

# Understanding Permanent Magnets

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### Theory and Applications

Modern permanent magnets play a vital role in a wide range of industrial, consumer and defense products. Efficient use of permanent magnets in these devices requires a basic understanding of magnetic theory. To achieve this end it is helpful to understand that all magnetic fields are the result of electrons in motion.

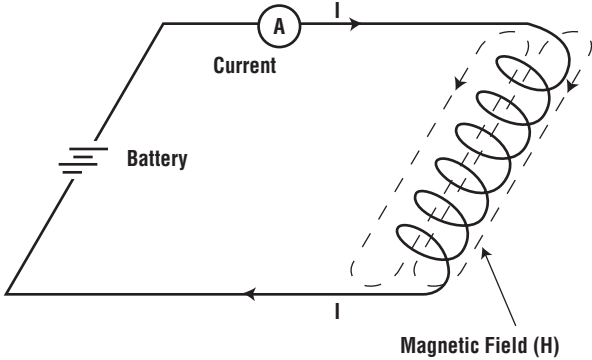


Figure 1 - Magnetic field resulting from current flow in a coil.

In the electrical circuit, Figure 1, a DC voltage is developed in the battery which causes a current, I, to flow through the wires to the load. This current flow, which is the movement of electrons between atoms in the conductor, causes a magnetic field to be established around the wire. The magnitude of the field is measured in ampere-turns per meter in the International System (SI) or in oersteds in the gram-centimeter-second (cgs) system and is designated by the symbol H.

In permanent magnets the electrons-in-motion phenomenon still explains the magnetic field produced within the magnet.

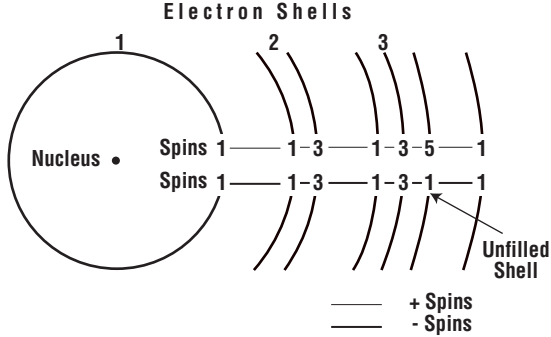


Figure 2 - Electron shells in an atom of iron.

As shown in figure 2, within the third electron shell of the iron atom, there exists an imbalance in the spin direction of the electrons. This imbalance creates a magnetic moment in the iron atom. However, this atomic magnetic moment alone is insufficient to cause ferromagnetism. Additionally, there must be cooperative interatomic exchange forces that maintain neighboring atoms parallel. The present theory states that these parallel groups of atoms form domains or areas within the ferro-magnetic body that are magnetized to saturation, but that the magnetization direction between the domains need not be parallel. When the magnet is demagnetized it is only demagnetized from the viewpoint of the external observer. The domains are not demagnetized but are fully magnetized with neighboring domains being magnetized in opposite and mutually canceling directions. The magnet becomes "magnetized" when an external magnetizing field is applied to the magnet of sufficient magnitude to cause all the domains to rotate and align in the direction of the applied field.

## Understanding Permanent Magnets (Cont)

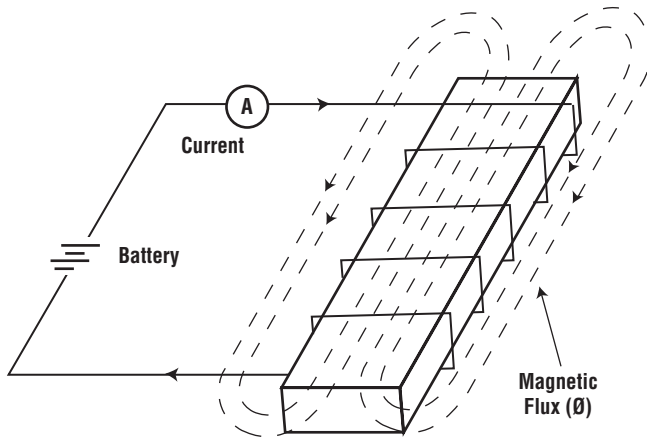


Figure 3 - Magnetic induction - Flux ( $\emptyset$ )

When a ferromagnetic material is placed in the coil of Figure 1, an additional magnetic field is induced in the material as shown in Figure 3. This induced field is called flux, from the Greek verb meaning to flow. The symbol for flux is  $\emptyset$ .

