Basics of Magnetism

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Magnetism and magnetic effects are known to nearly everyone but the explanation of how magnetism behaves can be very complicated. This presentation will attempt to simplify magnetic theory to permit the understanding of magnetic fields and their influence on various materials. The nature and strength of these fields will be discussed as will be the practical limitations of magnetic field strengths that can be produced today. Magnetic, paramagnetic and diamagnetic materials will be identified and the behaviour of these materials will be discussed. The effect of magnetic fields on moving charged particles will also be explained.

A magnetic field surrounds an electrical conductor carrying a steady state electric current (D.C.). In an electrical loop this field tends to enlarge the circuit shown in Figure 1 by pushing the parallel conductors apart whereas electrostatic forces try to bring the conductors together, see Figure 1.

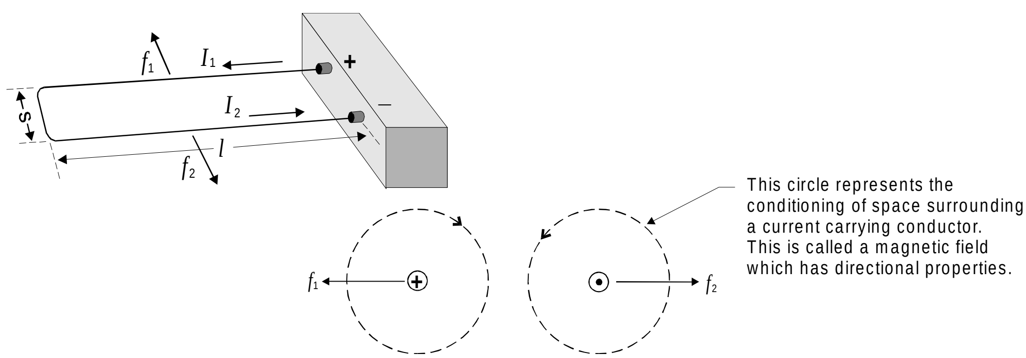

Figure 1 - Mechanical Forces on an Electrical Loop Carrying D.C.

The forces f_1 and f_2 are equal and opposite and lie in the plane of the two conductors. The forces are perpendicular to the axes of the conductors. The magnitude of the force equals:

$$f_1 \;=\; f_2 \;=\; k\frac{I_1 I_2}{s}\,l \quad \text{newtons}$$

If the force is expressed in newtons, the currents in *A* and the distances in *m*, then the proportionality constant *k* has a numeric value of 2 x 10^{-7} when the conductors are in a vacuum. A very important new constant is now defined μ_0 which is called the permeability of free space.

$$k = \frac{\mu_0}{2\pi} = 2 \text{ x } 10^{-7}$$

or

$$\mu_0 = 4\pi \text{ x } 10^{-7}$$

The 2π is a numeric constant that appears in geometrical descriptions of systems possessing circular or cylindrical symmetry.

In Figure 1, we refer to the conditioning of space around a current carrying conductor as a magnetic field. This field has a directional property as shown by the arrows. It also has a flux density property which indicates the strength of the magnetic field. This vector is designated by the letter *B* and defines flux density and the direction of the field. Magnetic flux was originally described as lines or kilolines where flux density of 1 line per cm^2 was defined as a gauss. Although gauss (or plural, gausses) is still in use, the ISO standard for flux is the Weber and flux density is in Webers per m^2 or Teslas. (A Weber is 10^8 lines and a Tesla is 10^4 gausses.)

