PERMANENT MAGNETS

A REPORT

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INTRODUCTION.

Although a vast amount of scientific investigation has been done, and a great deal has been written on the subject of permanent magnets, it remains one upon which very little practical, useful information exists. The reason for this is the fact that no laws have yet been discovered, fixing any relation between the qualities of the permanent magnet, and the character of the materials and the conditions of manufacture, upon which the magnetic qualities of the magnet depend.

Any one who has the means for forming, hardening, and magnetizing a piece of steel, can make a permanent magnet of some sort, but to manufacture permanent magnets of uniform high magnetic quality, requires something of the scientist, the chemist and the metallurgist, together with the requisite special equipment and an organization experienced in this class of work.

The writers will endeavor to compile the best data available from the more prominent scientists, chemists, and metallurgists of the day, and in addition do some research work on the production of magnets under different heat treatments of the steel.

THEORY OF MAGNETISM.

It was early suggested that magnetization is a molecular phenomenon. The fact that a magnet may be broken into an almost unlimited number of pieces, each of which remains a magnet with a north and south pole of its own, points very strongly in this direction. This view is also confirmed by the fact that a tube of iron filings, when placed along the poles of a strong magnet becomes magnetized, and when removed remains magnetized, until by shaking or jarring it is demagnetized.

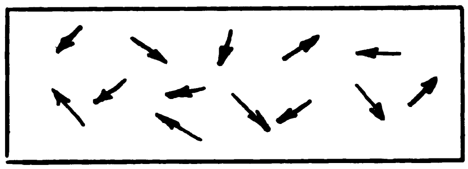
More convincing still is the fact that a long wire of soft iron may be strongly magnetized and by a slight jar lose nearly all of its magnetism.

Most striking of all, however, is the fact that a piece of iron when raised to red heat loses its magnetic quality. (Proof of the above statements can be found in any Gen. Physics).

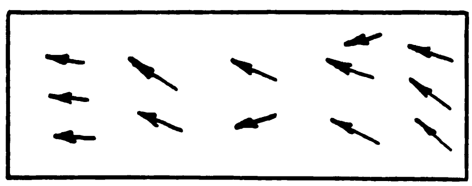
All of these facts lead us to think that magnetization is not a property of the surface of a body or of the body as a whole, but of its inermost structure. The evidence is indeed overwhelming in favor of the view that magnetism is a molecular or atomic phenomenon.

The second step was made by W. E. Weber, who

explained ferromagnetism by assuming that the molecules of iron are themselves small permanent magnets, arranged in no particular order, as indicated by Fig. below.



If these molecular magnets were perfectly free to turn, it is clear that any magnetic force acting upon them would be sufficient to bring them all into line and thus produce at once the maximum intensity of magnetization. In order to avoid this, Weber imagined each molecule in its original direction. The effect of this restraining force is represented in the Fig. below. The magnetic field does not bring all the tiny magnets into perfect parrallelism, but merely brings them more or less into line, as there shown.



The third step is to develop this theory so as to enable one to include in his explanation the facts of paramagnetism and diamagnetism. This extension of the theory we owe to Rowland, J. J. Thomson, and Lagevin. A brief outline of this theory is as follows: It is well known that a small circular electric current behaves like a small magnet. In 1876, Professor Rowland showed by a justly celebrated and difficult experiment that a revolving electric charge produces the same magnetic effects as an electric current. In 1897, J. J. Thomson demonstrated the existence of small electric charges, having a mass about 1/1700 that of a hydrogen atom. These small charges are negative in sign and can be obtained from a great variety of sources. They are called electrons. The present view (1915) of an atom is that it is built up, in part at least, of a number of electrons in rapid rotation about a central nucleus of positive electrification. Each of these electrons moving in its orbit is equivalent to a minute magnet. This view is supported by strong experimental evidence, such as that of the Zeeman effect.

Assuming an atomic structure of this kind, P. Langevin in France has pointed out the possibility that these electronic orbits, in any one atom, may be oriented in a great variety of ways.

In the case of diamagnetic substances, these orbits are supposed to be distributed in such a symmetrical way that they produce no magnetic field outside of the atom, the diamagnetic atom has no magnetic moment of its own. If, however, this diamagnetic substance be placed in a magnetic field, lines of magnetic force will be thrust thru any of these orbits which are not exactly parallel to the field, and as one looks along the lines of force, those electrons which are revolving in a clockwise sense will be accelerated, those revolving in a counter-clockwise sense will be retarded; so that, in either event, the magnetic moment of the atom will be increased in a sense opposite to that of the field. In other words, an atom with a perfectly symmetrical distribution of electronic orbits when placed in a magnetic field behaves as a diamagnetic substance.

In the case of a paramagnetic substance, it is supposed that the orbits of the electrons are distributed in such a way that they do not exactly cancel the effects, on one another; that is, these atoms have a magnetic moment of their own, and being little magnets will fall into alignment, more or less, when acted upon by an external field. The turning of these tiny magnets will of course, always be in such a sense as to bring the S pole of the atom to face the N pole of the field-producing magnet. Atoms which are symmetric will therefore behave in a paramagnetic way. But superposed upon this effect will be the diamagnetic effect discussed in the preceeding paragraph. In most cases however, these diamagnetic effects are small in comparison with the effect of rotating the orbits. What sort of resistance these orbits offer to rotation is entirely unknown.

In the case of ferromagnetic substances, the experimental facts of Ewing's model lead one to think that there are mutual actions between the atome or molecules. When an external field is applied to a ferromagnetic substance, the natural groupings of the molecules are changed; these elementary magnets fall into new positions of equilibrum, one after another and we have the effects known as permanent magnetism, etc. The key then to ferromagnetism is the attraction and repulsion of one molecular magnet upon the other.

By going one step farther and assuming that diamagnetism is an atomic phenomenon while paramagnetism is a molecular property, one may explain an important fact discovered by P. Curie, namely, that the susceptibility of paramagnets varies inversely as the absolute temperature. On the other hand K. T. Comton and E. A. Trousdale offer experimental evidence, obtained by X-ray photography, for thinking that paramagnetism is not a molecular, but an atomic, phenomenon.

THE IMPORTANCE OF QUALITY.

In the majority of cases, the purpose for which permanent magnets are used is such that the quality, accuracy, efficiency, or usefulness of the machines or instruments of which they form a part, depend directly upon the magnetic qualities of the permanent magnets used. In electrical measuring and recording instruments, the maintenance of accuracy depends absolutely upon the retentivity of the magnets. In the case of magnetos, efficiency and successful operation are both determined by the quality of the magnets.

The qualities of the permanent magnet, that is, characteristics which determine its quality as a magnet, remain unchanged indefinitely. They are a characteristic of the particular piece of steel, in its particular state, just as its hardness, tensile strength or elastic limit. A great many people confuse state of magnetization with magnetic quality, whereas they mean totally different things. Demagnetizing a magnet changes its state of magnetization, but does not alter its quality; a finished piece has, before it is magnetized, the qualities which determine how good a magnet it will be when magnetized. The quality of a magnet can be affected only by some treatment which will at the same time affect its physical characteristics, such as by heating or annealing.

