amperes per square foot of surface.

Circulation of the Electrolyte: In order to insure a uniform
composition of the electrolyte in all the tanks a slow circulation was maintained all the time by the system shown diagrammatically in Fig. 3. The electrolyte is syphoned from the last tank T, into the receiver A. As the bottle fills up its weight extends the spring, S, until the lever, E, attached to it, gets into such a position that the weight, W, rolls by gravity from left to right. This operation extends the spring still further and opens the value, V, thru the cord, C, and the pulleysystem $p_1, p_2, p_3$. The value V admits compressed air into the receiver A, which closes the checkvalue "b" at the end of tube "a" and forces the electrolyte up into the receiver B. The pressure is indicated on the gage, G, and a safety valve, H, keeps the pressure within safe limits, about 10 pounds. As the liquid is transferred from A to B the spring, S, contracts until W rolls back into its original position thereby closing the valve thru the cord $C_2$. In the closed position the valve, V, admits the air from A to the atmosphere. Another check-valve, d, prevents the liquid from flowing back into A after the removal of the pressure. An overflow tank, C, takes care of any excess liquid thru the standpipe, e. The electrolyte flows from B thru, f, into the filter-tank D, provided with an upward filter, filled with fine quartz sand. From D, the electrolyte flows by gravity thru the refining tanks by syphons, as the table upon which they stand is provided with a slope of three inches in 14 feet.

Fig. 4 is a photograph of the plant. It shows 12 refining tanks and one filter tank. The first six tanks are
Fig. 4. Electrolytic refining plant.
used for the primary refining and the next six for the secondary refining. The tanks are 8 1/2" by 10 1/2" by 12 1/2" high, and each contains three anodes and two cathodes, the size of each being 6" X 12", with an active surface of 6" X 9". The anodes of one tank are connected to the cathodes of the next tank thru triangular brass bars supported on wooden connecting strips between the tanks.

As the water of the electrolyte is evaporated it is replenished by destilled water and the density kept constant at 1.16 by addition of more salt according to the formula given. The anodes are removed and cleaned twice a week and the cathodes three times a week.

The iron obtained was rather spongy and the deposition not very uniform. Its chemical composition showed by analysis to be as follows:

<table>
<thead>
<tr>
<th></th>
<th>Single deposition</th>
<th>Double deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>.028%</td>
<td>.01%</td>
</tr>
<tr>
<td>Carbon</td>
<td>.083%</td>
<td>.01%</td>
</tr>
</tbody>
</table>

As the Swedish Iron Anodes contained only .0002% Sulphur, no Phosphorus or Manganese, no analysis was made for those elements.

The doubly refined iron can therefore be taken as between 99.97% and 99.98% pure.

2. Crucibles.

On account of the high melting point of pure iron, about 1525° C, it was necessary to employ crucibles made from fused magnesia, MgO. A very pure grade of magnesite was
Fig. 5. Electric arc furnace.
employed that had previously been calcined at 1000° C. This material was placed in a specially designed electric arc furnace shown in Fig. 5, holding about five pounds of material. The inside chamber 4" X 4" X 6" is lined with 1/2" graphite plates surrounded on all sides by 2" of calcined magnesite. Outside this is placed firebrick laid on the flat side, so that the total wall thickness is 7". The electrodes, consisting of 2" graphite rods, enter thru holes in opposite sides and slant slightly. It generally takes one hour to bring the material to the fusion point.

The material thus obtained is ground down to 40 mesh and mixed with hydrated magnesia Mg $(0 \text{ H})_2$. The latter prepared by mixing 1000 grams of Mg O with 600 c.c. of water and allowing the mixture to react for 24 hours in a stone mill. Just enough of this binder is used with the fused material to make it moist enough to mould. The crucibles are formed in a steel mould in a press capable of exerting a pressure of 4000 pounds. Twenty four hours are generally sufficient to dry the crucibles, and they are then baked in an electric furnace at 1800° C for two hours. Covers are made from the same material and in a similar manner. The size of these crucibles is 3 1/4" high by 3" in diameter at the top, sufficiently large to hold 500 grams of crushed electrolytic iron. As magnesia becomes soft at the temperatures needed for melting the iron, it is necessary to place the magnesia crucibles inside graphite crucibles. The latter, provided with covers, also help in keeping out impurities.
Fig. 6. Electric furnaces and crucibles.
3. Furnace.

The furnace used is a Hoskins 30 K.W. radiation furnace, shown in Fig. 6. The current is sent thru graphite plates, 30 on each side of the heating chamber, placed with their flat sides against each other. On the back side the two sets are connected by means of heavier plates and on the front side each is connected to the source of energy thru round graphite electrodes and water cooled terminals outside the furnace. The current is delivered from the transformer at 25 volts, 60 cycles, so that at full load the furnace takes 1400 amperes. The current can be regulated by means of screws on the back by either increasing or decreasing the pressure on the plates. The maximum temperature of the furnace is 2000° C.