There is another vector which describes the magnetic field. This vector is called the magnetic field intensity vector and is designated by the letter *H*. This vector is determined only by the size of the electric currents and the configuration of the conductors carrying these currents. When the resulting magnetic field is in a vacuum, then the *B* and *H* vectors are related, $B = \mu_0 H$

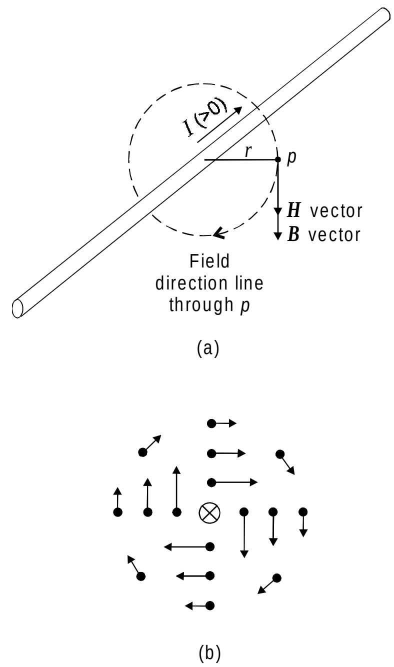

Figure 2

μ_0 can now be seen as the slope of the curve when *B* is plotted against *H*.

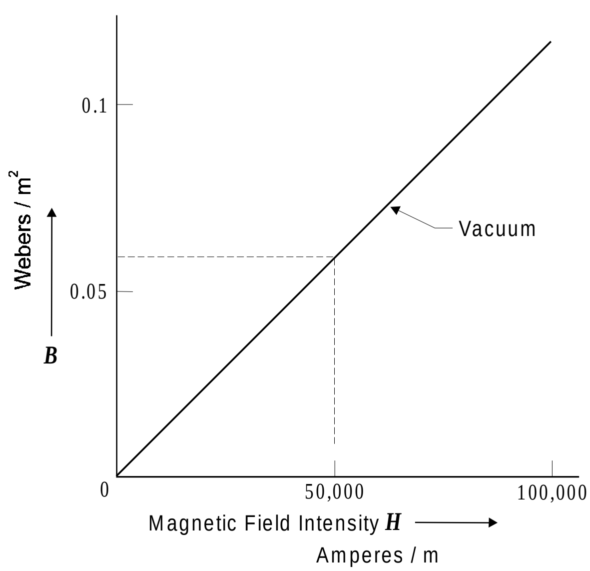

Figure 3 - BH Curve in a Vacuum

Magnetic field intensity H was originally defined in units of ampere-turns (NI) per cm since it was found that a conductor wound in the form of a coil could produce intense magnetic fields inside the coil. The unit in use today is in amperes per metre and relates to the number of amperes flowing into a plane surface which bisects the coil in its long axis.

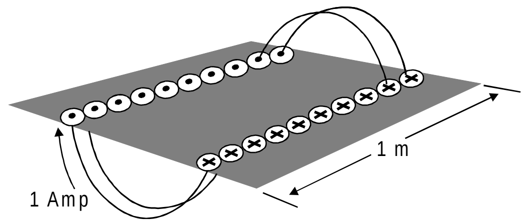

Figure 4 - This illustration shows H = 10A/m

Because of the small value of μ_0 ($4\pi \times 10^{-7}$), strong magnetic fields cannot be easily created in a vacuum or air which has a very similar value of μ_0 to that of a vacuum. If certain elements such as iron, cobalt or nickel are inserted into a coil which produced a certain magnetic field strength when the core space was occupied by air, the flux density of the magnetic field is greatly increased. The contribution to the flux density of this field must have been produced by the core material itself stimulated by the magnetic field intensity vector H. The contribution to the magnetic field flux density by iron is best shown in a plot of B against H (Figure 5).

This plot shows a variable slope for the BH curve for iron. Iron has what is called a relative permeability which varies with the flux density in the iron.

$$B = \mu_r \mu_0 H \qquad (\mu_{relative} \text{ is expressed as } \mu_r)$$

μ_r can have very high values since portions of actual BH curves are nearly vertical. It is interesting to note that very pure iron has a saturation flux density B_s of 2.15 webers/metre^2 with a magnetic field intensity H of 50,000 amperes/meter (far off the scale on this BH curve). This value of H produces a flux density B in a vacuum of only 0.06 webers per metre. The maximum contribution of the iron therefore is 2.09 webers/m^2.