THE IMPORTANCE OF UNIFORMITY.

The design of a machine or instrument in which permanent magnets are used, is, of course, based upon some known or assumed qualities of the magnets to be used, and good design requires that the magnet, in its design, be adapted to the use to be made of it, and the conditions under which it is to operate. When this has been done, it is necessary that the magnets be uniform in quality, otherwise the finished product will vary in quality, accuracy or efficiency by the same amount that the magnets do.

This uniformity of magnetic quality is especially important where two or more magnets are acting in parallel on the same magnetic circuit, because so placing magnets of unequal strength and retentivity has an effect similar to that obtained by placing batteries or generators of different voltage in parallel. The same statement holds true for magnets made up of two or more leaves, and in the design and manufacture of compound magnets, it is a matter of importance to see that the several portions are so related and of such uniformity that they will operate properly together.

For the same reason, it follows that maximum magnetic quality in a magnet of considerable cross-section, can only be obtained by the use of steel of an analysis, and a treatment, which will insure uniform quality throughout the cross-section of the magnet. It is this feature which limits the cross-section which can be successfully used, and makes necessary the use of steel of different chemical content, subjected to correspondingly different treatment, if the best results are to be obtained in the magnets of different cross-section.

THE QUALITIES OF PERMANENT MAGNETS.

Generally speaking, there are two things which are a measure of the quality of a permanent magnet. They are:

1. The residual induction or residual magnetic flux.
2. The retentivity or coercive force.

When materials have been magnetized and the magnetizing field is reduced to zero, a certain percentage of the initial induction, B, is retained. This is called residual induction and is designated by the symbol B. Different substances retain magnetism with varying degrees of avidity or strength. The strength of field necessary to reduce B_r to zero, that is, to demagnetize the material, is called the coercive field and is designated by Hcoer. or H_c.

While these two qualities or characteristics are somewhat related, in so far as the conditions which affect them are concerned, the existence of maximum residual induction does not necessarily imply that the retentivity is a maximum residual induction does not necessarily imply that the retentivity is a maximum, or vice versa. The best permanent magnet is the one in which both these qualities are at the maximum. It requires long experience in the selection of steel and the utmost skill in the treatment of it to produce permanent magnets which are

uniform in both residual induction and retentivity.

Almost all kinds of steel which can be tempered will retain a portion of their initial magnetism if magnetized. There are, however, very few kinds of steel which make relatively good permanent magnets, and the quality of the magnets made from any kind of steel depends upon a great many things. They are:

1. Chemical content.
2. Conditions under which the billets are made.
3. Annealing.
4. Rolling conditions.
5. Furnace conditions and treatment during the forming or forging of the magnets.
6. Conditions under which final heat treatment is done.
7. The mechanical operations performed after final heat treatment.
8. The process of maturing.
9. Method of magnetizing.

From this, it is easily seen that from the time the steel is melted until the magnet is finished, there are conditions and processes which materially affect the final quality of the magnet. The matter is still further complicated by the fact that the effect of one condition or process on the quality of the magnet may depend upon one or more of the other variable conditions.

For example, the result obtained from different heat treatments may depend somewhat upon the chemical analysis. The fact that a change in one may alter the effect of a change in another condition, necessitates the keeping of continuous records of all the conditions, in order to so control them as to produce a product of maximum quality and uniformity.

In Fig. "1" are the magnetization curves of three kinds of iron; these curves show the relation between the magnetizing force, or the magnetic fields in the air surrounding the iron, and the corresponding magnetic density in the iron itself when acted upon by the field in the air. These curves show the relative ease with which these materials are magnetized, but have nothing to do with their ability to retain magnetism.

They are important nevertheless, because a permanent magnet is required to drive its magnetic flux throughout its own length, as well as thru the magnetic circuit upon which it is operating. It follows therefore that any condition in manufacture which increases the magnetic resistance or reluctance of a magnet without a corresponding increase in the retentivity is detrimental to its quality.

In Fig. "2" are shown the hysteresis curves of the same three pieces of iron. These curves are obtained

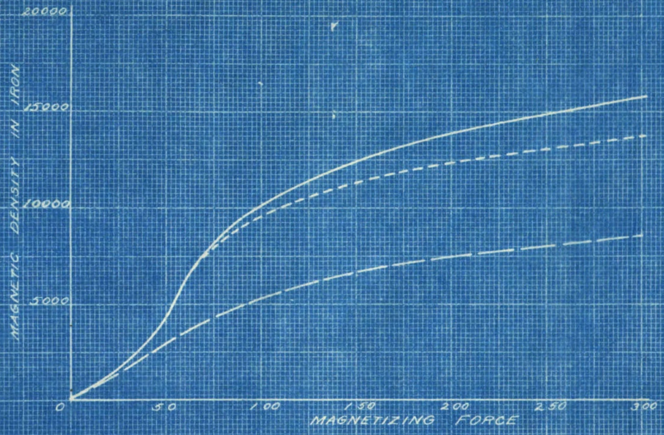
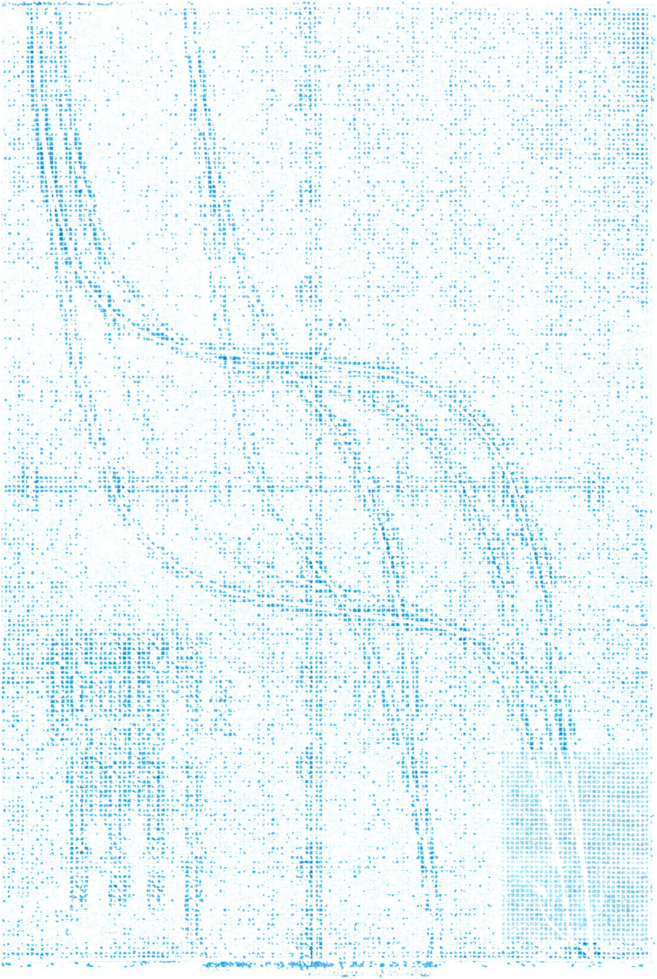


Fig. 1. Induction curves of three specimens of hardened metals. The value along the horizontal line show intensity of the magnetic field in air and the values along the vertical line, corresponding intensity in the metal when placed in the air field.



by magnetizing the iron to a known maximum magnetic density, represented by the point "A" on the curve. The magnetizing force is then gradually reduced, the magnetic density falling along the curve as indicated by the arrow.