4. Alloying material.

As already mentioned, the alloying material used in these experiments is a boron compound known as "Boron Suboxide." It is manufactured by the General Electric Co. and used chiefly in the production of copper castings. It has been described in detail in papers by Dr. E. Weintraub before the American Electro-Chemical Society in 1909 and 19107 where he gives its composition as $B_{15}O_2$ or $B_7O$. It does not alloy with copper, but has a great affinity for oxygen, as little as $1/30\%$ of the material freeing copper castings from blowholes.

5. Permeameter.

For testing the permeability of the alloys produced

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  " " " " " Vol. XVIII " 207
Fig. 7.

Fig. 8.

Permeameter & Connections.
a Hartmann and Braun permeameter has been used. It is shown
in the cut of Fig. 7. It is essentially of the yoke type and
based on property of bismuth to vary its electrical resistance
with the magnetic field in which it is placed. A small spiral
made from Bismuth, .036 cm. in thickness is placed at the end
of a brass tube and inserted into the magnetizing coil, C, in
such a way that the spiral will occupy a position in the center
of the coil. The ends of the spiral are connected by copper
wire to the terminals T₁. The iron to be tested is turned in-
to two rods as shown in Fig. 17, .99 cm. in diameter and about
15 cm. long, and one rod inserted from each end so that their
ends fit closely up against the bismuth spiral. The method
consists then essentially in measuring the resistance of the
spiral with different magnetizing forces by means of a bridge
arrangement as shown in Fig. 8. The apparatus is self-con-
tained, the ammeter A shows the magnetomotive force H, and the
scale S₁ shows the induction B, when the galvanometer G gives
zero deflection upon closing the key T. On account of the
variation of the resistance of the spiral with the temperature
this variation must be compensated for before inserting the
test pieces, by placing the key S₂ on the existing temperature,
and while keeping S₁ on zero, moving S₃ until balance is obtained. This adjustment must be made at intervals during the test
as the spiral is liable to warm up or cool down.
Calibration of the permeameter.

As the scales of the instrument read the total mag-
netomotive force, H, for the complete circuit, including the
Fig. 9. Connections for Galvanometer Calibration.

Fig. 10. Connections for Permeameter Calibration.
air gap, it was necessary to calibrate it in order to be able to obtain the true $B - H$ relation for the iron rods alone.

For this purpose one long rod 30 cm. long and two standard rods 15 cm. long were cut from the same plate of Swedish charcoal iron. The tube Bismuth spiral was removed and another tube made that extended clear thru the magnetizing coil. Upon this tube was wound 251 turns of #32 wire and the ends brought out to the terminals $T_1$. The long rod was inserted and the induction measured by means of a Leeds Northrup ballistic galvanometer, calibrated by standard cell and condenser.

The connections for the calibration of the galvanometer are shown in Fig. 9.

Voltage of cell = 1.422 volts
Capacity of condenser = $1/3$ m.f.
Deflection of Galvanometer = 75.0 small divisions
Quantity discharged thru Galvanometer = $1.422 \times 1/3 \times 10^{-6} = .475 \times 10^{-6}$ coulombs.
Quantity per unit deflection = $.00632 \times 10^{-6}$ coulombs
The connections for the permeameter calibration are shown in Fig. 10.

For the secondary circuit, if
$e_s$ = induced e.m.f. in secondary coil
$i$ = current flowing
$R$, $r$, & $S$ = resistances of rheostat, galvanometer and coil.
We have:
$e_s + i (R + r + S) = 0 \quad (1)$
\[ e_s = -N_s \frac{d \varphi}{dt} \times 10^{-8} = -i (R + r + S) \] (2)

Hence
\[ d \varphi = \frac{r + R + S}{N_s} i \, dt \times 10^8 \]

Integrating:
\[ \varphi = \frac{r + R + S}{N_s} q \times 10^8 \] (3)

where
\[ q = \text{total quantity discharged thru the circuit} \]

If \( D \) = deflection of galvanometer due to a quantity \( q \)
\[ q = 0.00632 \, D \times 10^{-6} \]
\[ R = 100,000 \, \text{ohms}, \quad r = 3430 \, \text{ohms}, \quad S = 90 \, \text{ohms} \]

Therefore
\[ R + r + S = 103520 \, \text{ohms} \]
\[ N_s = 251 \]

Substituting in (3)
\[ \varphi = 41250 \times 0.00632 \, D = 260.5 \, D \] (4)

Where \( \varphi \) = total change of flux in the magnetic circuit. The area of the rod = .78 sq. cm. The magnetomotive force was calculated and found to be \( 50 \times \text{current in amperes} \).

The B - H curve was then obtained by the method of opening the circuit, reversing it, again opening it and again reversing it, reading the deflection every time.