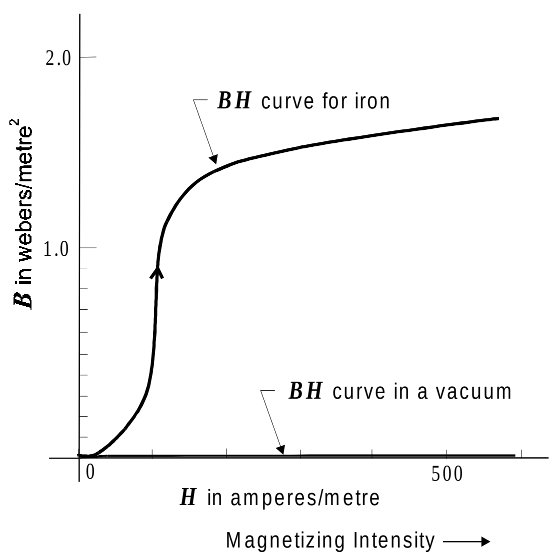

Figure 5 - BH Curves for Iron & in a Vacuum

The behaviour of non ferromagnetic materials in a magnetic field leads to two classifications, paramagnetic materials in which a very small contribution is made to the value of B over that of a vacuum and diamagnetic materials that tend to reduce the value of B to below that expected in a vacuum for a constant magnetizing field intensity. As indicated previously in a vacuum, $B = \mu_0 H$ with μ_0 being the proportionality constant relating the resulting flux density to the intensity of the magnetizing field H. As stated before μ_0 is the slope of the B vs. H curve in a vacuum. The value of μ_0 is modified by the value of μ_r which is called the relative permeability of a material for a given value of H.

$$\mu_r = \frac{B\ (material)}{B\ (vacuum)}$$

In a paramagnetic or diamagnetic material at a fixed temperature:

$$B = \mu_r \mu_0 H \text{ webers/metre}^2$$

Note that all materials are included in this relationship but for this part of the discussion, we eliminate ferromagnetic materials which have μ_r values approaching infinity under some values of H. If $\mu_r = 1$, then the magnetic field is being produced in a vacuum. The following table shows the deviation both plus and minus from unity when different materials are placed in a magnetic field.

Table 1 - Relative Permeabilities of Some Diamagnetic and Paramagnetic Materials

Material	Relative Permeability (μ_r)
Carbon (graphite)	$1.0 - (45 \times 10^{-6})$
Carbon (diamond	$1.0 - (6.2 \times 10^{-6})$
Copper	$1.0 - (1.1 \times 10^{-6})$
Silver	$1.0 - (2.5 \times 10^{-6})$
Oxygen (20°C)	$1.0 + (1330 \times 10^{-6})$
Aluminum	$1.0 + (8.2 \times 10^{-6})$
Air	$1.0 + (0.38 \times 10^{-6})$

Plus values increase the slope of the BH curve ever so slightly indicating that the material in the H field has itself made a small contribution to B. Such materials are called paramagnetic. Note that aluminum has a relative permeability of 1.0000082. For almost all practical purposes, we may approximate the relative permeabilities of all diamagnetic and paramagnetic materials as $\mu_r = 1$.

Ferromagnetism is displayed by only three pure elements, all of which are in period 3 of the periodic table with atomic numbers 26, 27, and 28. The elements are iron, cobalt and nickel. A few other elements produce effects similar to iron but at very low temperatures. The *BH* curve (Figure 5) shows the typical behaviour of iron in a magnetic field. When the magnetizing field is increased from zero, the flux density increases at a rate 50 to 200 times that produced in a vacuum. As the magnetizing field intensity is increased to about 10 to 100 amperes per metre, the flux density rises very rapidly and reaches a value of 10^5 times that observed in a vacuum at the same magnetic field intensity. As *H* increases further, the contribution of the iron to the value of *B* decreases until a maximum flux density of 2.15 webers/metre^2 is reached at H = 50,000 amperes/metre after which the *BH* curve follows the slope of the curve in a vacuum. At this point the iron is said to be saturated.