At the point "B" where the curve crosses the line of zero magnetizing force, the distance O-B represents the strength of permanent magnetism. If, now, the magnetizing force be reversed in direction and applied so as to reduce the residual magnetism, the magnetic density will continue to decrease until it becomes zero, where the curve crosses the horizontal axis at "C".

The demagnetizing force represented by the value O-C is that force necessary to balance the magnetizing force of the magnet itself; it is the measure of the difficulty of magnetizing the magnet, or of the power with which the magnet holds its magnetism. This quality is known as the retentivity or coercive force. The vertical distance O-B is therefore the measure of residual magnetism, or residual induction, and denotes the strength of the magnet in so far as its magnetic flux is concerned, whereas the distance O-C represents the tenacity with which the magnet holds its magnetism.

Both of these qualities are of extreme importance, and it cannot be said that one is more important than the other. High magnetic strength is of little value if that

strength is not made stable by high retentivity. Neither can a magnet be said to be of high quality if its retentivity be high and its strength low. Referring to Fig. "2", it will be noted that the retentivity of hardened cast iron is approximately 75% of that of hardened tungsten steel, while the residual density of cast iron is only about 30% of that of a tungsten magnet.

It should be born in mind, however, that both the magnetic strength and the retentivity of any finished magnet depend upon the varying conditions of manufacture which we have named above. Even with material of the same analysis, it is possible to make magnets of the same magnetic strength, but varying widely in retentivity. It is also possible by varying the conditions to make from the same steel magnets of the same retentivity, but varying widely in residual magnetism. In fact, it is quite difficult, using the same material, to keep from making magnets which vary in one or the other quality.

In Fig. "2" the curves shown are the result of carrying the magnetization and the demagnetization thru a complete cycle, but one-fourth of this cycle is all that is required in order to determine the qualities of the magnet, as shown in Fig. "3". Attention is called

to the fact that in the foregoing curves the magnetic density if expressed in the flux or magnetic lines per unit area, and the coercive force or the retentivity is given per unit of length; it follows therefore, that the total magnetic strength of a magnet having given residual flux per unit area is proportional to its cross-sectional area, and the ability of a magnet of given retentivity to hold its magnetism is proportional to its length; that is, the length of the var from which it is made.

THE EFFECT OF AN AIR GAP BETWEEN POLES.

In making tests such as are indicated in the results plotted in Fig. "2" and Fig. "3", the magnet under test constitutes the entire magnetic circuit. The curves give the result which would be obtained if the magnet were a closed ring with no air gap between the poles. In other words, they represent the quality of steel as a magnet, and that along. The useful flux of a permanent magnet operating across an air gap is always less than the flux which the magnet would give with no gap between its poles, or when magnetically "short-circuited". On account of the very high reluctance or magnetic resistance of air the residual magnetism of a magnet of a given length is lessened as the air path between the poles is increased, and right here comes a very important consideration in the design of apparatus embodying the use of permanent magnets.

Referring to Fig. "3", it will be noted that as the demagnetizing force is increased from 0, the residual magnetism reduces very slowly at first, and that as the demagnetizing force is increased the magnetism falls more and more rapidly until finally it comes down along an almost vertical line. This indicates that for moderate demagnetizing forces the permanent magnetism

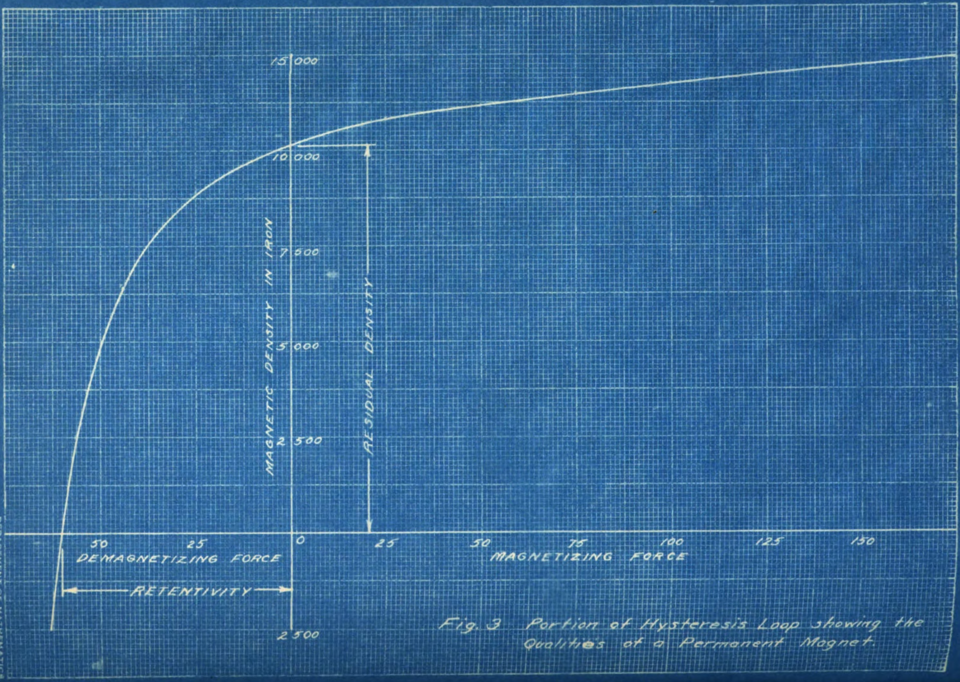


Fig. 3 Portion of Hysteresis Loop showing the Qualities of a Permanent Magnet.

is very stable, but that if the demagnetizing action be carried beyond a certain value the flux becomes unstable and the magnet will not recover its strength when the demagnetizing force is removed.

Since the introduction of an air gap between the poles of a permanent magnet has the effect of partially demagnetizing it, and the extent of demagnetization depends upon the relative length of the magnet and the air gap, it is important that the ration of length of magnet to length of air gap be such that the magnet will not be demagnetized by the air gap to the point where magnetization becomes unstable. In some types of apparatus the permanent magnets used are required to operate in opposition to a coil of wire carrying an electric current, as in the case of a magneto, the demagnetizing effect of which is added to that caused by the air gap, and in designing apparatus of this character it is important to take into account the effects of both the air gap and the coil.

If the magnetization in a permanent magnet be once reduced to the point where it becomes unstable, the magnet will not recover, so that it is important to bear in mind that the characteristics of the magnet and the magnetic circuit on which it operates must be such that the maximum reduction of flux under any condition of operation must not be to a point where the flux becomes unstable.

Since the retentivity of a magnet is the measure of its stability in opposition to demagnetizing effects, the reader will readily see that this quality is of equal, if not greater importance, than the magnetic strength. It is possible, by the proper selection of steel and the use of a heat treatment corresponding to the characteristics of the steel, to produce magnets of uniformly high retentivity without sacrificing magnet strength. It is also possible by using a heat treatment adapted to the character of the steel to obtain maximum strength without sacrificing its retentivity.