Example:

<table>
<thead>
<tr>
<th>Corrected Current</th>
<th>Change</th>
<th>Deflection</th>
<th>From (4)</th>
<th>Av.</th>
<th>Av.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.041</td>
<td>1 - 2</td>
<td>6.8</td>
<td>1780</td>
<td>4170</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 - 3</td>
<td>25.2</td>
<td>6550</td>
<td>4225</td>
<td>2420</td>
</tr>
<tr>
<td></td>
<td>3 - 4</td>
<td>6.7</td>
<td>1750</td>
<td>5400</td>
<td>3100</td>
</tr>
<tr>
<td></td>
<td>4 - 1</td>
<td>26.0</td>
<td>6800</td>
<td>4280</td>
<td></td>
</tr>
</tbody>
</table>
Fig. I1
Calibration Curves for Hartmann & Braun Permeameter.

I - Actual Saturation Curve by Galv. & Test Coil.

II - Saturation Curve for same Iron by Permeameter.

III - Difference betw. I & II, representing an Air-gap of .04 cm.

Swedish Charcoal Iron used.
In this manner was obtained the true saturation curve as shown in Fig. 11.

The bismuth spiral was then replaced and the B - H curve obtained in the same way as above by using the test coil of 251 turns on the brass tube inserted into the magnetizing coil from the opposite end to the one containing the spiral. In this case the two standard specimen were used.

The curve thus obtained was found to coincide with the one obtained with the same test pieces by means of the bismuth spiral and permeameter scale. This curve is also plotted in Fig. 11.

The difference between these two curves is found to be practically a straight line. The equivalent airgap corresponding to this straight line is found in the following manner:

\[ f_e l_e = f_a l_a + f_i l_i \] (1) where "a" refers to airgap "e" equivalent "i" refers to iron.

or since

\[ f l = N I = \frac{10 H}{4 \pi} \] (2)

\[ H_e l_e = H_a l_a + H_i l_i \]

or since

\[ H_a = B \quad \text{and} \quad l_a \text{ practically equals } l_i \]

\[ H_i = H - B \frac{l_a}{l_i} \] (3)

or

\[ l_a = \frac{l_i}{B} (H_e - H_i) \] (4)

From Fig. 11 for \( B = 6000 \quad H_e - H_i = 16.0 \)

Therefore, \[ l = \frac{15}{6000} \times 16 = .04 \text{ cm.} \]
that is, the equivalent airgap of the magnetic circuit is .04 cm. Even with this small airgap the inaccuracy of determining H for small values of B makes the instrument practically useless for obtaining the hysteresis loop. It must therefore be limited to the measurement of permeability.

5. Annealing furnace:

The furnace used to anneal the alloys is shown in Fig. 6, in front of the large furnace. It is a Hoskins 110 and volts, 16 amperes 1000° C furnace, was used successfully for all the alloys except four pairs of rods. It broke down while these were in the furnace, and they consequently had to be annealed in a larger, radiation type furnace.
1. Cleaning the iron.

After removing the electrolytic iron from the refining tanks it was thoroughly rinsed in boiling water to remove all of the salts adhering to it, and after drying, it was stored away.

Due to the spongy condition in which the iron was deposited, it left a very large surface exposed to the attack of the air, and it rusted very badly. On this account it was deemed necessary, as a precaution at least, to remove this oxide previous to melting it. This was done as follows: 500 grams of the crushed iron was weighed out and placed in a constantly stirred 1:3 hydrochloric acid bath, until the iron appeared bright all over. Boiled water was then introduced into the vessel thru a glass tube that was used at the same time to stir the iron. After the bath became clear, distilled water was introduced in a similar manner. Finally the water was poured off and two baths of denatured alcohol was applied. In most cases the required amount of alloying metal was then added to the iron after pouring off the alcohol, and the mixture at once placed in the crucibles ready for melting; but in some cases the iron was dried and left a day or two, showing only small traces of rust. In two of the early melts, 3 B 05 and 3 B 06 this procedure was not followed, but iron was selected that was rather free from oxide, and there seemed to
be little difference in the behaviour of the iron after melting. However, two melts were made from badly oxidized iron, and in this case the ingots were so full of blowholes that they were useless.

2. Melting the alloy.

After placing the iron and alloying metal in the magnesia crucible, the cover was cemented on by means of magnesite, and the whole placed inside the graphite crucible and covered by a graphite lid. Two pairs of crucibles were placed in the furnace at a time. The current was started, brought up to 110% normal value in about 5 minutes, and left at that value for two hours, when it was reduced to normal load and left there for another hour. By means of pyrometric measurements once for all, this procedure would bring the temperature up to $1600^\circ$ C and leave it at that temperature until the current was shut off, when it would decrease very slowly. After 18 hours the furnace to be handled would still be too hot to allow the crucibles without asbestos gloves.

No stirring of the molten metal was done, and it was left to cool in the crucibles. In some cases the ingots could be removed without trouble, but—in perhaps most cases—the crucibles had sagged a little or altered their shape, so that they would have to be broken to pieces.

