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A Paper read before the Northern Centre on the 16th November, 1938

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Elementary magnetic theory.

In dealing with this subject it is essential to consider first a few of the elementary facts concerning magnetism. While magnetism has been known for over 2000 years it was only established as a science in 1600 by William Gilbert. It was later very greatly influenced by other scientists such as Ewing and Weber, who developed the theory regarding polarity of molecules, and Faraday, who in 1831 made the important discovery of the Electro Motive Forces induced in conductors by their movement through magnetic fields and the mutual inductive effects between circuits which are magnetically linked.

First of all consider the properties of a magnet, which are three in number:—

1. The attractive property by virtue of which a magnet will attract pieces of iron and steel.
2. Directive property due to which a magnet, if suspended, will take up a definite geographical position.
3. Inductive property by means of which it will impart all its properties, either temporarily or permanently, to other magnetic materials.

What is understood by magnetic materials? The simplest definition is that a magnetic material is any substance to which the three foregoing properties may be imparted. Iron is, of course, the principal one and there are relatively few substances which have magnetic properties in any way comparable with those of iron. The chief among them are nickel, cobalt, alloys of these materials, some compounds of iron and alloys of manganese. These materials are generally known as Ferromagnetics and they are characterised by high magnetisation values in weak magnetic fields and also by the fact that, in general, they are capable of being permanently magnetised. Their magnetic properties are of very varied character and are markedly influenced by mechanical and thermal treatments of the material.

It is because a knowledge of the magnetic characteristics of these ferromagnetic materials used in electrical machinery and apparatus is of fundamental importance, that the laws relating to the magnetic circuit will be considered from its elementary stages.

It is not often realised that all our practical units of electrical measurement are based on one fundamental unit—the unit magnet pole. It is that strength of pole, which, at one centimetre distance in air from a similar pole, will repel it with a force of one dyne. A magnetic field of unit intensity is one which exerts a force of one dyne on a magnet pole of unit strength placed in it. It has unit quantity of magnetism—the Maxwell or Line of force—per square centimetre. It therefore follows that unit strength of pole has 4π maxwells radiating from it.

The C.G.S. or Absolute unit of current is similarly based on the magnetic effect it produces and the C.G.S. unit of Electromotive Force on the cutting of unit quantity of magnetism per second.

Most members know that a conductor carrying a current possesses a magnetic field which is concentric round the current. Fig. 1 shows the relative directions

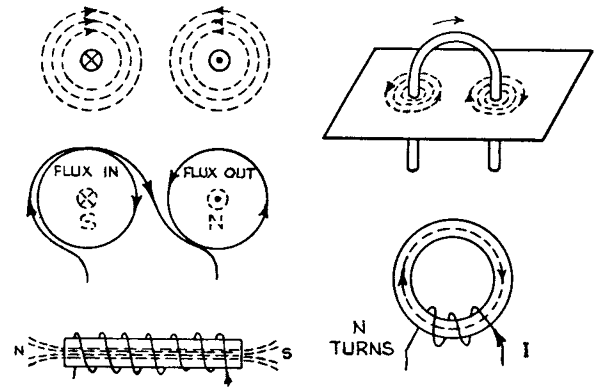

FIG. 1.

of current and magnetic field which can be remembered either by what is familiarly known as the Corkscrew Rule or by Maxwell's Rule, which states that the directions of current and field are related in the same way as the directions of translation and rotation of a right-handed screw.

The resultant magnetic field of a solenoid, *i.e.*, a coil wound in a helix, is similar to that of a bar magnet and a solenoid so behaves. The greater the number of turns and the greater the value of the current, the greater will be the intensity of the magnetic field at the centre of the solenoid.

$$H = \frac{0.4\pi NI}{l} \text{ gausses}$$

where N No. of turns
I Current in amperes
l length of solenoid in cms.

H is the intensity of the field at the centre of the solenoid in gausses or maxwells per sq. cm.

An electromagnet is merely a solenoid with an iron core added. The effect of the iron core is to increase enormously the intensity of magnetisation produced by the same excitation. This is due to the permeability of the material. This is that power possessed, in greater or less degree, by all magnetic materials, of concentrating within themselves the lines of force of the magnetic fields in which they are placed, and of adding lines of force due to their own molecular magnets. This point will be referred to later in the paper.

The permeability of air is taken as unity, and those of other materials represent the ratios of the magnetisation produced in those materials to that produced in air with the same magnetising force.

If B is the flux density produced in the magnetic material and μ the permeability

$$B = \mu H = \frac{0.4\pi NI\mu}{l} \text{ gausses.}$$

If A is the cross sectional area of the material in sq. cms.

ϕ the total flux in maxwells $= BA$

$$= \frac{0.4\pi NI\mu A}{l}$$

which may be written

$$\frac{0.4\pi NI}{\left(\frac{l}{\mu A}\right)} = \frac{\text{(Magneto-Motive-Force)}}{\text{(Reluctance)}} .$$

Here we have a formula which is very similar to that for the flow of a current in an electrical circuit $I = \frac{E}{R}$. We also have an expression for the reluctance or magnetic resistance similar to that for the resistance of a conductor $\left(R = \rho \frac{L}{A}\right)$ especially when it is remembered that μ is the equivalent of conductivity. The one difference which is important is that μ is not a constant value in the same way as the conductivity of, say, copper is constant. The value of μ varies with the degree to which the material is magnetised, *i.e.*, μ varies with H and B.

If values of B and H are plotted, graphs are obtained which are of considerable interest but, as they are not straight lines, the values of $\frac{B}{H}$ must necessarily be variable ratios.

The curves for various magnetic materials disclose their magnetic behaviour under different magnetising conditions and therefore their relative advantages and disadvantages for specific purposes can be ascertained.