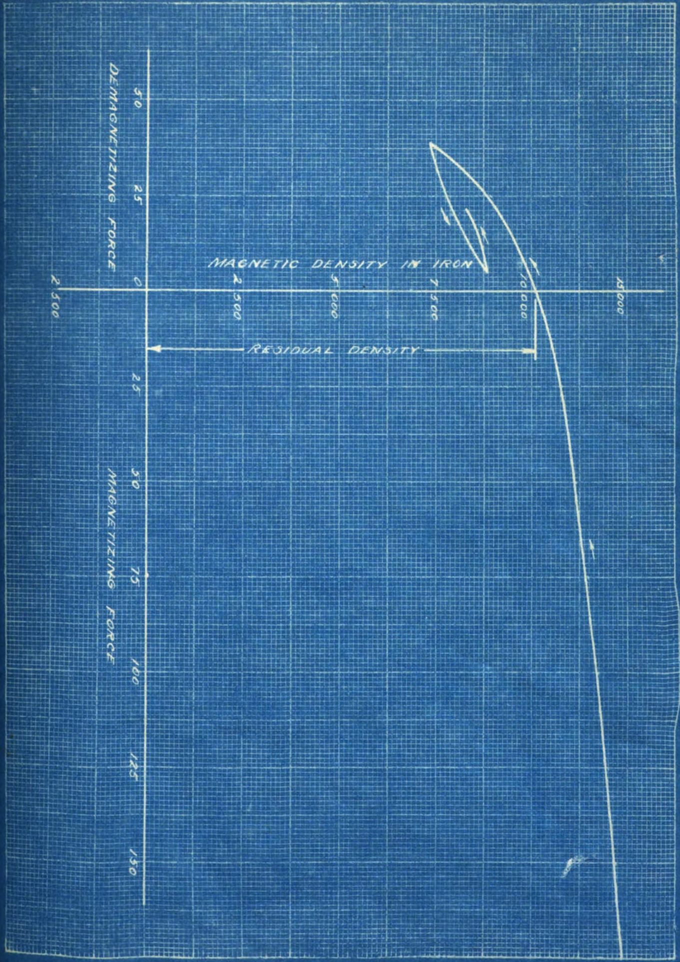
It is essential, for the best results, that the magnet be selected or designed for the magnetic circuit on which it is to opperate, and for any magnetic circuit considered there is a cross-section and length of permanent magnet which will give the maximum flux, with the requisite stability, using a minimum amoung of magnet steel.

AGING OR MATURING OF MAGNETS.

In some classes of apparatus, particularly electrical indicating, integrating and recording instruments, the maintenance of the initial calibration and accuracy of the instruments, requires that the magnets be brought to as stable a magnetic condition as possible before the instrument is calibrated. This is called aging or maturing of the magnets. Bringing a magnet into a condition where its flux will be stable requires two things, viz:

1. A physical treatment of the steel after quenching, which makes further changes in its structure, molecular condition or magnetic quality improbable.
2. A magnetic treatment of the magnet after magnetization, which will make changes in its state of magnetization, under the conditions of ordinary operation improbable.

When a magnet is hardened it, of course, undergoes very rapid structural changes, and for a time after quenching there is a change in donditions taking place, quite rapidly at first and gradually decreasing until the physical properties become stable. This stability of structural state of the steel can be hastened by physical treatment, which process is called aging or


DEMAGNETIZING FORCE
MAGNETIZING FORCE
MAGNETIC DENSITY IN IRON
RESIDUAL DENSITY
50
25
0
25
50
75
100
125
150
2 500
2 500
5 000
7 500
10 000
15 000

maturing. Obviously the treatment applied must be such as to only age the steel without impairing its magnetic qualities.

As has been already stated, it is possible after magnetizing a magnet to bring it to a state of magnetization, in which the total or useful flux will not be greatly altered by such demagnetizing action as that to which the magnet will be subjected in use, provided, of course, it is properly designed for the magnetic circuit on which it is used. It should be clearly understood that this treatment does not alter the retentivity of the magnet, but simply changes the magnetic state in such a manner that the ratio of change in flux to magnetizing or demagnetizing effects is reduced at that part of the magnetic cycle represented by the state of residual magnetization.

In Fig. "3" we have given a curve showing the relation between residual density and magnetizing and demagnetizing forces, from the point of maximum magnetiaation to complete demagnetization, when the change from one state to another is gradual and uninterrupted. It will be noted that upon the application of a demagnetizing force, the residual induction begins to drop and as the force is increased the reduction becomes more rapid, until a point is reached where the curve is almost parallel to the flux ordinate.

This means that with a magnet in this state of magnetization the flux of the magnet will vary along this curve when the magnet is subjected to any exterior magnetizing or demagnetizing force, such as the action of a coil on stray fields, etc. In order to make the value of the residual flux as stable as possible, it is necessary to have the curve as nearly parallel as possible to the horizontal axis.

In Fig. "5" is shown the curve of a magnet taken as it is put through this stabilizing process. The arrows indicate the direction of magnetization or demagnetization. After the magnet has been fully magnetized, a demagnetizing force is applied which removes a portion of the flux. It is next subjected to a magnetizing force, and then to a demagnetizing effect, which has the effect of bringing the curve more nearly parallel to the base line, although the residual induction is somewhat reduced. It is obvious that this treatment should be applied after the magnetic circuit on which the magnet is to operate has been completely assembled.

MATERIALS OF MANUFACTURE.

Permanent magnets can be made of cast iron, of steel carrying from .3 to 1.5% of carbon, or of alloy steel containing carbon, together with tungsten, molybdemum, chromium or vanadium. Cast iron magnets are used principally in galvonometers and similar apparatus, where weight is not objectionable and efficiency is not a matter of importance.

CARBON STEEL MAGNETS.

For some classes of work, where space and weight are not of importance, magnets made of a good grade of open hearth carbon steel are used. By a careful selection of such steel with reference to its carbon, manganese, sulphur and phosphorus content, it is possible by proper heat treatment to produce magnets having a flux or magnetic strength of about 75% that of tungsten or chromium steel magnets of the same cross-section, and a retentivity of about 70% of that of the better grades of steels just named.

TUNGSTEN STEEL.

For many years prior to the outbreak of the European war the alloy steel most commonly, in fact almost universally used in the manufacture of high grade permanent magnets, was one containing principally carbon, tungsten and chromium, and in which the percentage of manganese, sulphur and phosphorus were kept to the lowest practical limits. Such an alloy, if properly made in the steel mill and intelligently processed in the magnet-making plant, will produce magnets of high strength and permanence. Due to the very high cost and the inability to obtain tungsten steel during the war, it was necessary to develop other alloys for use in the manufacture of permanent magnets.

CHORIUM STEEL.