The degree to which this induced field is concentrated is known as magnetic induction or flux density per unit area normal to the direction of the magnetic path and is designated by the symbol  $B$ . In the cgs system, the magnetic induction is measured in maxwells (or lines) per square centimeter. One line per square centimeter equals one gauss. In the SI system, magnetic induction is designated in Tesla. One Tesla equals 10,000 gauss. The relationship between  $B$  and  $H$  for a ferro-magnetic material can be illustrated by its normal magnetization curve shown in Figure 4.

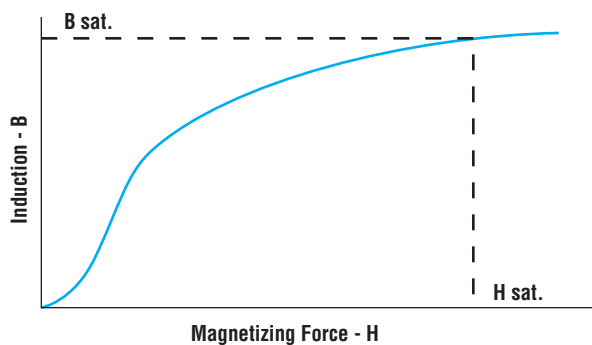


Figure 4 - Normal magnetization curve.

If the coil in Figure 1 is wound around a steel core, an electromagnet is created which allows for more efficient magnetization.

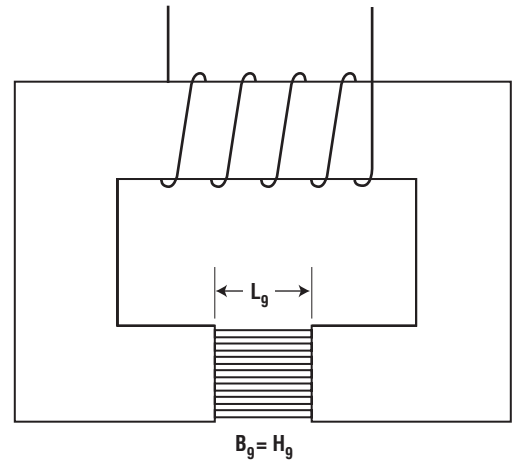


Figure 5 - Iron core electromagnet.

When a magnet sample is placed between the poles of the electromagnet with minimal air gap between the poles of the electromagnet and the sample, an accurate magnetization curve and hysteresis loop of the sample can be generated.

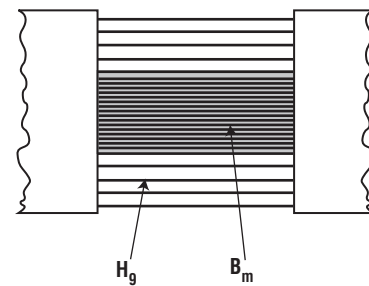


Figure 6 - Electromagnet gap and test sample.

## Understanding Permanent Magnets (Cont)

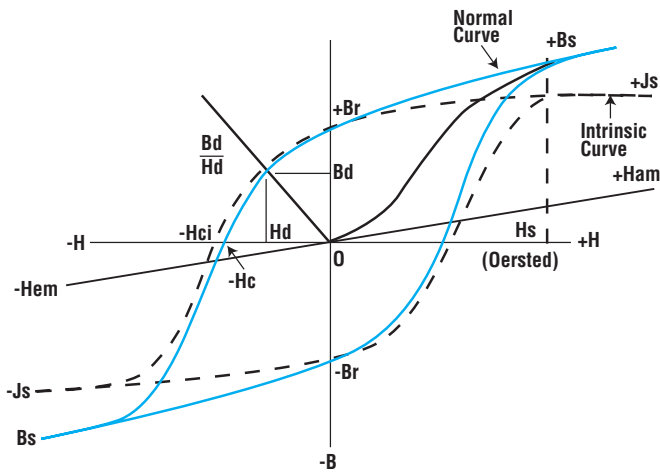


Figure 7 - Hysteresis loop.