A typical B-H curve is shown on Fig. **2** together

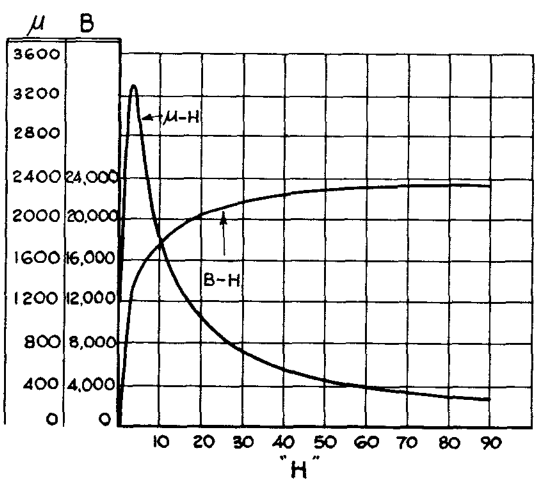

FIG. **2**.

with a μ-H curve showing the variation of the permeability values with varying magnetising values. The maximum value of permeability shown in the example means that, due to the presence of the material within the coil, the magnetic flux is increased over 3000 times.

It will be noticed that in this, as in most magnetic materials, the flux density increases enormously at first but afterwards at a less rapid rate until a point is reached, known as the " saturation point," when the increase in magnetisation is due solely to the increase in the magnetising force.

Another interesting and important phenomenon is illustrated in Fig. **3**. If the magnetising force, after

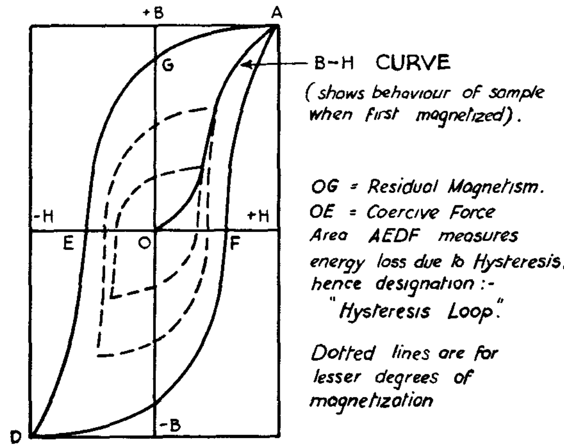

FIG. **3**.—GROUP OF MAGNETIZATION CURVES.

being applied, is gradually reduced, the flux density does not decrease in the same rate as it increased, and when the magnetising force has been reduced to zero, there will be a certain amount of residual magnetism. The term " remanence " is used for the residual magnetisation when the magnetising force is reduced to zero from the value giving saturation. To reduce the magnetisation to zero an opposing field must be applied and the value of this demagnetising field is known as the " Coercive Force." If this magnetising force is then increased, magnetisation values similar to those shown by the portion of the curve, ED, are obtained. For a complete alternating cycle of magnetisation, the values of the flux densities form a graph similar to AEDF, the enclosed area of which is a measure of the amount of work done on a cubic centimetre during one complete magnetic cycle. This curve is known as a " hysteresis loop " and the work done, which is simply wasted in the form of heat, is known as the hysteresis loss. This is of great technical importance and will be referred to later.

At this point it is desirable to deal with the molecular or physical conception of magnetism as deduced by Ewing and Weber. The theory assumes that each molecule of a magnetic substance is in itself a permanent magnet possessing north and south-seeking polarity. With the material in the unmagnetised condition, the molecules are assumed to be lying in all directions or to be linked up into local groups or chains so that there is no external magnetic field. Under the action of a magnetising force these groups are broken up and the molecules drawn into magnetic alignment giving a cumulative magnetic effect and generally an external magnetic field.

There are many striking and interesting supports to the theory, but it is only proposed to mention a few of the most important.

1. The various degrees of susceptibility and of retentivity possessed by the various qualities of iron and steel. The greater molecular rigidity of hard steel requires a greater coercive force to effect a change of magnetic condition —in other words it is more difficult to magnetise or demagnetise.
2. The effect of vibration or any molecular disturbance on magnetisation or demagnetisation. Magnetisation is assisted by light blows on the material while under the action of the magnetising force. Conversely, magnets are weakened by rough usage or the molecular disturbance of great heat.
3. The production of heat and molecular noises in a piece of magnetic material subjected to rapid changes of magnetisation. The molecules can be heard to move and the energy used in overcoming the friction opposing the movement, and which causes the hysteresis or lagging behind, previously mentioned, is transformed into heat.
4. The alteration in the size and shape of a magnetic material due to magnetisation. This phenomenon is known as magneto-stricture and practical use is made of it in depth-sounding devices for ships and in certain types of frequency indicators.
5. The tendency to reach magnetic saturation, *i.e.*, when all the molecules have been brought into alignment.
6. Iron loses its elasticity and its magnetism at the same critical temperature (769°C.)—known as the Curie point.

There are many other supports to the theory and whatever modifications of the original conception have been considered desirable in view of Ampere's idea of circulating currents proposed more than a century ago, and later the electronic view of the structure of the atom, we must accept the idea of elemental magnets, the varying orientation of which gives the various stages of magnetic condition. It has certainly been definitely established that in a ferromagnetic material there is a close connection between the magnetic and mechanical properties. Variations in chemical composition, in molecular structure, the presence of cracks and internal strains, processes of mechanical treatment have all been proved to result in variation of magnetic characteristics.

Magnetic and non-magnetic alloys.

Non-magnetic alloys can be produced although one or more of the constituents may in themselves be magnetic. An example of this is the cast iron alloy produced by Ferranti Ltd. under the name of "Nomag," which contains 10% nickel and 5% manganese. The following comparative figures illustrate the advantageous properties of the alloy:—

	Permeability.	Microhm Resistance Cm³.	Temp. Coefft.
Cast Iron...	330	95	.0019
Nomag ...	1.03	140	.0009
Brass ...	1.00	7.5	.003

It can be cast with the same facility as cast iron, brass or aluminium and has the same appearance as cast iron with which it compares favourably as regards strength and machining properties. The cost is from 30-40% higher than cast iron, but about half the cost of gun-metal formerly used for magnetic separation.

Conversely, strongly magnetic alloys can be produced from (so called) non-magnetic constituents. These are generally of three metals such as manganese, tin and copper or manganese, aluminium and copper.

Magnetic materials may in general be divided into two classes:—firstly, those which can be easily magnetised but quickly lose their magnetism when the magnetising force is removed, and, secondly, those which though difficult to magnetise, retain a large part of their magnetisation even if subjected to considerable demagnetising forces.