By the use of chromium alloys, produced under correct conditions and treated according to processes particularly adapted to them, magnets are being produced which, from the standpoint of both strength and retentivity, are the equal to the tungsten product. It is a fact that the chromium alloys do not permit of as wide a range in the manufacturing and the heat treating conditions as the tungsten steel, but with proper and uniform conditions the product shows greater uniformity than was the case with the tungsten alloy. That is, the average results with chromium steel alloys are in every way equal to those obtained with tungsten steel, and the product does not vary from the average by nearly so wide a margin as in the case of the tungsten alloy.

ANALYSES AND HEAT TREATMENTS OF THE STEELS USED BY SOME OF THE MORE PROMINENT MANUFACTURERS.

INDIANA STEEL PRODUCTS COMPANY.

Analysis.

Tungsten steel		Chromium steel	
Carbon	0.65	Carbon	0.65
Tungsten	5.75	Chromium	2.40

Heat Treatment.

The steel is hardened at the correct heat, which varies according to the size, from 1480 to 1550 degrees F., and quenched in water or a solution so that the material is hardened throughout the entire section.

SPLITDORF ELECTRICAL COMPANY.

Analysis-chromium steel.

Carbon	0.889
Chromium	2.03
Vanadium	Traces.

Heat Treatment.

The steel is heated to 1480 degrees F., and quenched in water.

THE ESTERLINE COMPANY.

Analysis-chromium steel.

Carbon	0.89
Phos.	0.017
Sulphur	0.023

Silicon	0.25
Mang.	0.44
Chrom.	3.03

Heat Treatment.

The steel is heated to 1525-1550 degrees F., and quenched in oil.

STROMBERG-CARLSON TELEPHONE MANUFACTURING COMPANY.

Analysis.

Tungsten steel.		Chromium steel.	
Carbon	0.39	Carbon	0.89
Tungsten	6.00	Chromium	2.00-2.35

Heat Treatment.

Chrome magnets are hardened at a temperature of about 1450 degrees F., while the Tungsten magnets are hardened at 1550 to 1600 degrees F.

THE BRITISH THOMSON-HOUSTON COMPANY, LIMITED.

Analysis.

Tungsten steel	Grade 1.	Grade 2.
Tungsten	5.960	5.460
Manganese	0.245	0.404
Carbon	0.616	0.698
Chromium steel.		
Chromium	2.000	
Carbon about	0.750	

Heat Treatment.

The steel is heated to 750 degrees C, or 1380 degrees F., and quenched in water.

THE SUMITOMO CHUKOSHO, LTD. OF OSAKA, JAPAN.

This company has recently patented a new magnetic steel containing from 0.3 to 0.2 per cent carbon and about 35 per cent cobalt alloyed with either chromium, molybdenum, or tungsten. It is claimed that magnet steel of this composition will give a coercive force appreciably over 200, coupled with a remanence of about 10,000.

K. S. MAGNET STEEL.

In June 1917, a new alloy steel was discovered by K. Honda, a Japanese scientist. This steel possesses a very high coercive force, and no doubt is the best magnet steel known.

The composition of this steel is given as Carbon 0.4 - 0.8 percent, Cobalt 30 - 40 percent, Tungsten 5 - 9 percent, Chromium 1.5 - 3 percent. Tempering is best effected by heating to 950 degrees C, or 1740 degrees F., and quenching in heavy oil. Measurements of the residual magnetism for specimens of different composition, give values from 920 to 620 C.G.S. units; the coercive force for the same specimens ranged from 226 to 257 gauss. Artificial aging heating in boiling water and by repeated mechanical shock reduced the residual magnetism only 6%. The hysteresis curve for a magnetizing force of 1,300 gauss were taken for annealed and tempered specimens; for the annealed specimen the coercive force was 30 gauss and for hardened steel the coercive force was 238 gauss and the energy loss per cycle 909,000 ergs. The hardness of annealed and tempered specimens was found to be 444 and 652 respectively on the Brinell scale and 38 and 55 on the Shore scale. The miscostructure of the hardened steel showed a finer grain than for the annealed.

MAGNETO MAGNETS.

As is well known, the permenent magnets are the most important part of any magneto, and unless the magnet be a thoroughly good one and well magnetized, the magneto will give a very poor performance on test. The manufacture of magneto magnets is attended with considerable difficulties because it is essential that the magnet be finished to fine mechanical accuracy, and at the same time, the magnetic characteristics must be extremely good. Broadly speaking, the essential characteristics are:

1. The magnet must be thoroughly sound throughout its whole structure. That is, there must be no visible or incipient cracks or flaws.
2. The grinding of the pole pieces and edges must be carried out to the necessary fine limits of accuracy demanded by the design of the magnetos.
3. The magnetic characteristics must pass a certain minimum. In other words, the magnet when fitted to the magneto must be capable of creating in the armature core a certain number of magnetic lines and of maintaining these during subsequent life of the magneto.

Under working conditions, the magneto is subjected to considerable vibration and extreme and frequent variations in temperature. Any permanent magnet is liable to lose its strength when operating under such conditions, and to guard a loss of this nature, it is necessary in hardening the magnet to aim at what is termed a coercive force, not less than a certain minimum. Experience has shown that a save minimum is 55, and with certain grades of magnet steel it is quite safe to go below this figure. The coercive force figure is simply an indication of the power of the magnet to retain its magnetic field. That is, it is a measure of the magnetic tenacity of the steel.

It is also desirable that the magnet should produce, when fitted in place, as large a flux as possible. The actual working flux in the armature core varies between 20,000 and 50,000 magnetic lines, the former figure applying to polar inductor magnetos, and the latter figure to large rotating armature magnetos. Small rotating armature machines have an active flux much nearer the lower figure specified. Now the value of this flux, for a given design of magneto, is greatly dependent on what is called the remanence of the magnet. An average figure is 10,000 and it is desirable that the remanence should be as high as possible. The remanence figure is an indication of the flux that would circulate around the magnet if its poles were bridged with a heavy soft iron keeper, and it were then magnetized in that condition.

There has been a great deal of controversy about the coercive force and the remanence. It so happens that it is only possible to increase one of these factors at the expense of the other. That is, if the coercive force be increased abnormally, as it can be by special methods of hardening, the remanence will be lowered, and vice versa. It is contended in certain quarters that a magnet with a very high coercive force (70) and a fairly low remanence (9,000 to 9,500) is better than one having a fairly low coercive force (55) and a very high remanence (10,500 to 11,000). From experience, it has been shown that the best results are obtained by striking a happy medium, and that it is really a retrograde move, with the magnet steels at present available, to increase the coercive force beyond a range of from 60 to 65.

If an endeavor be made to push the coercive force beyond the upper limit, the difficulties of manufacture will be increased considerably, and the steel will be brought to such a degree of hardness that incipient cracks are likely to develop much more rapidly. No compensating advantage will be obtained, and as a matter of fact, the active flux created in the magneto armature may tend to diminish in consequence of the lower remanence. It must be pointed out that different steels behave in different ways, and while it may be quite safe to work down to a coercive force of 55 with one grade of steel, another grade having slightly different composition will demand a minimum figure of at least 60. This curious difference in behaviour can be explained, but the explanation is outside the scope of this work.

MAGNET TESTING.