Ferromagnetism is due to the alignment of the electrons having uncompensated spins in each atom. Table 2 below shows that the 3_2 electron shell is not completed until element no. 29 copper is reached which shows that the 10 possible spaces are filled. The missing electrons in this shell are those that would have compensated (opposed) the magnetic moments of electrons already occupying the 3_2 shell.

Table 2 - Magnetic Properties of Atoms in the Transitional Series

Element	Number of 3_2 Electrons	Number of 4_0 Electrons	Number of Uncompensated Spins in an Isolated Atom	Number of Uncompensated Spins per Atom in Solid Metal
Scandium	1	2	1	0
Titanium	2	2	2	0
Vanadium	3	2	3	0
Chromium	5	1	4	0.4
Manganese	5	2	5	0.5
Iron	6	2	4	2.21
Cobalt	7	2	3	1.72
Nickel	8	2	2	0.6
Copper	10	1	1	0

Manganese has 5 uncompensated electron spins per atom but in the solid material this is reduced to 0.5. This is due to the formation of covalent bonds, involving electrons of opposite spins, between electrons in adjacent 3_2 shells. In solid metal iron has the largest number of uncompensated electron spins of all the transition elements.

In iron domains exist in which adjacent atoms have aligned their uncompensated electron spins. In unmagnetized material the magnetic domains are arranged in a random manner ensuring cancellation of magnetic effects. When an external magnetizing field is applied the domains most nearly in line with the applied field grow in size with respect to adjacent domains with other orientations. The field produced by the domains themselves assist in switching of other domains to line up with the larger domains. Domains can then be rotated to line up exactly with the applied magnetizing field. This is shown Figure 6.

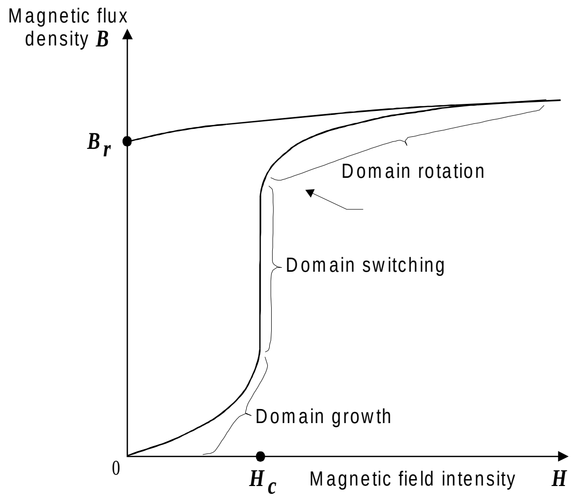

Figure 6 - Basic Features of a Magnetization Curve for a Ferromagnetic Material

Very powerful magnetic fields can be built up in the iron cores of coils of conductors carrying large electric currents. These magnetic fields are of little value unless they can be produced across an air gap. The air gap even of small dimensions has a high resistance to the “flow” of magnetic flux. This magnetic resistance is called reluctance (R) and is defined in a form similar to resistance for electrical circuits where resistance varies as the length of the conducting path and inversely as the cross-section area of the conducting path. This is expressed in symbols as

$$R \, \alpha \, \frac{l}{A} \quad \text{or} \quad R = \rho \frac{l}{A}$$

where: ρ is the resistivity of the conducting material

In a magnetic circuit, Reluctance (R) replaces resistance and l is the length of the magnetic path and A its cross-sectional area. The proportionality constant is $\mu_r \, \mu_0$ which is the permeability of the magnetic flux path and is analogous to electrical conductivity which is the reciprocal of ρ:

$$\mathsf{R} = \mu_r \mu_0 \frac{l}{A}$$

In a magnetic circuit, the path through which magnetic flux passes has a cross-sectional area *A* and length *l*. This flux is produced by *NI* as shown by the expression for flux in the core of a coil of *N* turns and a current *I* amperes:

$$\phi = BA = (\mu_r \mu_o H)A$$
$$= \mu_r \mu_0 \left(\frac{NI}{l}\right) A$$
$$= \left(\mu_r \mu \frac{A}{l}\right) NI \textit{ webers}$$

note:

$$B \;=\; \text{flux density} \;=\; \mu_r \mu_0 H$$

$$\frac{NI}{l} \;=\; \begin{array}{l}\text{ampere turns/m}\\ \text{or amps/m}\\ \text{(see Figure 4)}\end{array} \;=\; H$$

It is clear that NI is the cause of the flux in the same way that electromotive force (emf) causes current flow in an electric circuit so the name magnetomotive force (mmf) is appropriate to describe NI as the causative agent in producing magnetic flux in a magnetic circuit. Although the word flux suggests flow, magnetic flux has directional properties but is the manifestation of a stationary field under the stimulus of a constant mmf.

If we use the symbol F for mmf, the reluctance and flux are related to mmf as follows:

$\mathsf{F} = \phi \mathsf{R}$ which has the same form as Ohm's Law V = IR

The difficulty of producing high flux density in air without the use of ferromagnetic materials can best be shown by a numerical example:

Consider the coil in Figure 7. Because of thermal limitations, the maximum current that could encircle the air space surrounded by the coil might be 2 x 10^4 amperes. The magnetic field intensity H at the centre of the coil would be:

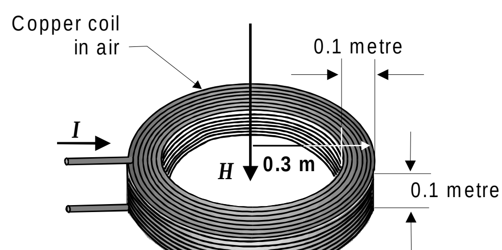

Figure 7 - A Circular Coil in Air

$$H \;=\; \frac{NI}{2r} \;=\; \frac{2 \text{ x } 10^4}{0.6} \;=\; 3.33 \text{ x } 10^4 \text{ amperes/metre}$$

This would produce a magnetic flux density of:

$$B \;=\; \mu_0 H$$
$$=\; 4\pi \text{ x } 10^{-7} \text{ x } 3.33 \text{ x } 10^4$$
$$=\; 4.18 \text{ x } 10^{-2} \text{ weber/m}^2$$

Consider now a coil wound on a toroidal iron core with an air gap cut into it such as shown in the following diagram:

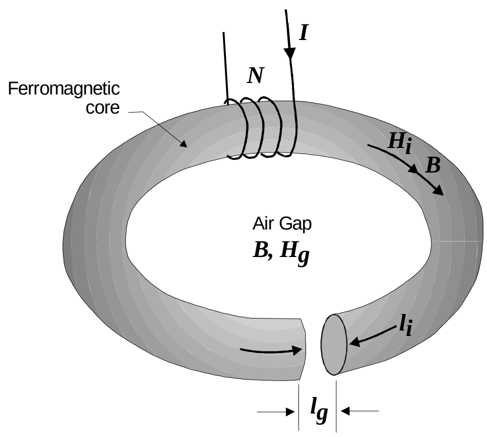

Figure 8 - A Toroidal Core with an Air Gap

The magnetic field intensity H to achieve a value B of 1.5 webers/m^2 can be read off the BH curve for iron shown in Figure 5. A value of H = 200 amperes/metre would produce the required flux density in the core material. Since no iron core is present in the gap, the flux density is produced by a magnetic field intensity of :

$$H_g = \frac{B}{\mu_0} \quad (\text{remember } B = \mu_0 H) \quad B = 1.5 \text{ webers}/\text{m}^2$$