The first class comprises the so called magnetically soft materials used for the various forms of electromagnets, such as relays, transformers, repeating coils, loading coils, etc., and for the magnetic circuits of dynamos, alternators, and motors. These materials will be dealt with first.

In the selection of a material for a specific purpose there are six qualities which have to be considered.

(1) Permeability which is a measure of the ease with which the material may be magnetised.

(2) Remanence or residual magnetism already described.

(3) Coercive force or extent of demagnetising force required to eliminate the remanence.

The hysteresis losses are proportioned to the frequency and are dependent upon the relative values of the remanence and the coercive force.

(4) The saturation point or maximum flux density readily obtainable.

(5) Electrical resistance. When a core is energised by an alternating current, induced currents are set up in the magnetic material itself which, if allowed to flow, cause wastage in the form of heat. The loss may be reduced by suitably sectionalising the core by building it up of laminations insulated from one another. Similarly, using a magnetic material of high electrical resistivity means feebler eddy currents and smaller losses. The eddy-current losses are proportioned to the square of the frequency.

Hysteresis losses and electrical resistance are therefore of considerable importance in the design of apparatus for alternating current.

(6) Constancy of characteristics with age and use.

At the close of the 19th century the various grades of iron in use had a maximum permeability of 2000-3000 and the hysteresis and eddy current losses were high. The best transformer sheets were of Swedish charcoal iron with maximum permeability of about 2300. Moreover the ageing properties were such that the losses sometimes doubled within a few months, necessitating dismantling and re-annealing.

Sir Robert A. Hadfield, in conjunction with Bartlett, found that certain iron aluminium and iron silicon alloys had much greater permeabilities with lower hysteresis losses and higher electrical resistances. The 4% silicon alloy which we know as stalloy was first produced with a maximum permeability of about 3600 and having an electrical resistance about five times that of iron, thus largely eliminating eddy current losses. More important still, the quality improved with age. With improved manufacturing methods the losses were still further reduced and the permeability raised and the best quality of stalloy now produced has a maximum permeability value of about 9500.

By refined methods of preparation and more particularly by subsequent heat treatments, carefully controlled, silicon iron alloys have been produced with maximum permeability values up to about 60,000 and with high resistivity and low hysteresis.

These high maximum values are obtained at the low flux densities associated with telephone apparatus operated by speech currents. The material is therefore largely used in cores of induction coils, retardation coils and transformers.

Nickel-iron alloys.

Throughout the 19th century the alloys of nickel and iron were receiving the attention of many investigators on account of the many valuable physical properties which they were found to possess. In 1889 B. Hopkinson investigated the magnetic properties of iron alloys containing varying percentages of nickel and discovered that a steel containing about 25% of nickel was non-magnetic.

Many others examined the magnetic properties of the whole range of alloys but little commercial application resulted, except perhaps with the non-magnetic steels with about 25% nickel which were and still are used to some extent where strength combined with non-magnetic properties is desired.

In 1921 the Western Electric Company of America took out patents for alloys containing about 78% of nickel. These would give, it was claimed, under specified treatments, permeability figures higher than the best pure iron or silicon iron alloys then known.

These alloys were given the name of permalloys and the one first manufactured had a composition of 78.5% nickel and 21.5% iron, all impurities being kept to a minimum. The treatment necessary consisted in first heating the alloy to 900°C. for an hour and cooling slowly, afterwards re-heating to 600°C. and cooling at a fairly definite rate.

In 1923, patents for a series of nickel-iron alloys having similar properties but containing certain quantities of copper and manganese, were taken out by Messrs. Smith and Garnett, and are now held by The Telegraph Construction and Maintenance Co. Ltd., London, who produce the alloys under the name of " Mumetal " and " Radiometal."

A similar group of alloys produced in Germany under the name of " Isoperm " have additions of copper or aluminium to the nickel-iron base. Low hysteresis and good magnetic stability is claimed and mechanical straining is one of the features of the treatment by which these properties are obtained.

Another alloy known as " Permax " produced in France is essentially a nickel-iron alloy containing additions of other metals and is said to be remarkably constant in its magnetic properties.

Figs. **4**, **5** and **6** are typical of the magnetic behaviour of these alloys.

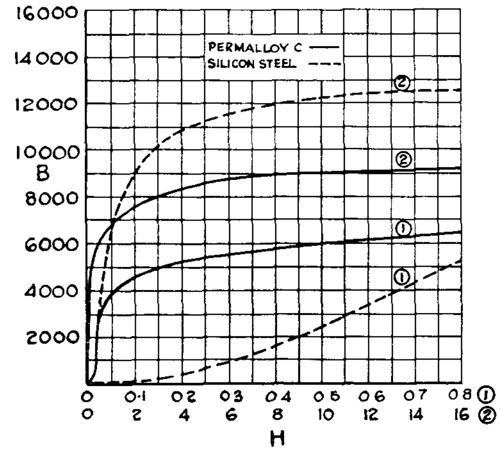

Fig. **4**.—Representative B-H Curves for Permalloy C and Annealed Silicon Steel.

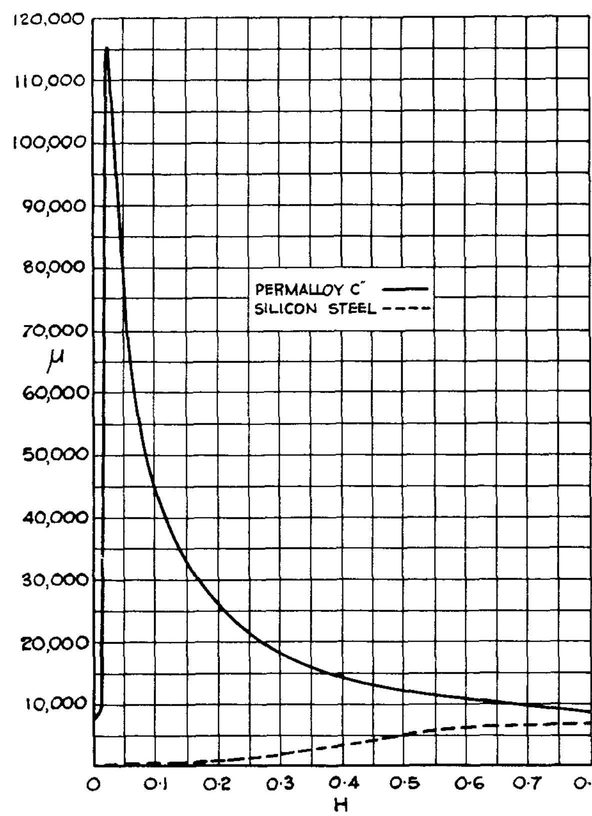

Fig. **5**.—Representative μ-H Curves for Permalloy C and Annealed Silicon Steel.