When an unmagnetized magnet is placed in the electromagnet and a magnetizing field,  $H$ , is applied, the induction,  $B$ , will increase proportional to  $H$  along a line beginning at 0 (zero) and extending through point,  $+Bs$ . At point,  $+Bs$ , the slope of the line equals 1, and the magnet is saturated. Additional magnetizing force,  $H$ , will increase induction only by the amount of the increased applied  $H$ .

From point,  $+Bs$ , if the magnetization force,  $H$ , is gradually reduced to zero, the resultant magnetization in the material will decrease to a value  $Br$ , known as residual induction.

If the magnetizing force is then reversed (by reversing the current in the coil of the electromagnet) and increased in the negative direction, the resultant magnetization in the material is reduced to zero.

At this point the value of the demagnetization force is  $-Hc$ , known as coercive force and is a measure of the material's resistance to demagnetization.

Increasing the demagnetizing force in this opposite direction will magnetize the material in an opposite polarity saturation being represented by  $-Bs$  (see diagram). Reducing the  $H$  to zero is represented by  $-Br$  and by once again reversing the current through the coil of wire the material is gradually remagnetized to its original polarity, thus completing the hysteresis loop.

The "loop" follows the measured "B" in the material and is called the normal curve. However, it should be noted that not all observed flux is produced by the magnet. If no permanent magnet were present, a field would be produced in the air by the electromagnet.

The magnetizing force,  $H$ , of one oersted would produce an induction,  $B$ , of one gauss (straightline  $-Hem$ ,  $O$ ,  $+Hem$ ). The observed (measured) flux is the sum of the flux which would

be produced by the electromagnet without the magnetic material, plus that produced by the magnetic material, which is called the normal curve.

Flux density produced by the magnet alone is called intrinsic induction ( $J$  curve) and can be found by simple arithmetic or by graphical means: 1st quadrant use  $J = B - Hem$ , and for the second quadrant use  $J = B - (-Hem) = B + Hem$ .

It should be noted that in the first quadrant, normal induction is always greater than intrinsic induction. In the second quadrant (the demagnetization portion of the curve) the intrinsic induction is greater. This is because of the negative value of  $Hem$  in the second quadrant. It is also obvious that  $-Hci$ , the point on the  $-H$  axis the  $J$  curve crosses, is always greater than  $-Hc$  due to  $J = B + Hem$  in the second quadrant. The value of  $Hci$  is very close to the amount of  $H$  field required to completely demagnetize the magnetic material.

In magnetic design, where one is concerned with determining the amount of flux a magnet is capable of producing, the normal demagnetization curve is used. The intrinsic curve is of interest only when there is a concern with a permanent magnet's reaction to the external magnetic field.

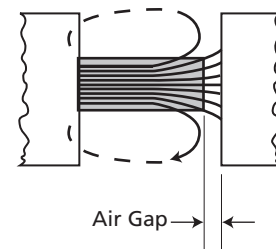


Figure 8 - Air gap influence.

Let us look back at the magnetized magnet in the electromagnet. If after returning the magnetizing field to zero (the induction in the sample is at  $Br$ ), instead of reversing the field we introduce an air gap between the magnet and the electromagnetic pole, the magnet will still become somewhat demagnetized and the flux density in the sample will decrease below  $Br$  to some  $Bd$  value as shown in Figure 9.

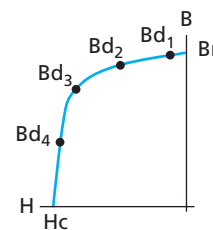


Figure 9 -  $Bd$  (flux density) versus air gap size.

## Understanding Permanent Magnets (Cont)

The flux density in the magnet will be reduced because the flux in the magnet is no longer passing straight through the magnet from end-to-end but is "leaking" back around the magnet itself. Because this leakage of flux is in the opposite direction of the internal magnet flux, it has a demagnetizing influence on the magnet. As the air gap in the circuit increases, the leakage flux becomes greater. As a result, the magnet flux is decreased.