The ingots were in nearly all cases satisfactory, only in rare cases did blowholes appear, and in these cases this may be attributed to too low a temperature in melting down, giving the gases not sufficient time to escape.
3. **Forging** the ingots into rods:

From the description of the furnace it will have been noted that the resistor consists of graphite plates. These plates are naturally the hottest part of the furnace and would be in a good condition to burn, if any oxygen should be present. It was rather expected that these plates would take care of all the oxygen present, leaving the atmosphere if not reducing, at least neutral. The experience in forging the ingots and the final results seem to indicate that the iron was slightly oxidized.

At first a great deal of trouble was experienced in forging. The ingots were reheated to forging heat in an ordinary forge and forged under a steam hammer. But in spite of every precaution in cleaning the ingot beforehand, removing surface flaws, and gentle application of the hammer, most of the ingots would crack to pieces. This was the case with remelted Swedish charcoal iron as well as with the electrolytic iron alloys, and it seemed to make no difference as to the percentage of the alloying metal. It was observed all this time that the iron was exceedingly soft when cold and worked easily in the lathe. Consequently it was tried to forge the ingots at a rather dull red heat or between dull red and a bright red. The attempt proved very successful, and very little trouble was had in forging the remainder of the ingots. But the cost of the experiment was rather high, for out of a total of 52 ingots, only 19 made their final appearance as rods. The reason why the ingots should not forge at a forging heat will be discussed later.
4. Turning the rods.

The forged rods were from 15 to 18 inches long by 1/2 inch square. From these were made two test pieces as shown in Fig. 17 for the permeability test, each about 5 1/2 inches long by .98 cm. in diameter, and one test piece for the tensile test, 2 1/2 inches long by 5/16 inch diameter over the middle 1 1/2 inch, with 1/2 inch threaded ends. One unbroken test piece is shown in Fig.17. The remainder of the rods were reserved for metallographic work.

5. Testing the rods unannealed.

These test pieces were first tested in the unannealed state. The permeability test was performed on the Hartmann and Brown Permeameter, the resistance test on a Thomson's Double Bridge, especially adapted to low resistance work, and the tensile tests on an Olson's 10000 pound testing machine, driven uniformly by an electric motor. This latter test involved measuring the ultimate tensile strength, and the yield point and breaking load if possible. After the removal of the test pieces from the machine the elongation between two previously made punch marks, and the reduction of area at the fracture were measured.

The results of these tests are shown in Section IV.

6. Annealing.

After completing the tests of the rods unannealed, they were placed, four pairs at a time in the annealing furnace already described. In order to prevent oxidation a small amount
Molten Iron and Carbon in Solution.

Freezing begins. Iron with 2.2% Carbon separates and is precipitated from solution.

Freezing begins. Graphite separates.

Austenite solution.

Freezing ends.

2.2% Carbon

Eutectic Alloy (Iron with 4.3% Carbon)

Fig. 12. Complete Roberts-Austin-Roozeboom Diagram for Iron and Carbon.
of illuminating gas was introduced together with the pyrometer thru the hole in the back of the furnace, and the hole plugged up with magnesite. Only enough gas was used to allow a small flame appearing at the front of the furnace.

The pyrometer used is a Heraeus Le Chatelier platinum - platinum - 10% rhodium outfit, indicating the temperature directly in degrees centigrade. The thermocouple was placed in a tube of "Electroquartz" and the wires insulated from each other by means of a one-bore fire clay tube.

The normal current was turned on and the temperature rose uniformly to 900° C in about 50 min. The current was then regulated so as to keep the temperature at that point for 30 minutes, when the current was turned off and the furnace allowed to cool down slowly. The cooling was effected in about six hours.

The temperature selected for annealing, 900° C, was chosen from a consideration of the Roberts-Austin diagram for the transformation characteristics of iron and carbon. This diagram is reproduced in Fig. 12. A B C is the curve for beginning solidification, AaD that for completed solidification. Between Aa and G03 the iron (ferrite) and the carbon are in solid solution and is called austenite. At the curve G03 ferrite begins to be precipitated until the solution contains ferrite with .9% carbon. Upon passing the point 3, this final eutectoid is decomposed into ferrite and cementite and is called pearlite. Consequently an iron containing less than .9% of carbon will upon cooling contain ferrite and pearlite, the
amount of pearlite depending upon the amount of carbon; if this is .9% all of the resulting mass will be pearlite. As the iron under consideration here contains only about .01% carbon, no attention needs to be given to the part of the diagram to the right of S.