One striking and important characteristic of the nickel-iron alloys is their high initial permeability, *i.e.*, the permeability in magnetic fields of strengths approaching zero. The following comparative figures, 40 for hard steel, 200 for low carbon dynamo steel, 250 for best soft iron, 400 for silicon steel and up to

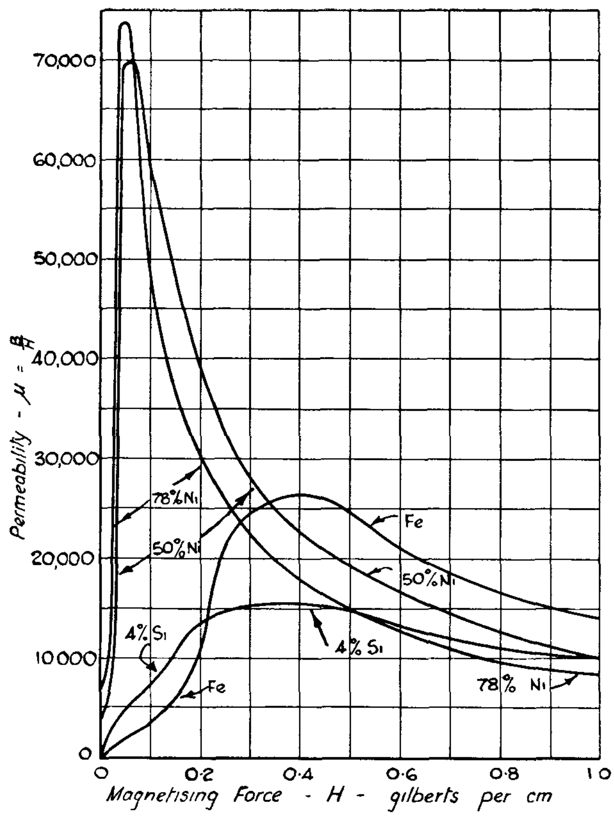

FIG. 6.—μ-H CURVES FOR 78 PER CENT. NICKEL ALLOY, 50 PER CENT. NICKEL ALLOY, 4 PER CENT. SILICON-IRON ALLOY AND PURE IRON.

about 13,000 for the special nickel-iron alloys, show that in apparatus operated at very low magnetising forces, the new alloys have remarkable advantages.

Mumetal containing 6% copper has a slightly lower initial permeability than the binary alloy, but has a higher electrical resistance which is of value in reducing eddy current losses.

Since the first discovery of these high permeability materials, the addition of small proportions of nearly all known metals to the nickel-iron alloy base has been made in order to improve the properties in various required directions. The various patent specifications cite special additions for the purpose of deoxidising the alloys or for improving their uniformity, workability, constancy of properties, or for raising electrical resistance.

Aluminium, cadmium, magnesium, manganese, are included for their deoxidising properties. Aluminium, chromium, manganese, molybdenum, silicon, tantalum, tungsten and vanadium, like copper, raise the electrical resistance. Aluminium, chromium, cobalt, molybdenum, silicon, titanium, tungsten and vanadium improve the constancy of magnetic permeability in varying magnetic fields. Cobalt lessens the hysteresis loss, manganese diminishes the coercive force and assists forgeability, molybdenum increases the initial permeability, improves the uniformity of the alloy and minimises the effect of " strain."

Special additions are also sometimes made to render the alloys brittle, so that they may be more readily crushed when they are required in the form of dust in the construction of dust cores. Considerable care has to be taken in the preparation and utilisation of the alloys so as to obtain the greatest use of their properties. They must be made from as pure materials as possible, the presence in the alloy of impurities such as sulphur and carbon being in general very detrimental. For this reason they are usually melted in special induction furnaces.

The importance of correct heat treatment has already been mentioned. In the early days of the development of the alloys, great care was necessary to prevent stresses and strains in the materials after the final heat treatment, as these proved to have deleterious effects on the magnetic properties. Special subsequent treatments were necessary to restore the best characteristics.

With the fuller knowledge obtained during the past few years, materials have been developed in which the bad effects of overstrain have been greatly minimised by admixture of other elements, thus widening the industrial application to cases in which extreme care in handling or manipulation is not possible.

It is advisable, however, to carry out the final heat treatment as late as possible in the course of their incorporation in any structure. For example, in the use of nickel-iron tapes or wires for the continuous loading of submarine telegraph cables, the alloy is heat treated after it has been wound on to the conductor.

The use of added inductance to telephone and telegraph circuits to counteract the attenuating and distorting effects of capacity, and so to improve transmission, was suggested as early as 1887 by Oliver Heaviside, but it was not until 1899 that practical use was made of the suggestion when Pupin showed the conditions under which the added inductance or " loading " could be applied at intervals along the line.

The problem of loading submarine cables was less easy to solve, but in spite of this, the first loaded submarine cable was laid between England and France in 1910, with coil loading. Owing to difficulties experienced with this type, attention was directed to the mechanically sounder type of cable in which the loading is made continuous by the application of a layer of magnetic material wrapped round the full length of the conductor. In 1910 the first continuously loaded telephone submarine cable was laid, the copper conductors being wrapped with layers of thin iron wire or tape.

The electrical characteristics in a submarine telegraph conductor were such that the continuous loading as applied to the telephone cable was not an economic proposition until a material of higher initial permeability than the iron or silicon iron alloy was available. With the advent of the nickel-iron alloys the situation was changed, and after investigation and large scale experiments, cables were laid round the conductors of which was wrapped a continuous wire of the nickel-iron alloy. The general result of this type of cable was that the speed of working was increased some six to ten times. All the more recent submarine telegraph cables have been so " loaded."