The testing of magnets to determine their suitability for use has been a difficult and contentious problem, mainly owing to the disagreement between leading authorities as to the true criterion of magnetic quality. Quite recently is has been agreed by those able to pronounce judgment on this subject, that the particular characteristics of a magnet which are of importance depend on three distinct factors:

1. Remanence,
2. Coercive force,
3. The shape of the remanence-coercive force curve.

This will be made clear by reference to curve 1, Fig. 6. If we assume that a magnet is wound over its whole length with a magnetizing coil, and then has its poles bridged by a substantial soft iron keeper making a good contact with them, the flux density in the body of the magnet after passing a very heavy current through the coil and again breaking the circuit, would be represented by B_r which is called the remanence.

Now if a reverse current be passed through the coil, the magnet can be slowly demagnetized by gradually increasing the value of this current. With special apparatus, the value of the flux density in the magnet

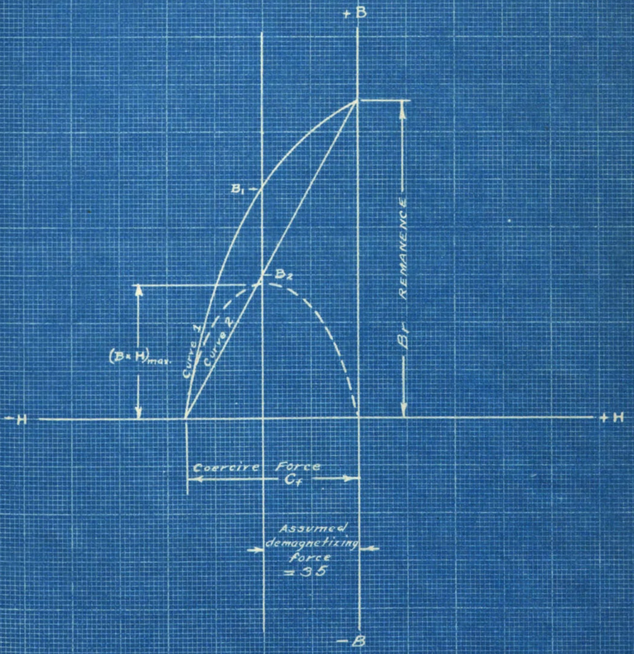


Fig. 6. H-B CURVE FOR A MAGNET

can be readily measured for any value of demagnetizing current, and by plotting these readings curve 1, Fig. 6, is obtained. Corresponding to some definite value of the demagnetizing current, the flux density is brought to zero. This corresponds to the point where the curve strikes the axis of abscissae. The coercive force C_f is calculated from this demagnetizing current by taking into consideration the length of the magnet and the number of turns of the coil.

The important agreement on this matter that has now been reached, relates to the ordinate OB_1 which is the actual flux density in the magnet at some intermediate point in the demagnetizing force (H), and can be taken as the figure of merit when comparing the magnetic quality of magnets that are closely alike. It will be noted that it depends on the three factors already enumerated. Experience shows that if the value of the demagnetizing force (H) be fixed at approximately 35, then the corresponding value of OB_1 gives an accurate indication of how the magnet will perform in the instrument for which it is designed. In other words, OB_1 under these conditions is a figure of merit.

A good method for testing magnetos is shown in Fig. 7. The apparatus used comprises a moving coil type of measuring instrument, from which the ordinary

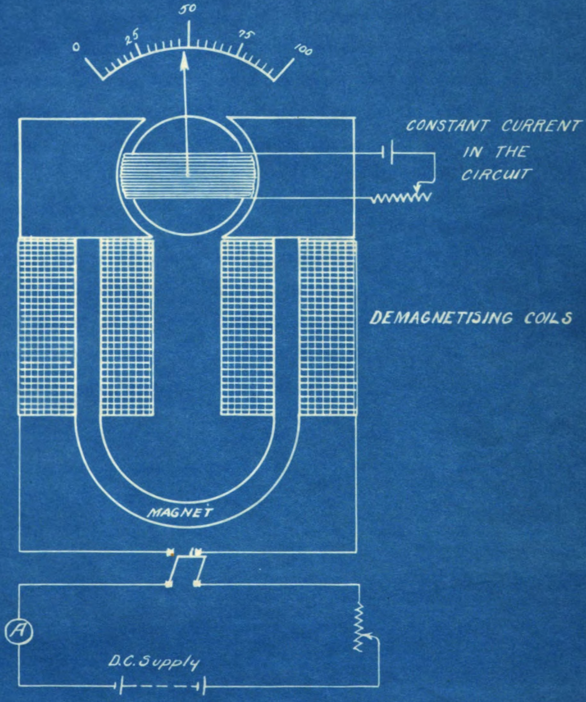


Fig. 7. A Magnet Testing Outfit

permanent magnet has been removed, special pole pieces being provided so that the magnet to be tested can be brought quickly into contact with them. With a constant current flowing thru the moving coil, the deflection of the pointer on the uniformly graduated scale gives a direct indication of the flux in the magnet.

In the testing outfit as shown diagrammatically in Fig. 7, two demagnetizing coils are fitted to the top of the instrument case so that these embrace the limbs of the magnet when it is fitted to the poles. The magnet is first magnetized on a separate and distinct magnetizing outfit. With each magnet, three readings are taken:

1. The first reading immediately after magnetizing the magnet and fitting it to the instrument. Call this d_1.
2. The circuit through the demagnetizing coils is then completed through a large variable resistance, and the demagnetizing current gradually increased. Corresponding to a demagnetizing force of approximately 35, the deflection is again observed. Call this d_2.
3. The demagnetizing current is further increased until the deflection is just zero. The demagnetizing current is carefully noted. Call this cl.

By using standard magnets of different magnetic characteristics, it is possible to calibrate the instrument so that the actual coercive force and remanence figures for any magnet tested can be deduced from the readings d_1 and c_1. Briefly, if the readings as set forth above be taken with a set of standard magnets of any particular make, and it is necessary to use standards representative of each quality of steel, the results can be plotted to give two straight lines:

(a) The first connecting d_1 and the product $(B_r \times C_f)$.

(b) The second connecting c_1 and C_f.

From these calibration curves, the values of B_r and C_f for any magnet tested, can be deduced from the readings d_1 and c_1, by referring to the calibration curves that have been plotted from readings given by standard magnets of corresponding make.

But as already pointed out, B_r and C_f are not the whole story, and the reading d_2 taken by itself, is a criterion of magnetic quality, when testing magnets in bulk which are, as is usual, closely alike. The fallacy of depending entirely on the remanence and the coercive force figures, and fortunately, dependence has been placed on figures almost entirely in the past, is made

apparent by curve 2 in Fig. 6. It is a hypothetical case, but assuming that a magnet gave such a demagnetizing curve, it should be noted that the active flux in the armature core of the instrument to which it is fixed would be approximately OB_2/OB_1 or 60 per cent of the flux produced by the other magnet when fitted to the same instrument, despite the fact that the remanence and the coercive force figures are identical.