The magnemotive force

$$\begin{aligned} \mathcal{F} &= H_g l_g + H_i l_i \qquad \text{where } l_g = 0.01 \text{ metre, } l_i = 1 \text{ metre} \\ &= \left(\frac{1.5}{4\pi \times 10^{-7}}\right) 0.01 + (200)1 \\ &= 12200 \text{ amps} \end{aligned}$$

Note that if the gap were increased to 2 cms and the same flux density was needed, the required current would jump to 24,200 amps. Compare the contribution of the iron core to the flux density obtainable without it. In the example of the aircored coil 20,000 amperes produces a flux of only 0.0418 webers/metre^2 whereas the coil with the iron core could produce 1.5 webers/metre^2 in the air gap with a current of 12,200 amperes. The iron core permitted 98% of the mmf of the coil to appear across the air gap. Most of the useful application of magnetism depends on high flux densities in air gaps. The main exception is in the continuous iron core of transformers.

If a magnetized needle is balanced on a pivot such that it can swing freely in a horizontal plane, it will align itself between the north and south magnetic poles of the earth. Such an instrument is called a magnetic compass and the north seeking pole is called a north pole. Where air gaps exist in magnetic paths, a north pole exists where the flux density vector B leaves the iron core and enters the gap. If the air gaps are small, the flux density is uniform in the gap and follows a path very close in size to the iron core. Some "fringing" occurs. If the air gap is large, say in the case of a bar magnet, the magnetic flux radiates in all directions from the pole. The magnetic flux loops back to the south pole of the magnet to complete the magnetic circuit. This is the appearance of this field when iron filings are sprinkled on a piece of cardboard placed on the top of a bar magnet:

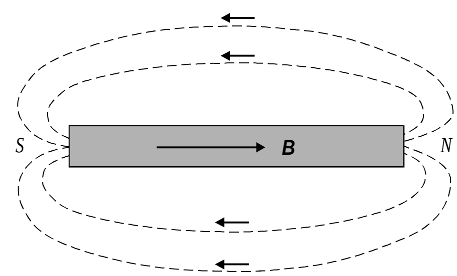

Figure 9 - The Magnetic Field Surrounding a Bar Magnet

If sufficient iron filings are sprinkled on the cardboard, the magnetic reluctance is lowered in what used to be the air path giving a false impression of the size of the magnetic field in the air around the magnet. Only when air gaps exist do magnetic poles manifest themselves. When the separation of poles are small, the flux is uniform across the air gap. When the separation is increased sufficiently, the flux density obeys an inverse square law as if the pole pieces were hemispherical radiators. At larger distances, the field of a dipole varies as the cube of the distance.

The magnetic field produced in the space surrounding the magnet is opposite in direction to the field within the magnet and hence has a demagnetizing effect on the permanent magnet. Many permanent magnets are made in a horseshoe shape to shorten the path between the poles and hence enhance the flux density in the gap and also reduce the demagnetizing field surrounding the magnet. Even so a "keeper" made of iron is placed across the poles when the magnet is not in use to prevent a loss of magnetic properties.

In Figure 5 we have shown a BH curve for iron with H increasing until the iron approached saturation. If H were to be reduced to zero, the curve would not retrace itself to zero but follow a path to the left of the original path. If the current in the magnetizing coil were AC then H would pass through zero and demagnetize the iron specimen and magnetize it in the opposite direction and so on. Such a curve is shown in Figure 10 for an example of soft iron.