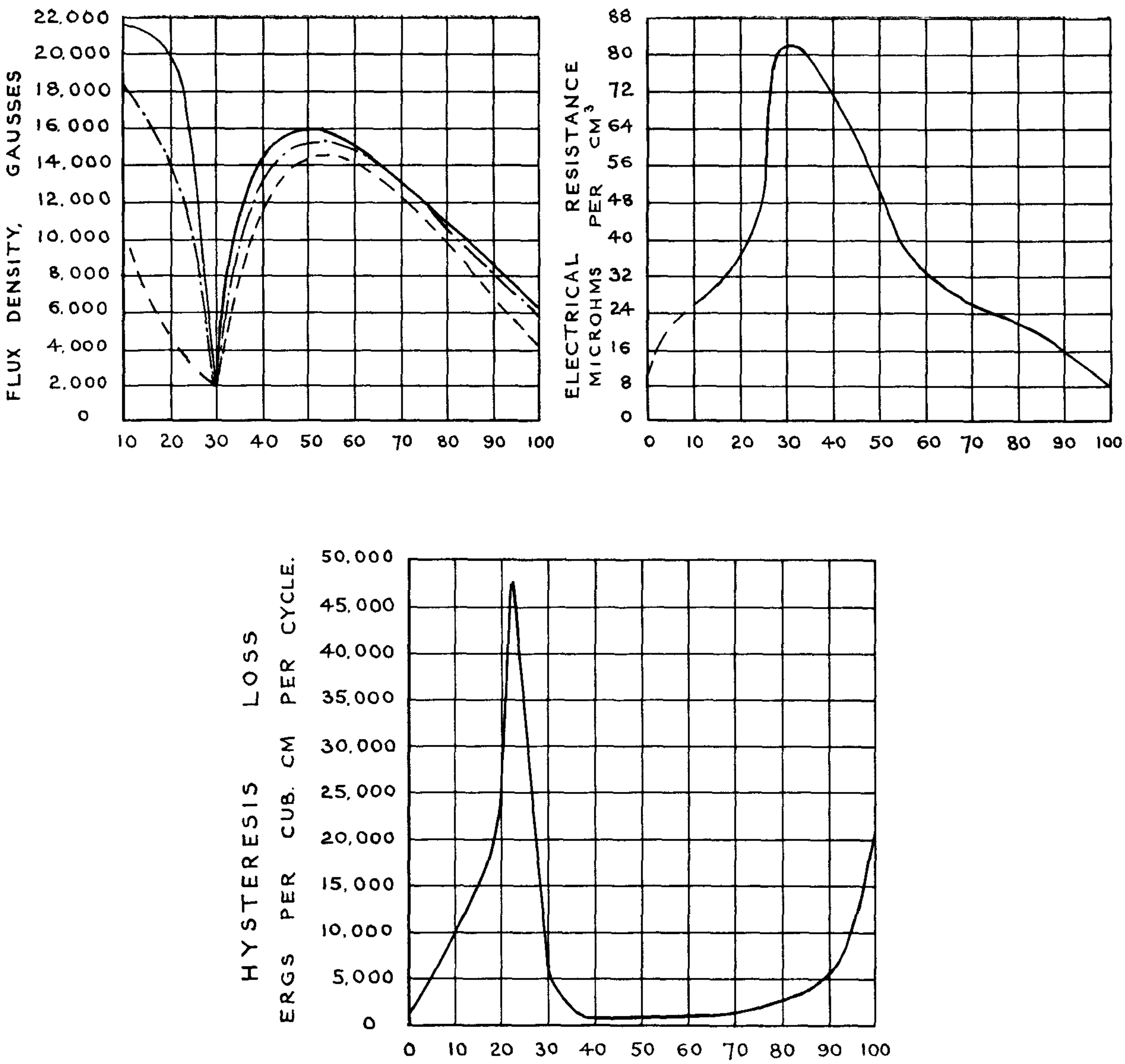

FIG. 7.—NICKEL CONTENT PER CENT.

By using carrier currents a number of channels for both telegraph and telephone working is also made possible.

To adapt Permalloy for high frequency use, about 4% of the iron content was replaced by a like amount of chromium. This alloy has a resistivity higher than Stalloy and an initial permeability about ten times as great, while its coercive force is only about one-tenth. While it is relatively expensive it has been largely used in audio frequency and carrier frequency coils. In the form of a thin tape it has also been used for the continuous loading of telegraph submarine cables.

In addition to their use for the continuous loading of submarine cables, the alloys have also been used for land cables where their introduction into the inductance coils has permitted a considerable reduction in size and resulted in very appreciable savings in the cost of loading.

In this, as in several other applications, it has been found beneficial to employ the magnetic material in the form of dust. Compressed powdered iron had been used for the cores of loading coils and transformers. Those were made of electrolytically deposited iron powdered into fine grains, which were covered by chemical or electrochemical treatment with an insulating film and then compressed under high pressure (200,000 lbs./sq. in.). A maximum permeability figure of about 500 was obtained, but the resistivity being about 60 times that of ordinary iron considerably reduced eddy current losses. With the Permalloy and similar alloys, the admixture of other elements assists in the provision of a material which may be crushed into a dust of a fineness of less than a 200 mesh. The dust is mixed with a suitable binding material and the whole is then fabricated into the required shape of core, and heat treatment is subsequently applied.

Wide control of the magnetic quality of the built-up core is possible by suitable adjustment of the proportions of alloy and binding material, with or without the admixture of a certain proportion of inert spacing material. Some modern core materials are made from cellulose acetate of the non-inflammable type as used in the cinema industry. The finely divided iron or alloy powder is put into the film during a suitable viscous stage in the manufacture. The iron particles, whose size will vary more or less with the frequency at which the coil is to be used, are thus insulated from each other and the complete core is formed by rolling the film into a compact mass.

The high permeability at low field strengths, combined with low hysteresis and eddy current losses, has led to the use of these alloys for cores of current transformers, especially in precision measuring instruments. The use of these materials for the cores of audio frequency transformers and chokes in radio work has led to a marked reduction in the size of the apparatus, and has certainly been found to provide such improved characteristics as to give more faithful reproductions of the transmitted waves.