How far down the demagnetization curve the magnet flux moves will depend upon the air gap size and the geometry of the magnet.

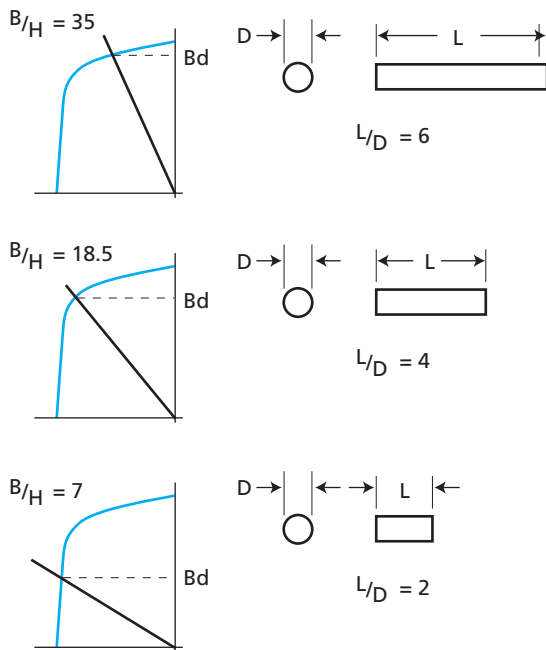


Figure 10 - Open circuit conditions.

When the magnet is removed completely from the electro-magnet, the flux density in the magnet will drop to its open circuit flux density. As shown by Figure 10, the open circuit flux density is dependent upon the geometry of the magnet which can be equated to an operating slope, B/H, or permeance coefficient. For a given magnet geometry the flux density, Bd, will fall along the B/H operating slope and its actual value will depend upon where the demagnetization curve crosses the B/H slope.

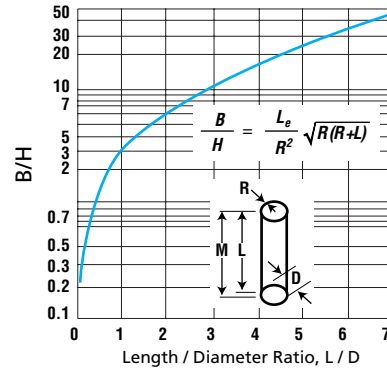


Figure 11 - Permeance Coefficient, Pc or B/H for axially magnetized cylinders of Ferrite or Rare Earth magnets