Now, if the iron could be cooled suddenly from a temperature above GCS, some of the solid solution would remain in the transition stages, martensite, troosite, osmondite, or sorbite, all of which would tend to decrease the mobility of the ferrite crystals. The sudden cooling would also tend to prevent the transformation of gamma iron, (above 890° C) and beta iron (above 760° C) into alpha iron (below 760° C). The rate of cooling determines the degree of the transformation, and the more complete it is the softer and more strongly magnetic will be the iron. If iron that has been cooled too suddenly for the transformation to take place, be reheated to above GCS all of the previous crystalization will disappear, and upon slow cooling the desired transformation may be obtained. For nearly pure iron it is seen that GCS lies near 900° C, consequently such iron must be heated to about 900° C to effect the desired result.

In spite of the precaution taken to prevent the rods from oxidizing, they were coated with a thin layer of oxide upon removal from the furnace. The thickness of this layer was found to be about .005 cm., so that the reduction of diameter amounted to about 1%, and the reduction of area to about 1.5%. This was corrected for in the final results.
IV RESULTS OF TESTS.

The method of marking the specimens is as follows:

Sw. I - 2 stands for Swedish charcoal iron not remelted, specimen No. 2.

1 - 02 stands for Swedish charcoal iron remelted in electric furnace with no addition, specimen No. 2.

3 - 09 stands for doubly refined electrolytic iron melted without addition of any alloying metal, specimen No. 9.

3 B 12 stands for doubly refined electrolytic iron melted with boron, specimen No. 12.

As the results will be recorded later in an Engineering Experiment Station bulletin, the tables for the B - H curves will not be reproduced here, except for two of the specimen to show the method.

The following is a list of the specimen tested:

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Description</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sw. I 3</td>
<td>Swedish iron not melted</td>
<td></td>
</tr>
<tr>
<td>1 - 02</td>
<td>Swedish iron remelted with no addition</td>
<td></td>
</tr>
<tr>
<td>3 - 09</td>
<td>Electrolytic iron with no addition</td>
<td></td>
</tr>
<tr>
<td>3 B 23</td>
<td>&quot; &quot; &quot; .25% boron</td>
<td></td>
</tr>
<tr>
<td>3 B 05</td>
<td>&quot; &quot; &quot; .5% &quot;</td>
<td></td>
</tr>
<tr>
<td>3 B 24</td>
<td>&quot; &quot; &quot; .75% &quot;</td>
<td></td>
</tr>
<tr>
<td>3 B 06</td>
<td>&quot; &quot; &quot; 1.0% &quot;</td>
<td></td>
</tr>
<tr>
<td>3 B 26</td>
<td>&quot; &quot; &quot; 1.5% &quot;</td>
<td></td>
</tr>
<tr>
<td>3 B 13</td>
<td>&quot; &quot; &quot; 2.0% &quot;</td>
<td></td>
</tr>
<tr>
<td>3 B 14</td>
<td>&quot; &quot; &quot; 3.0% &quot;</td>
<td></td>
</tr>
<tr>
<td>3 B 18 + 3 B 22</td>
<td>&quot; &quot; &quot; 4.0% &quot;</td>
<td></td>
</tr>
</tbody>
</table>
TABLE III

Data for B - H Curve for
Sw. I - 3

Area unannealed = .773 sq. cm.
" annealed at 950° C = 765 sq. cm.

For annealed rods.

<table>
<thead>
<tr>
<th>$H_e$</th>
<th>$B'$</th>
<th>$B$ (corrected)</th>
<th>$H_e$ (For air)</th>
<th>$H_i$ (For Iron)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>19</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>3350</td>
<td>3390</td>
<td>10</td>
<td>0</td>
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<tr>
<td>20</td>
<td>6950</td>
<td>7040</td>
<td>19</td>
<td>1</td>
</tr>
<tr>
<td>30</td>
<td>10500</td>
<td>10630</td>
<td>27.7</td>
<td>2.3</td>
</tr>
<tr>
<td>40</td>
<td>13000</td>
<td>13170</td>
<td>34.0</td>
<td>6.0</td>
</tr>
<tr>
<td>50</td>
<td>14450</td>
<td>14630</td>
<td>37.6</td>
<td>12.4</td>
</tr>
<tr>
<td>59.</td>
<td>15130</td>
<td>15330</td>
<td>39.5</td>
<td>19.5</td>
</tr>
<tr>
<td>73.5</td>
<td>15960</td>
<td>16160</td>
<td>41.6</td>
<td>32.0</td>
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<tr>
<td>98</td>
<td>16720</td>
<td>16930</td>
<td>43.5</td>
<td>54.5</td>
</tr>
<tr>
<td>125.0</td>
<td>17300</td>
<td>17520</td>
<td>45.0</td>
<td>80.0</td>
</tr>
<tr>
<td>145</td>
<td>17700</td>
<td>17930</td>
<td>46.0</td>
<td>99.0</td>
</tr>
<tr>
<td>172</td>
<td>18100</td>
<td>18330</td>
<td>47.0</td>
<td>125.0</td>
</tr>
<tr>
<td>195</td>
<td>18430</td>
<td>18680</td>
<td>48.0</td>
<td>147.0</td>
</tr>
<tr>
<td>245</td>
<td>19100</td>
<td>19350</td>
<td>48.0</td>
<td>197.0</td>
</tr>
</tbody>
</table>
TABLE IV

Data for B - H Curve for

3 B 20 (8%)  
(Tested with Sw. I. - 3 annealed)  
(See Table III)  

Area unannealed = .775 sq. cm.  
" annealed at 900° C = .770 sq. cm.  