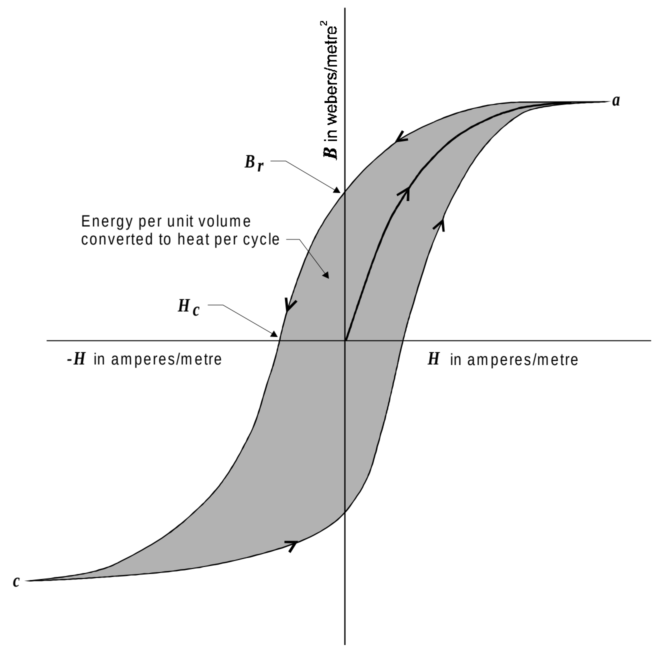

Figure 10 - Cyclic Energy Loss per Unit Volume in Ferromagnetic Materials

Here the core material must be magnetically soft and this loop which is called a hysteresis loop should be as narrow as possible to lessen losses in the magnetic core. If this hysteresis loop is narrow, then the amount of -H required to demagnetize it would be small also. This value is H_c (see Table 3).

In permanent magnets, the magnetization of the core material is done once during manufacture and it is desirable that the hysteresis loop be as wide as possible such that the H_c (called the intrinsic coersive force) is as large as possible. A curve for a permanent magnet material is shown opposite:

(Please note on Table 3 that H_c for Cobalt Rare Earth 4 is 640,000 amps/metre.)

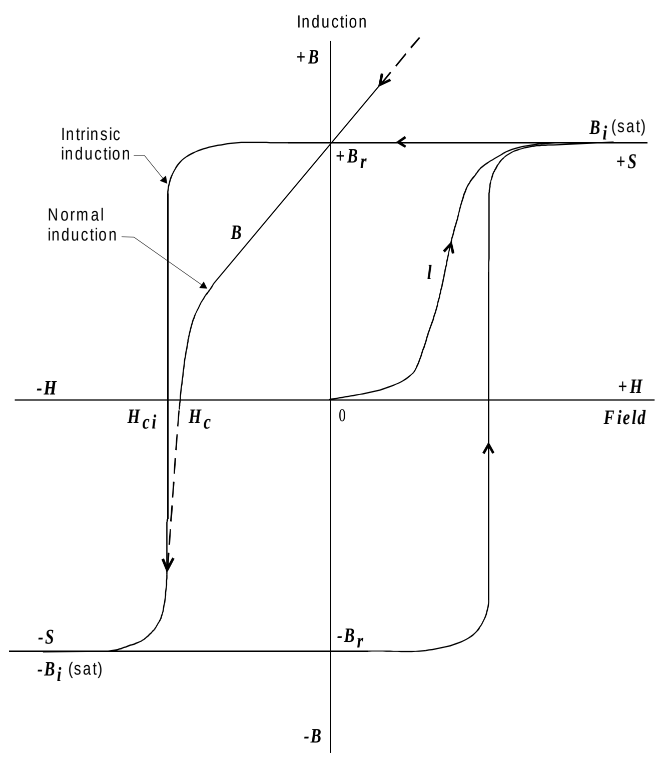

Figure 11 - A Hysteresis Loop for a Permanent Magnet Material

Note that after the initial magnetizing force is reduced to zero, the value of B remains very close to its saturated value as shown by B_r on the ordinate. The values of H_c (the value of -H to achieve demagnetization differ very greatly between iron suitable for transformer cores and alloys suitable for permanent magnets. For example:

Table 3

	B at Saturation	Residual B_r	H_c
Highly Purified Iron	2.15 Webers/m^2	1.3 Webers/m^2	4 Amperes per metre
Cobalt Rare Earth 4	---	1.13 Webers/m^2	640,000 Amperes per metre

The cobalt rare earth 4 magnetic material requires greater than 1,600,000 amperes per metre magnetizing field.