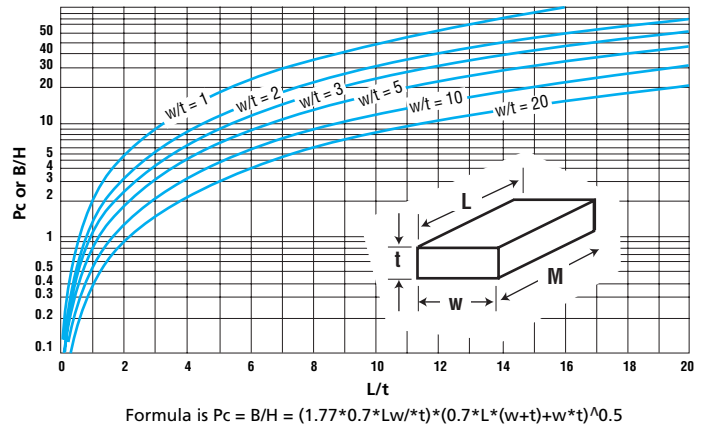


Figure 12 - Permeance Coefficient, Pc or B/H for rectangles of Alnico magnets

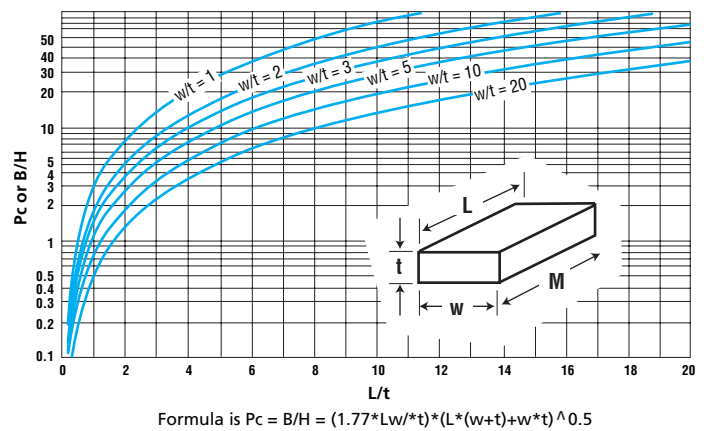


Figure 13 - Permeance Coefficient, Pc or B/H for rectangles of Ferrite or Rare Earth magnets

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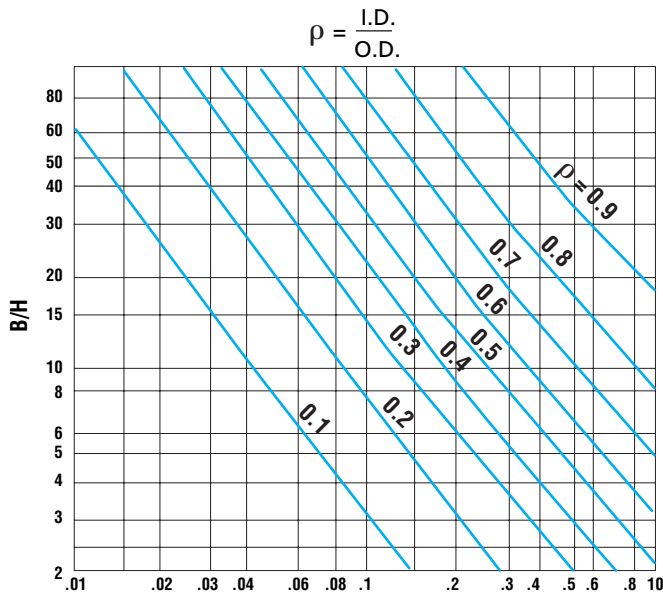


Figure 14 - Permeance coefficients for tubular magnets with axial magnetization.

Figures 11, 12, 13 and 14 equate the magnetic dimensions to B/H for three magnet geometries and are very helpful for determining the open circuit operating slope and flux density values for these geometries.

All of the previously discussed conditions apply to magnets that operate under static conditions; that is, where there is no external demagnetizing field applied to the magnet and its B/H operating slope will remain constant. If an external demagnetizing field is applied to a magnet that is working in an air gap, the flux density in the magnet will decrease as shown in Figure 15.

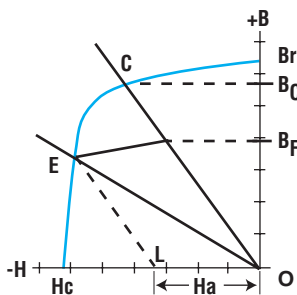


Figure 15 - Externally applied field,  $H_a$ .

Line OC depicts the operating slope of a magnet in a circuit with some air gap, and  $B_c$  represents the flux density in the magnet. If an external field of magnitude,  $H_a$ , is applied to the magnet, the flux density of the magnet will decrease to point E. Note that the new operating slope line, LE, is parallel to OFC.

For magnet materials that exhibit a “knee” in the demagnetization curve, when the external demagnetizing field is removed the flux density does not return to point C, but instead will return along a line with the slope of recoil permeability represented by EF. Note that when the external field is removed, the magnet operating slope returns to the original value along line OFC to a new flux density,  $B_f$ . (The slope of line EF is referred to as the recoil or reversible permeability of the magnet.)

A similar flux loss will occur if the circuit air gap is increased and then decreased, or if the magnet is magnetized outside of the circuit, that is, in the open circuit condition, and then inserted into the circuit.

With materials that exhibit straight line demagnetization curves (ceramic, Samarium Cobalt or Neodymium Iron Boron), the flux loss is greatly reduced or eliminated.

### Conclusion

Understanding the fundamentals of magnet operating conditions helps to remove the mystery often associated with these materials.

### References

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