The agreement is that the maximum value of the product of flux density and demagnetizing force reached during the demagnetizing process, can be taken as a figure of merit, provided that the remanence and coercive force figures are of the same order. A large number of tests have revealed the fact that on the average the minimum point on this new curve lies approximately along a line drawn through the abscissa whose point H equals 35. On this basis, the ordinate OB_1 is approximately a measure of the maximum product referred to, and the two methods of testing should therefore yield substantially the same results.

TESTING PERMANENT MAGNETS BY THE USE OF A MAGNETOMETER.

The apparatus used in this method of testing is shown in Fig. 8 and consists of:

1. A magnetometer,
2. A telescope with a scale attached,
3. An apparatus for the holding of magnets to be tested with divisions marked off in cm. for obtaining the distance of the magnet from the magnetometer.

The magnetometer consists of three small magnets made from 3/4" lengths of a watch spring and a small mirror about 1/2" square fastened upon a nonmagnetic holder, as shown in the right hand corner of Fig. 8. This apparatus is suspended by a single strand of silk fibre in a box like structure. The silk fibre is attached to a pin which is adjustable so as to be able to raise and lower the magnetometer. The box enclosing the magnetometer has a glass front facing the telescope and scale so that the deflections of the magnetometer can be caught from the mirror.

The deflections of the magnetometer are read through the telescope from the scale attached.

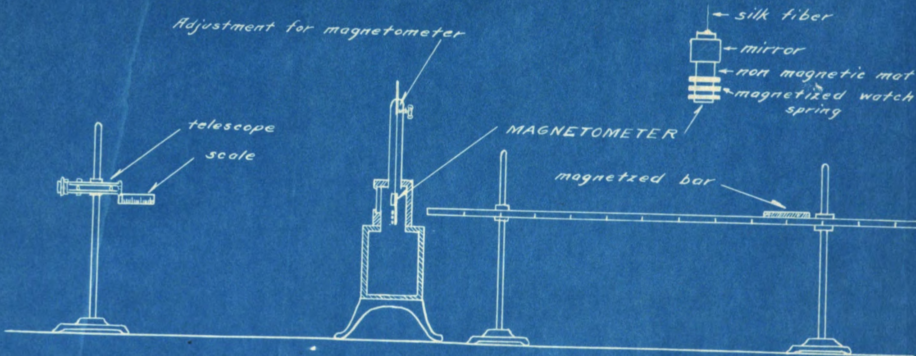


Fig. 8 Magnetometer Apparatus

TO SET UP THE APPARATUS.

The apparatus is set up as shown in the figure with the watch spring magnets of the magnetometer acting in the same direction as the earth's magnetic field. The telescope is set at a distance of 90 cm. from the center of the magnetometer and the scale set at 25. The device for holding the magnets to be tested is placed in the same plain as the magnetometer and at right angles to the earth's magnetic field.

TESTING THE MAGNETS.

The center of the magnet to be tested is placed at a distance of 100 cm. from the magnetometer with the axis of the magnet perpendicular to the earth's magnetic field from the center of the magnetometer. The lines of force from the magnet attract one pole of the watch spring magnet and repell the other thus producing an angle between the axis of the watch spring magnet and the earth's magnetic field. That is, the permanent magnet deflects the watch spring magnet from the action of the earth's magnetic field to the extent of the intensity of the permanent magnet. These deflections are measured from the deflections of the scale in the mirror thru the telescope. These deflections are averaged for both poles of the magnets and the magnetic moment and the pole strength of the magnet is obtained from the following formulae:

$$\frac{M}{H} = \frac{d^3 \tan \theta}{2} \text{ or } M \text{ equals } \frac{H d^3 \tan \theta}{2}$$

Pole strength equals M/l c.g.s.

Where:

M equals the magnetic moment,

H equals the horizontal component of the earth's magnetic field which was 0.173 under conditions of testing.

d equals the distance of the center of the permanent magnet from the center of the magnetometer.

tan theta equals one half the deflection read upon the scale divided by the distance of the telescope from the magnetometer.

l equals the length of the permanent magnet.

RESEARCH WORK ON PERMANENT MAGNETS.

OBJECT:

The object of this research work is to obtain the comparative pole strength of permanent magnets produced under magnetization during different heat treatments of the steel, and to prove certain assumptions in connection with the theories of magnetism.

ASSUMPTIONS:

That is the molecular theory of magnetism is true; then it is the opinion of the writers that upon heating a piece of steel, the molecules will be in a more pliable state and therefore more easily moved. That is, the freeness of movement of the molecules increases in some proportion to the increase of temperature in the steel. Now if a piece of steel is heated to a certain temperature and while at this heat, the steel is magnetized by a suitable flux, then the molecules will arrange themselves more easily and in a less distorted fashion than under ordinary magnetization of the cold steel. In fact, there should be a greater number of molecules in a better alignment due to a greater freedom of motion of these molecules, and upon bringing the temperature of the steel down to that of the troom, the molecules should be in a less strained condition than under the ordinary means of magnetization. With these conditions prevailing, a stronger magnet should result from the heating, and it was under these assumptions that the writers experimented, the results of which follow.

Of course, the electron theory has replaced the molecular theory to a certain degree, but the correctness of this theory is questioned by some of the foremost physicists of the day. This theory is, as explained in a previous article, that the atoms of a substance are built up, in part at least, of a number of electrons in rapid rotation about a certain nucleus of positive electrification. Each of these electrons moving in its orbit is equivalent to a minute magnet. In case of diamagnetic substances, these orbits are supposed to be distributed in such a symmetrical way that they produce no magnetic field outside of the atom. The diamagnetic atom has no magnetic moment of its own. In the case of paramagnetic substances, it is supposed that the orbits of the electrons are so distributed that the atoms have a magnetic moment of their own, and being little magnets will fall into alignment when acted upon by an external field. In the case of ferromagnetic substances, there seem to be mutual actions between the atoms or molecules. When an external field is applied to a ferromagnetic substance, the natural groupings of the molecules are changed; these elementary magnets fall into new positions of equilibrium, one after the other, and we have the effects known as permanent magnetism. The key then to ferromagnetism is the attraction and the repulsion of one molecular magnet upon another.

The theory of magnetism is that the diamagnetic effect is probably present in all substances; but in many cases, it is masked by the paramagnetic turning of the molecule, and there is also present a mutual action between molecules. The same reasoning and assumptions, as were brought forth under the molecular theory, can be applied to the above theory.

THE LABORATORY WORK IN THIS CONNECTION.

The steel used in this experiment was of the following composition:

Carbon	0.890
Chromium	3.030
Manganese.	0.440
Phosphorus	0.017
Silicon.	0.250
Sulphur.	0.023

The steel had been hardened by heating to 1525 - 1550 degrees F., and quenching in oil.