Modern permanent magnet materials are compared on the basis of the amount of potential energy in the magnetic material. This is approximately equal to the product B_rH_c. For a good permanent magnet, material such as Alnico V, this product is about 1000 joules/metre^3. This energy value is also given in MG•Oe (MegaGauss • Oersteds).

In general (the exception being Cobalt Rare Earth 4) the B_r for these materials is not as high as that achieved by electromagnets with soft iron cores. The permanent magnets are superior to electromagnets for many uses since they maintain their fields without using electric power and without the generation of heat. All magnetic materials are heat sensitive, the upper limit being the Curie temperature at which magnetism disappears.

The final discussion will be on the Hall Effect in which magnetism has an effect on moving charge carriers.

Electric surface charge distribution produced by magnetic forces acting on negative charges moving in a metal conductor are shown in Figure 12.

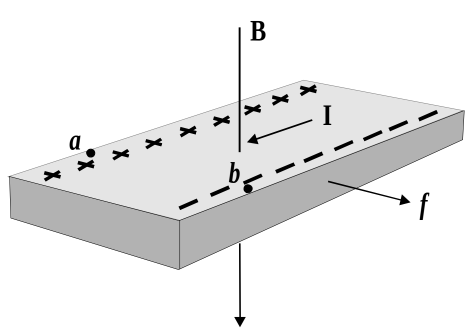

Figure 12 - Hall Effect

If the charge carriers are negative they experience a force due to the magnetic field which displaces them in the direction of the force. Due to this displacement of negative charge, a positive charge is induced on the opposite side of the conductor. The magnetic force is counteracted by the electric attraction of the field produced by the charge separations. A voltage can be measured between *a* and *b*, which is called the Hall Effect. In water, both positive and negative ions exist and a similar charge separation occurs when a magnetic field vector is introduced perpendicular to the flow plane. This separation can only be maintained while under the influence of the magnetic field vector and when the water was in motion. If the magnetic field was removed – say the affected water were to pass by the magnetic device supplying the B vector, then the electrostatic field would bring the separated charges together until the field was reduced to zero. Even if the electric field were absent, which it isn't, turbulence would see to the thorough admixture of ions.

The earth is a magnet and has a horizontal and vertical magnetic field component except at the magnetic equator. The vertical component of this field results in charge separation in rivers and streams. This phenomenon has been studied and the potential differences measured are due to the Hall Effect.

In a paper by Boteler and Cookson on Telluric Currents and Their Effects on Pipelines in the Cook Strait Region of New Zealand published in Materials Performance, March 1986, the authors state:

> *"Movement of the conducting seawater through the earth's magnetic field generates an electric field in the water given by:*
>
> $$\underline{E} = \underline{v} \times \underline{B} \qquad (1)$$
>
> *In the Cook Strait region, the vertical component of the earth's magnetic field is 53.5 x 10^{-6} Tesla, so a water velocity of 1 knot produces an electric field:*
>
> $$E = 26 \text{ mV}\bullet\text{km}^{-1} \qquad (2)$$
>
> *In the southern hemisphere the vertical component of the earth's magnetic field is directed upwards so a southwards water flow generates a westward electric field across the strait. This drives a westward electric current across the strait causing an accumulation of positive charge on the west side of the strait and negative charge on the east side of the strait. For a 26 mV•km^{-1} electric field across the 30 km width of the strait, this gives a potential difference across the strait of 0.8 V."*

Electric instruments use the Hall Effect to measure current flow with fixed magnetic fields and the magnitude of magnetic fields with fixed electric currents in the sensor unit.