Within the whole range of nickel-iron alloys a very wide variation of magnetic and electrical properties is available. Fig. **7** shows how flux density, electrical resistance and hysteresis losses vary with the nickel content. By judicious selection, therefore, alloys of very different properties may be obtained from the one series. For example, if high resistivity combined with high permeability is desired an alloy of between 40 and 50% nickel might be selected, whereas if high resistivity and low magnetic permeability is desired, the 30% alloy could be used. For certain purposes the 50% alloy will have advantage over the 78% nickel. It has a higher saturation value and more than double the electrical resistance, whilst at magnetising forces between 0.08 and 0.32 gilberts per centimetre it has a higher permeability than the 78% alloy. Modifications of the 50% alloy are largely used in the making of the low frequency radio transformers referred to, giving a very uniform transmission over ranges of frequency between 40 and 6000 periods per second. They are also used largely in the construction of moving iron measuring instruments—ammeters and voltmeters. This type of instrument is cheap to construct, and simple in operation, but owing to hysteresis errors and the variations with frequency, could not formerly be used as a precision instrument. The low hysteresis loss and high permeability of Permalloy and other similar alloys have enabled these errors to be reduced to a minimum.

The fact that such alloys are so much softer magnetically, than the softest annealled iron, has made it possible to design and manufacture relays of much greater speed and sensitivity than formerly.

The alloys are also used as magnetic shields for electrical instruments and in many other similar cases where the effects of external magnetic fields have to be guarded against.

Mention has already been made of the addition of special metals to the alloys in the nickel-iron series to obtain particular properties.

Among these cobalt is very effective in reducing the hysteresis loss of the alloys and materials with particularly valuable properties are made up of the three magnetic metals—nickel, iron and cobalt. With suitable composition, alloys can be obtained with negligible hysteresis loss. These alloys, which are also characterised by a constancy of permeability at low field strengths, are known as "Perminvars."

Fig. **8** shows comparative hysteresis loops of one

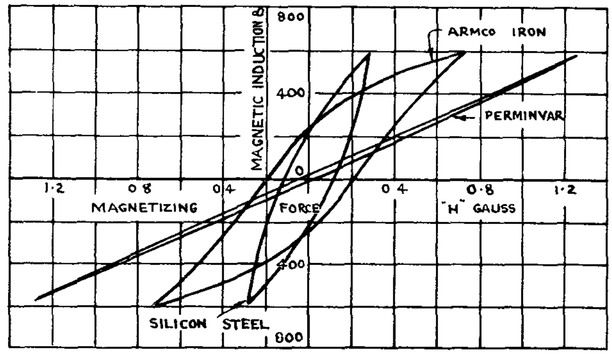

FIG. **8**.—HYSTERESIS LOOPS OF "PERMINVAR" SILICON-IRON AND "ARMCO" IRON.

of this series and of silicon steel and pure iron. The advantage of the Perminvar type will be apparent, especially in its application to high frequencies. The value of this type is also enhanced by the high electrical resistance, a combination of properties resulting in a minimum total watt loss.

The special feature of the Perminvar group is an initial permeability which is constant over a limited range of applied magnetising fields. In general it is, however, inferior to Permalloy and its application is limited to apparatus or circuits where it is desired that inductance shall not vary with current and where exceptionally high permeability is not essential. One drawback at present to its wider use is its loss of Perminvar characteristics if carried even momentarily to flux densities of too high a value (only a few thousand gausses).

Typical compositions as used for loading tapes are 45% nickel, 23% iron, 25% cobalt, 7% molybdenum and 45% nickel, 27% iron, 25% cobalt, 2.6% molybdenum and .4% manganese (for end sections).

Cobalt iron alloys.

Another important material has been developed which, unlike the Permalloys, does not reach saturation until the flux density reaches a high value. In many magnetic circuits, it is desirable to have at some points the highest practicable flux density. The pull of a relay armature, for example, is proportional to the square of the flux density in the air gap. Flux density, as we have already seen, is proportional to the permeability of the core and to the ampere turns of the winding. Any improvement therefore in the core material in this respect makes possible a reduction in ampere turns with resultant saving of power and copper, or, alternatively, with the better core material the same ampere turns will give a stronger pull on the armature. While satisfactory flux densities for most purposes have been secured at reasonable cost in ampere turns with a commercially pure soft iron such as Armco, the improved material effects economies in size and power cost, and makes practicable certain designs not otherwise possible.

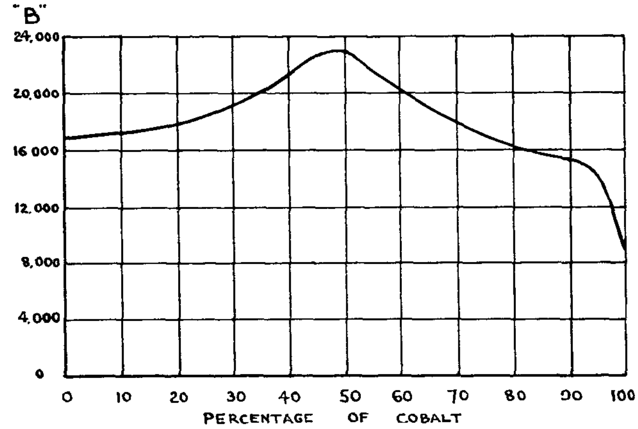

FIG. **9**.—EFFECT OF COMPOSITION OF IRON-COBALT ALLOY UPON FLUX DENSITY. (WHEN H = 50).