For annealed rods.

<table>
<thead>
<tr>
<th>$H_e$ (For Compl. Magnetic Circuit)</th>
<th>$B'$ (For Air Gap)</th>
<th>$B$</th>
<th>$H_a$</th>
<th>$H'_1$</th>
<th>$H''_1$</th>
<th>$H_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>6150</td>
<td>6200</td>
<td>17.0</td>
<td>3.0</td>
<td>.6</td>
<td>5.4</td>
</tr>
<tr>
<td>30</td>
<td>9250</td>
<td>9300</td>
<td>24.7</td>
<td>5.3</td>
<td>1.7</td>
<td>8.9</td>
</tr>
<tr>
<td>40</td>
<td>11560</td>
<td>11630</td>
<td>30.5</td>
<td>9.5</td>
<td>2.8</td>
<td>16.2</td>
</tr>
<tr>
<td>50</td>
<td>12900</td>
<td>13000</td>
<td>34.0</td>
<td>16.0</td>
<td>4.7</td>
<td>27.3</td>
</tr>
<tr>
<td>60</td>
<td>13850</td>
<td>13950</td>
<td>36.0</td>
<td>24.0</td>
<td>7.8</td>
<td>40.2</td>
</tr>
<tr>
<td>75.5</td>
<td>14900</td>
<td>15000</td>
<td>39.0</td>
<td>36.5</td>
<td>14.6</td>
<td>58.4</td>
</tr>
<tr>
<td>96.1</td>
<td>15780</td>
<td>15880</td>
<td>41.0</td>
<td>55.0</td>
<td>25.0</td>
<td>85.0</td>
</tr>
<tr>
<td>125</td>
<td>16470</td>
<td>16580</td>
<td>43.0</td>
<td>82.0</td>
<td>38.0</td>
<td>126.0</td>
</tr>
<tr>
<td>147.5</td>
<td>16900</td>
<td>17010</td>
<td>44.0</td>
<td>103.5</td>
<td>53.0</td>
<td>154.0</td>
</tr>
<tr>
<td>170.0</td>
<td>17300</td>
<td>17410</td>
<td>45.0</td>
<td>125.0</td>
<td>70.0</td>
<td>180.0</td>
</tr>
<tr>
<td>198.0</td>
<td>17700</td>
<td>17810</td>
<td>46.0</td>
<td>152.0</td>
<td>83.0</td>
<td>221.0</td>
</tr>
</tbody>
</table>
### TABLE V.