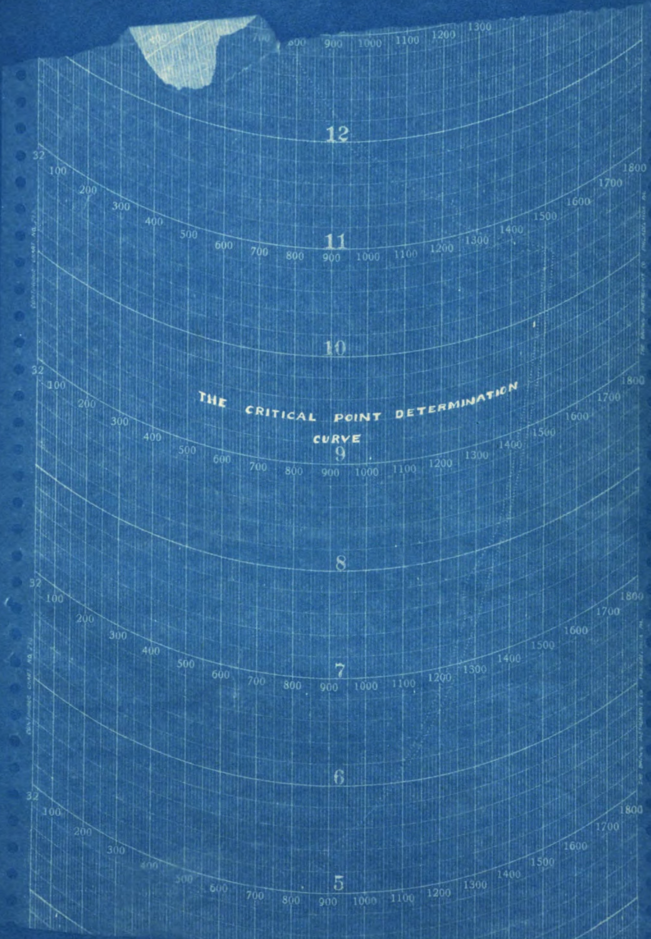
CRITICAL POINT.

A piece of the steel was annealed at 1450 degrees F., so as to be able to machine it. A 3/16" hole was drilled in one end of a piece 1-1/2" long to a depth of 3/4". The piece was then placed in the Brown critical point determination apparatus. The resulting graph is shown on the following page from which the critical point was found to be at 1250 degrees F.

HEAT TREATMENT AND MAGNETIZATION.

There were several plans considered for the heat treatment and magnetization but the writers finally come to the conclusion that the best method was to heat the steel to the right temperature, pass a flux thru the bar by means of a large electro-magnet for several seconds, and then to quench the bar while it was still being magnetized. To build an apparatus to do these three things, heat and steel quench and magnetize, in one unit would be a very difficult and unsatisfactory plan, so it was decided to magnetize and quench the steel outside of the furnace.

The steel (3/8" x 3/4" cross section) was cut in 6" lengths and numbered 1,2,3,4,5,6,7,8,11 and 12. The bars were heated to the following temperatures:


THE CRITICAL POINT DETERMINATION
CURVE

Bar No. 1	. . . .	Room Temperature
" " 2	. . . .	700 degrees F.
" " 3	. . . .	800 " "
" " 4	. . . .	900 " "
" " 5	. . . .	1000 " "
" " 6	. . . .	1100 " "
" " 7	. . . .	1200 " "
" " 8	. . . .	1300 " "

Bars 11 and 12 were heated to 1200 and 1300 degrees F., respectively for check bars.

The bars were heated to their respective temperatures and held at this heat for five minutes to insure a uniform heat throughout the bar. The bars were instantly placed between the poles of a large electromagnet and magnetized for 10 seconds while they were at heat. This process should have helped the formation of the alignment of the molecular magnets. The bars were then quenched with water while they were still being magnetized keeping the flux flowing thru bar for 50 seconds.

TESTING.

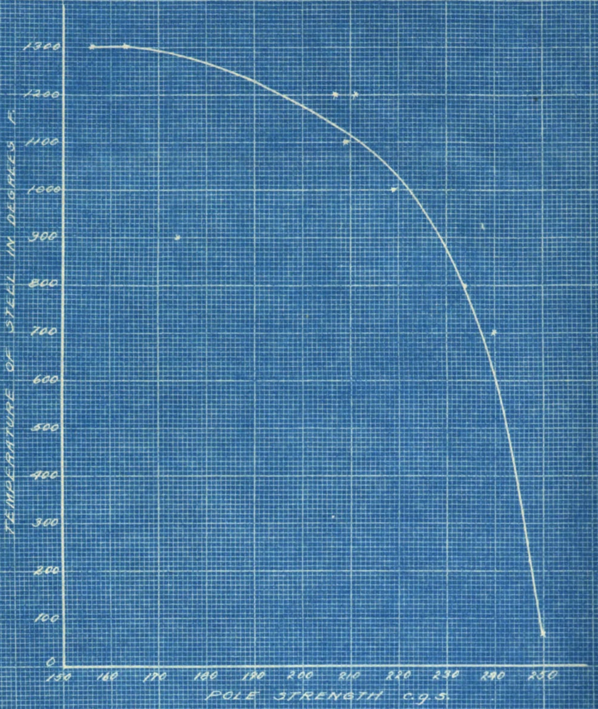
The pole strengths of the magnets were found by the use of the magnetometer apparatus which is fully described in the preceding article on testing permanent magnets. The bars were placed at a distance of 100 cm.

from the magnetometer and an average deflection was taken for both poles of the magnet. From these deflections, the magnetic moment and the pole density were figured. The formulae used for computing the magnetic moment and the pole density were:

$$\frac{M}{H} :: \frac{d^3 \tan \theta}{2} \text{ and Pole strength equals } \frac{M}{l_{(cm)}}$$

RESULTS:

Bar No.	Temperature of the bar	Deflection of Magnetometer	Pole strength in c.g.s.
1	room temp.	7.9935	249.8
2	700	7.5200	240.0
3	800	7.3320	233.8
4	900	5.4630	174.5
5	1000	6.8760	219.8
6	1100	6.5620	209.6
7	1200	6.4950	207.0
8	1300	5.1000	163.0
11	1200	6.9346	211.5
12	1300	4.8962	156.3



GRAPH showing the relation between the temperature at which the steel was subjected to magnetization and the resulting pole strength of the magnets formed.

CONCLUSIONS.

The results as shown in the table and graph prove to be quite the opposite from what was expected. According to the assumptions, the feasibility of which has not been denied by any of the physicists with which the writers have consulted, the steel should increase in magnetic density, to a certain extent at least, with a specified magnetization under a rise in temperature. This, however, was not the case but quite the opposite. The greater the temperature at which the steel was magnetized the lower the pole density obtained. The question arrises as to the effect of heat upon the matnetism of a piece of steel from the well known fact that heat destroys magnetism. This fact, however, does not tend to tear down the assumptions made, but quite the contrary.

The simple experiment of heating a magnet has been shown to everyone who has taken a course in physics and it not only substantiates the molecular theory but shows that the molecules have been distorted from their normal position during the process of magnetization and that heat does have an effect upon the movement of these molecules. What more proof does anyone want that the assumptions wer logical?Is it not reasonable to suppose that if this experiment were reversed and the heat used to make the molecules appliable, and a magnetizing force be then applied, and the material quenched, that it would produce stronger magnets with greater retentivity? There remains but one other conclusion to the results and that is that the fundamental idea of the molecular theory is incorrect. To decisively prove this would be a very laborious and difficult problem but the writers believe that they have one of the most important stepping stones in the process of destroying the molecular theory.

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