Fig. **9** shows what happens when cobalt is alloyed with iron in different proportions from all iron to all cobalt. In plotting the curve the magnetising force has been held constant at 50 and it will be seen that the maximum value of flux density (just over 23,000 gausses) occurs at half iron, half cobalt. This is almost saturation value for this alloy as will be seen from Fig. **10**. Iron, however, is far from its saturation

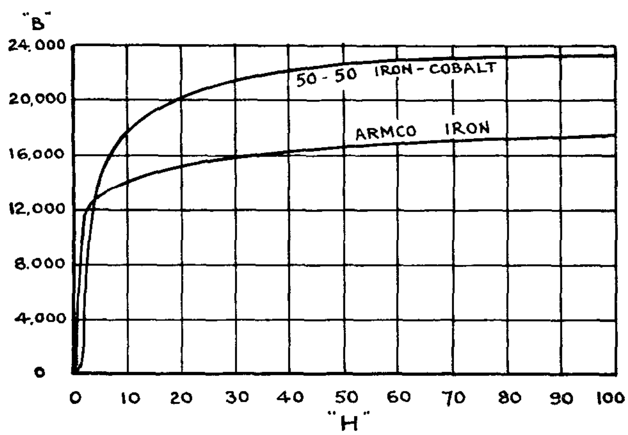

FIG. **10**.—MAGNETIZATION CURVES OF IRON-COBALT ALLOY AND OF IRON ALONE.

value of 22,000 gausses at this value of magnetising force. Above a density of 13,000 the alloy has a higher permeability value than the iron and the 50/50 cobalt iron alloy is therefore very useful for use in heavy duty relays or other apparatus requiring high flux densities. To facilitate fabrication, and reduce brittleness, about 2% of vanadium is added. This does not affect its magnetic characteristics, but, by increasing the electrical resistance three fold, very considerably reduces eddy current losses. This material "Permendur" is being used for the diaphragms in the new type of receiver for the Post Office hand micro-telephones. The particularly valuable feature is its high permeability values at high flux densities.

In many magnetic circuits, a part of the magnetic path has to carry not only a steady polarising flux but an alternating flux due to speech frequency or other currents. Fig. **11** shows that the 50/50 cobalt iron

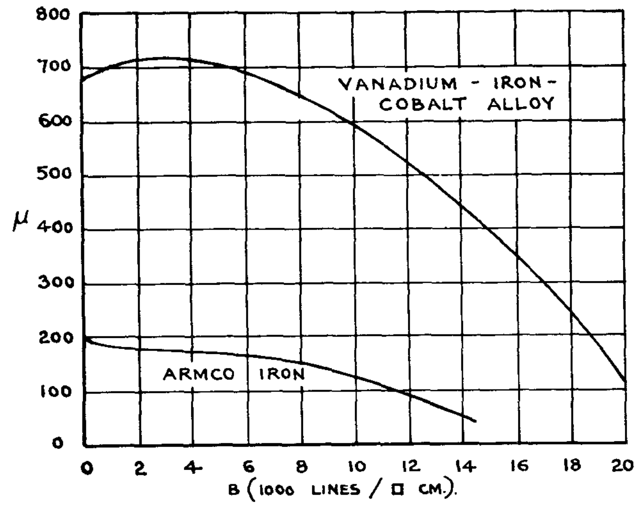

FIG. **11**.—PERMEABILITY FOR SMALL ALTERNATING FIELDS IN THE PRESENCE OF A STEADY POLARISING FIELD.

alloy is superior to iron in this respect, since the permeability to the small alternating flux is much higher at all the polarizing flux densities shown. It is therefore used largely for the pole tips of electromagnets and for the cores of polarized electromagnets.

Permanent magnets.

For these the second class of materials is used, viz., those having high values of remanence and coercive force.

In considering the demagnetisation curve (Fig. **12**)

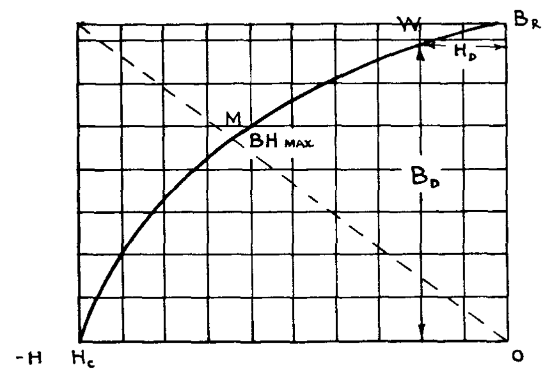

FIG. **12**.—DEMAGNETIZATION CURVE.

the magnet designer is interested in the value of the remanence B_R, the coercivity H_C and also in the shape of the curve.

In a permanent magnet circuit it is invariably necessary that there shall be an air gap in which to set up a strong magnetic flux. The introduction of the air gap causes the working flux density to fall to some such point as W on the curve. The working flux density B_W is therefore always lower than B_R, the amount depending on the extent of the air gap and the quality of the magnetic material. The permanence of the magnetic circuit will depend on the values of B and H at this point W. Without going into any proof, it is found that when W occurs at such a point that the product of B and H is a maximum, then it can be stated that the minimum volume of magnet material will achieve the desired result. This desirable point can be found by the simple geometrical construction shown dotted in the figure and is called the B.H. max. point. With this value and the values of B_R and H_C the designer can proceed to the choice of material best suited to his need.

Before 1910 the principal permanent magnet material was carbon tool steel containing from 1 to 1.5% carbon. These magnets are very susceptible to temperature variations and to mechanical shock and vibration. They are only successful where excessive dimension ratios can be employed.

By the addition of certain elements to ordinary carbon tool steel, materials of varying degrees of excellence have been produced at various times.

The origin of tungsten magnet steel is somewhat obscure, but dates back to about 1880. Silvanus Thompson in 1913 reported that two types were then in use, the best containing from 5 to 5½% tungsten. A good modern tungsten magnet steel contains about 0.67%, carbon, 0.35% chromium and about 6% tungsten.

In 1910 the chrome-steels were introduced.

1% of Chromium added to the steel increased its coercive force and permitted hardening by quenching in oil instead of water, thus reducing the risk of quenching cracks. The coercive force was of the order of 40 or 50 units. It is the least expensive of magnet steels and is largely used where weight is not of such importance as to preclude a magnet of sufficient length to retain its strength. It was largely used in magneto-generators and polarised bells. The addition of 4% of chromium gives a magnet steel with a coercive force of about 70 units. This is also an oil hardening steel and because of its freedom from quenching cracks and lower cost has largely replaced the earlier 5% or 6% tungsten steel which is a water quenched steel of similar magnetic characteristics.

Cobalt steel, dating from about 1917, marked a decided advance in permanent magnet steels. The alloy containing 35% cobalt, 7-8% tungsten and 3% chromium has a coercive force about three times that of the 4% chrome steel and is therefore very resistent to demagnetisation. One drawback to its extended use was its cost (about 12 times that of the 4% chrome steel) and alloys containing lower percentages of cobalt were therefore more commonly used. As, however, magnets of the cobalt alloy could be made shorter and lighter and still of the same strength, it was possible sometimes to reduce the actual cost of the item by using the much smaller weight of the more expensive material.