Mechanical Tests.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>%</th>
<th>Area sq.in.</th>
<th>Ultimate Strength lbs/sq.in.</th>
<th>Area of Fract. sq.in.</th>
<th>Red. of Area %</th>
<th>Elong %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sw. I.</td>
<td></td>
<td>.0728</td>
<td>40000</td>
<td>.0314</td>
<td>57%</td>
<td>36.0</td>
</tr>
<tr>
<td>1 - 03</td>
<td>0%</td>
<td>.074</td>
<td>55000</td>
<td>.0095</td>
<td>87.0</td>
<td>42.0</td>
</tr>
<tr>
<td>3 - 08</td>
<td></td>
<td>.079</td>
<td>70600</td>
<td>.035</td>
<td>55.7</td>
<td>20.0</td>
</tr>
<tr>
<td>3 - 09</td>
<td></td>
<td>.0782</td>
<td>71300</td>
<td>.038</td>
<td>51.3</td>
<td>25.0</td>
</tr>
<tr>
<td>3 B 05</td>
<td>1/2</td>
<td>.073</td>
<td>49600</td>
<td>.038</td>
<td>48.0</td>
<td>30.0</td>
</tr>
<tr>
<td>3 B 24</td>
<td>3/4</td>
<td>.073</td>
<td>62600</td>
<td>.0255</td>
<td>65.0</td>
<td>32.0</td>
</tr>
<tr>
<td>3 B 06</td>
<td>1</td>
<td>.072</td>
<td>51200</td>
<td>.0227</td>
<td>68.5</td>
<td>33.0</td>
</tr>
<tr>
<td>3 B 26</td>
<td>1 1/2</td>
<td>.08</td>
<td>49100</td>
<td>.0255</td>
<td>68.0</td>
<td>43.0</td>
</tr>
<tr>
<td>3 B 13</td>
<td>2</td>
<td>.0685</td>
<td>56500</td>
<td>.0255</td>
<td>63.0</td>
<td>40.0</td>
</tr>
<tr>
<td>3 B 15</td>
<td>4</td>
<td>.0778</td>
<td>57300</td>
<td>.0347</td>
<td>55.5</td>
<td>26.0</td>
</tr>
<tr>
<td>3 B 16</td>
<td>5</td>
<td>.0728</td>
<td>63200</td>
<td>.0416</td>
<td>43.0</td>
<td>23.0</td>
</tr>
<tr>
<td>1 B 01</td>
<td>1</td>
<td>.073</td>
<td>57600</td>
<td>.0314</td>
<td>56.0</td>
<td>26.0</td>
</tr>
<tr>
<td>1 Si.01</td>
<td>2 1/2</td>
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<td>74500</td>
<td>.0492</td>
<td>37.0</td>
<td>23.0</td>
</tr>
<tr>
<td>3 Al.02</td>
<td>2 1/2</td>
<td>.075</td>
<td>64400</td>
<td>.0705</td>
<td>6.0</td>
<td>10.0</td>
</tr>
<tr>
<td>3 Al.04</td>
<td>2 1/2</td>
<td>.077</td>
<td>96800</td>
<td>.072</td>
<td>6.5</td>
<td>12.0</td>
</tr>
<tr>
<td>Specimen</td>
<td>No. of Rods</td>
<td>% Alloying Metal</td>
<td>Resistance ohms/cm. $^3$ x $10^{-3}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td>-----------------</td>
<td>------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 - 02</td>
<td>2</td>
<td>0</td>
<td>.0193</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 - 09</td>
<td>&quot;</td>
<td>0</td>
<td>.0231</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 B 23</td>
<td>&quot;</td>
<td>.25</td>
<td>.0192</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 B 05</td>
<td>&quot;</td>
<td>.5</td>
<td>.0198</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 B 06</td>
<td>&quot;</td>
<td>1.0</td>
<td>.0208</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 B 26</td>
<td>&quot;</td>
<td>1.5</td>
<td>.0186</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 B 13</td>
<td>&quot;</td>
<td>2.0</td>
<td>.0206</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 B 14</td>
<td>&quot;</td>
<td>3.0</td>
<td>.0198</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 B 18</td>
<td>1</td>
<td>4.0</td>
<td>.0402</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 B 22</td>
<td>1</td>
<td>4.0</td>
<td>.0203</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 B 16</td>
<td>2</td>
<td>5.0</td>
<td>.0203</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 B 19</td>
<td>&quot;</td>
<td>6.0</td>
<td>.0233</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 B 20</td>
<td>&quot;</td>
<td>8.0</td>
<td>.0216</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 01</td>
<td>2</td>
<td>1.0</td>
<td>.020</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Si. 01</td>
<td>&quot;</td>
<td>2.5</td>
<td>.063</td>
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</tr>
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<td>3 Al. 02</td>
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<td>.0232</td>
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<tr>
<td>3 Al. 04</td>
<td>&quot;</td>
<td>2.5</td>
<td>.0545</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Electrolytic iron with 5.0% carbon
3 B 19 " " " 6.0% "
3 B 20 " " " 8.0% "

Table III gives the data for the B - H curves for Sw. I. - 3 annealed at 950° C.

Table IV gives the same for 3 B 20, but in this case only one rod was obtained, and consequently it has to be tested together with a rod of different composition, but whose B - H curve was known.

Table V gives the results for the mechanical tests of unannealed rods.

Table VI gives the results for the resistance test of unannealed rods.

The results of the various tests have been plotted in figures 13 and 16 incl.

Fig. 13 gives the B - H curves for the various specimen unannealed and Fig. 14 gives the B - H curves after annealing at 900° C.

In Fig. 15 the values of H are plotted against the percentage of boron added to the various specimen. The upper curves in the sets are for unannealed rods, the lower for annealed rods.

Fig. 16 is a summary of the mechanical tests of unannealed specimen together with the magnetic characteristics for B = 12000 and unannealed rods. The top curve shows the variation of ultimate strength, the second the variation of the reduction of area, and the third the variation of elongation, all plotted against the percentage of boron added.
Fig. 13
Saturation Curves for Iron-Boron Alloys. Unannealed.

- Swedish Charcoal Iron.
- " remelted in Electric Furnace.

Heavy Curve - Electrolytic Iron melted and forged.
Small figures under or after specimen mark give the % boron added to iron.
Fig. 14.
Saturation Curves for Iron-Boron Alloys
Annealed at 900°C.

- Swedish Charcoal Iron
- " " remelted in Electric Furnace
- Heavy Curve - Electrolytic Iron

Small figures under or after specimen mark give the % boron added to iron.
Fig. 15, a
Iron-Boron Alloys
\( B = 12000 \)

Fig. 15, b
Iron-Boron Alloys
\( B = 16000 \)
Fig. 16.  
Iron-Boron Alloys.

Ultimate tensile strength: lbs/sq.in.

Reduction of area in per-cent.

Elongation - per-cent.

H for B = 12000 (unannealed rods)

Per-cent boron added.
Fig. 17. Tensile test pieces after being broken.
In Fig. 17 is exhibited the tensile test pieces after the mechanical test, together with a pair of the magnetic test pieces.
V SUMMARY AND CONCLUSION

An inspection of curves 13, 14, and 15 shows that there is a marked improvement in the permeability as the addition of boron suboxide is increased from zero to 1 1/2 percent. With further increase the permeability decreases, at first slowly and then, after the four percent mark has been passed, very rapidly. Fig. 15 shows an improvement in the permeability for the annealed rods, especially for very low and very high percentages of boron.

In Fig. 16 is shown very effectively the relation between permeability and mechanical ductility. Just as the permeability is a maximum for 1 1/2% of boron suboxide, so the elongation and reduction of area at the fracture reach a maximum and the ultimate tensile strength reach a minimum for the same alloy.

Further inspection of figures 13 and 14 reveals the fact that the permeability of the Swedish charcoal iron has been very materially reduced by melting in the electric furnace without addition of any alloying metal. This fact together with the previously mentioned difficulty experienced in forging the ingots suggests strongly that the iron has been slightly oxidized in the electric furnace. As this oxidation can readily be avoided by surrounding the crucibles with charcoal or broken up graphite plates it seems very likely that the permeability of all the alloys will be raised materially. However, as far as comparison is concerned, the fact remains that for similar treatment the permeability is increased with small additions
of boron, and is higher for these alloys than for the Swedish charcoal iron.

The change in the slope of the B - H curves after annealing seems rather curious. Take, for instance, the curves for electrolytic iron without addition, 3 - 09, before annealing the curve is nearly straight at first and has a rather sudden bend, at $H = 30$, while after annealing the curve rounds off much more evenly with much higher permeability at low densities than for the unannealed rods. Just the opposite is the case with the remelted Swedish charcoal iron, and other alloys follow one or the other of these two, without any apparent connection with their composition.

The resistance tests do not bring out any marked difference one way or the other between the various alloys, except for 3 B 18, 4% boron, whose resistance is very high compared with the rest. 3 B 22 with the same percent boron does not show such high resistance, which seem to indicate that 3 B 18 is abnormal in some respect. For the B - H curve these two were tested together as only one rod was obtained for each. Fig. 15 shows that the points for these rods are far outside the average curves. The resistance test explains why this may be so, and justifies ignoring these points in drawing the curves.

That no increase takes place in the resistance is surprising in view of the results of Barrett, Brown and Hadfield, mentioned in the introduction, according to which 1% of one of the metals referred to increases the specific resistance of iron by an amount inversely proportional to the
atomic weight of the alloying metal.

According to their results 1% of Aluminium with an atomic weight of 27 increases the specific resistance by 11.1%, so that 1% of Boron whose atomic weight is only 11 should increase the specific resistance by

\[
\frac{27}{11} \times 11.1 \text{ or about } 27\% 
\]

As no increase in resistance takes place boron must be supposed to act like a nonmetal, like carbon for instance, in this respect. In order to obtain an alloy that would be suitable for magnetic purposes, then, it might be necessary to use an alloying metal besides boron, for instance aluminium or silicon to increase the resistance of the alloy, as this is desirable in order to keep the eddy currents as low as possible.

In conclusion the writer wishes to express his appreciation to Dr. Grinnell Jones of the Chemistry Department for assistance with the electrolytic refining plant, to Mr. Justa Lindgren for the close attention given to the chemical analysis of the iron, to Mr. A. T. Lanham of the forge shop for assistance with the forging of the ingots, and to Prof. H. F. Moore of the Theoretical and Applied Mechanics Department for assistance with the mechanical tests.
VI APPENDIX

On pages 91 - 93 of his book on "Composition and Heat Treatment of Steel" Mr. E. F. Lake, Steel Editor of the American Machinist, treats of boron and its influence upon iron and steel. On page 92 he says: "Boron may be said to give steel a hardness that increases its strength, up to a content of 2% of boron, provided the carbon is kept below .02%, but beyond a content of 2% boron or 0.2% of carbon the metal becomes so brittle that it is weakened and easily powdered under the hammer."

The mechanical tests recorded in this thesis do not seem to verify this statement. With a carbon content of .01% the ultimate strength decreased with increase of boron up to 1 1/2% while the ductility decreased.

In order to test the influence of boron upon iron of higher carbon contents, specimens were prepared using Swedish charcoal iron and 1% boron. This alloy has a B - H curve that almost coincides with that for 3 B 19, containing 6% boron, and the mechanical tests, (See Table V) show a slight increase in strength and hardness over the same iron to which no boron had been added.

While no general conclusion can be drawn from this one sample, it seems as tho boron may have a beneficial influence upon the magnetic qualities of iron of low carbon content, while its influence upon iron of .2% carbon or above may be detrimental.