Several applications in this respect could be mentioned where the reduction in size and weight of the magnetic components have been valuable in the production of small, neat and effective items of plant such as motor car magnetos, telephone generators, and bells, magnets for driving and for braking in electricity meters. It has had a considerable influence in the design of apparatus for aircraft as it has been possible

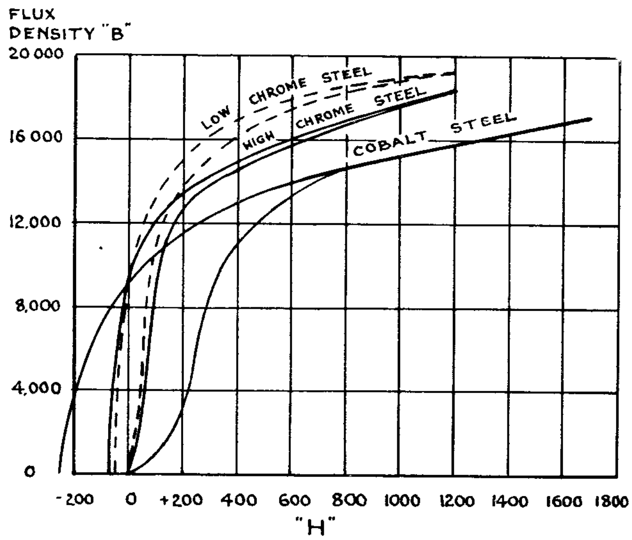

FIG. 13.

to reduce weight without reducing forces. As the cobalt steel can be cast, magnets of a theoretically correct shape can be made and the material thus used to the best advantage.

The cobalt steel helped in the improvement of telephone receivers of the H.M.T. type. Small straight bars were used in place of the heavier C or U-shaped tungsten magnets.

Another interesting application of the cobalt steel was for permanent magnets in moving coil loud speakers. Whereas formerly it was necessary to produce the strong magnetic field required by means of an electromagnet energised by current from accumulators, the high flux density obtainable with the new alloy has eliminated the need for this. The advantages of this type over one needing excitation from secondary cells or mains are obvious.

In modern gramophone pick-ups lightness is a vital consideration and cobalt steel was the first material to fulfil this condition while giving a satisfactory magnetic performance.

Further advances in the saving of space and reduction of leakage have been made from 1930 onwards in the new alloys containing nickel and aluminium.

An aluminium-nickel alloy, with composition nickel 25 to 30%, aluminium 10-15% and iron remainder, has a coercive force value more than double that of the cobalt steel. The higher coercive force is accompanied by a lower remanence so that in order to obtain the same magnet flux, the cross section of the magnet must be increased. Owing, however, to the greater resistance to self-demagnetisation due to the higher coercivity the magnets may be made much shorter. Usually the alloy is used in the form of small blocks and the flux of the magnet directed into the required path by means of magnetically soft pole pieces. Magnets in this material, correctly designed, will give for an equal volume of metal much higher performances than all the earlier permanent magnet materials.

An aluminium-nickel-cobalt steel, typical composition Al 10%, Ni 20%, Co 10%, has a still higher coercive force and a remanence greater than the aluminium-nickel steel, but lower than the cobalt or tungsten steels.

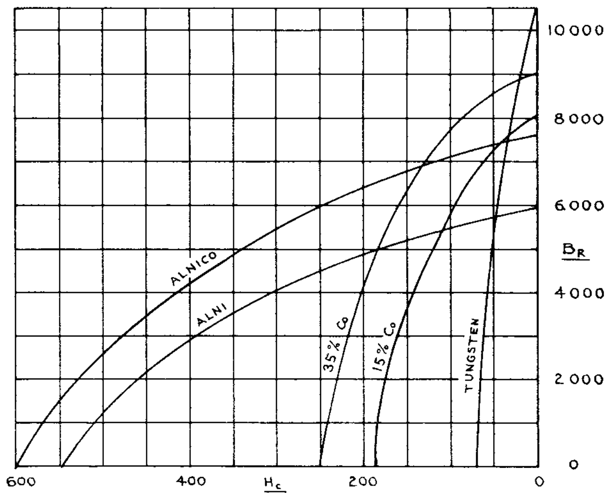

Fig. 14.—Demagnetization Curve.

These two alloys have made possible improved designs with still further saving of space and weight in many types of electrical equipment. Telephone receivers, moving coil speakers, ribbon microphones, magnetos, dynamos, cycle generators, etc. The aluminium alloys are extremely hard and brittle. They cannot be softened and drilled, but in general have to be cast in relatively simple forms. The working faces are then prepared by grinding.

In addition to their unusual magnetic qualities the new alloys have useful properties from the standpoint of corrosion resistance. Under tests unprotected Alnico magnets stand up much better than plated and lacquered tungsten and chrome steel magnets. Even better results are obtained by coating the Alnico magnets with a suitable aluminium spray paint.

The new receivers for the Post Office H.M.T's embody short magnets of Alni with pole pieces of Invar—a 36% nickel-iron alloy with low hysteresis losses. The diaphragm, as already mentioned, will be of Permendur, the 50/50 iron-cobalt alloy with 2% of vanadium added to permit rolling into sheets and to give resilience and stiffness. The electrical resistance being three times higher than Stalloy, the eddy current losses will be reduced.

Acknowledgments.

The compilation of this paper has been assisted by information readily afforded by many firms and also by the loan of samples and the author wishes to express thanks in this respect to the following:—

Mond Nickel Corporation Ltd., Research dept.
Standard Telephones & Cables Ltd., proprietors of Permalloy products.
Telegraph Construction & Maintenance Co., proprietors of Mumetal products.
Siemens Bros., Woolwich, loading materials.
Joseph Sankey & Sons, makers of Stalloy.
Darwins Ltd., Sheffield, permanent magnet materials.
J. Neill & Sons, Sheffield, do.
Ferranti Ltd., Nomag materials.
Research Dept. of the Post Office Engineering Dept.

Dorling & Co. (Epsom), Ltd. A7517