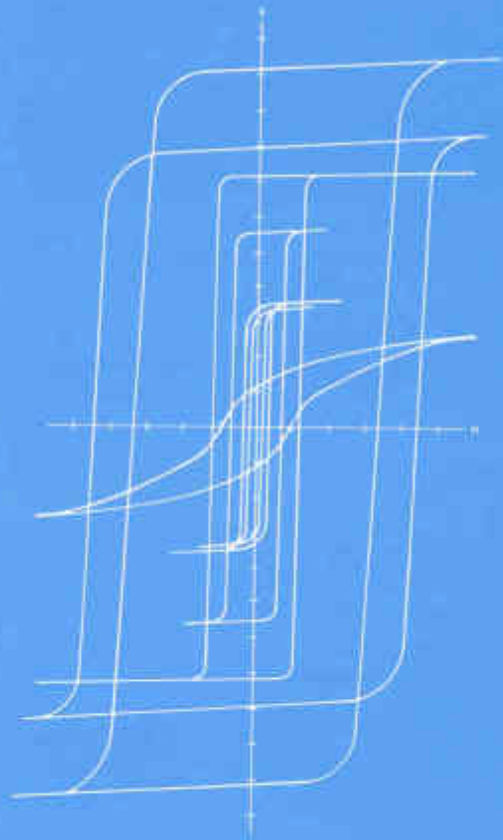


# Transformer and Inductor Design Handbook

Second Edition, Revised and Expanded  
Colonel Wm. T. McLyman



### 1.1.6 Permeability

In magnetics, *permeability* is the ability of a material to conduct flux. The magnitude of the permeability at a given induction is a measure of the ease with which a core material can be magnetized to that induction. It is defined as the ratio of the flux density  $B$  to the magnetizing force  $H$ . Manufacturers specify permeability in units of gauss per oersted (G/Oe).

$$\text{Permeability} = \mu = \frac{B}{H} \left[ \frac{\text{gauss}}{\text{oersted}} \right] \quad (1.1)$$

*Absolute permeability*  $\mu_0$  in cgs units is unity (1 gauss/oersted) in a vacuum.

$$\text{cgs: } \mu_0 = 1 \left[ \frac{\text{gauss}}{\text{oersted}} \right] = \frac{\text{tesla}}{\text{oersted}} \times 10^4 \quad (1.2)$$

$$\text{mks: } \mu_0 = 0.4\pi \times 10^{-8} \left[ \frac{\text{henry}}{\text{meter}} \right] \quad (1.3)$$

When  $B$  is plotted against  $H$  as in Figure 1.16, the resulting curve is called the *magnetization curve*. These curves are idealized. The magnetic material is totally demagnetized and is then subjected to

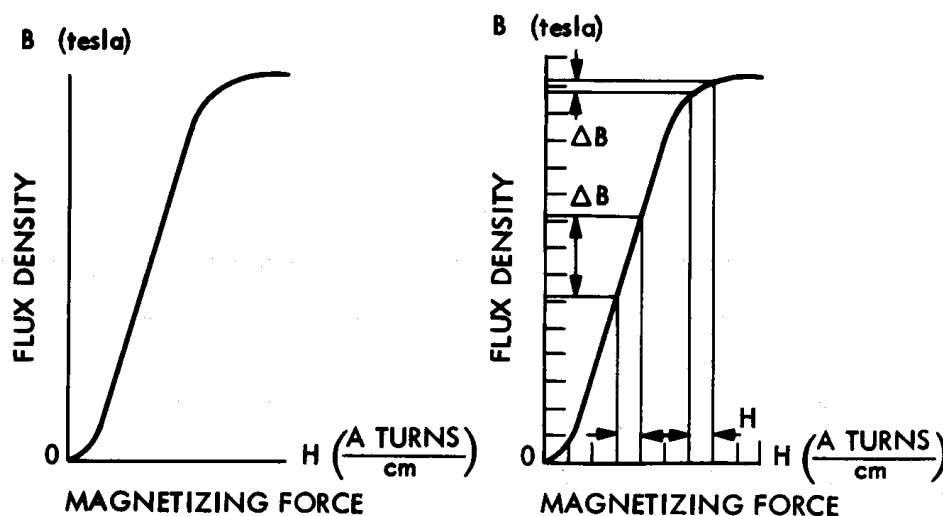


Figure 1.16. Magnetization curve.

a gradually increasing magnetizing force while the flux density is plotted. The slope of this curve at any given point gives the permeability at that point. Permeability can be plotted against a typical  $B$ - $H$  curve as shown in Figure 1.17a. Permeability is not constant; therefore its value can be stated only at a given value of  $B$  or  $H$ .

There are many different kinds of permeability, and each is designated by a different subscript on the symbol  $\mu$ .

$\mu_0$  Absolute permeability, defined as the permeability in a vacuum.

$\mu_i$  Initial permeability, Figure 1.17b, the slope of the initial magnetization curve at the origin. It is measured at very small inductions.

$\mu_\Delta$  Incremental permeability, Figure 1.17c, the slope of the magnetization curve for finite values of peak-to-peak flux density with superimposed dc magnetization.

$\mu_e$  Effective permeability. If a magnetic circuit is not homogeneous (i.e., contains an air gap), the effective permeability is the permeability of a hypothetical homogeneous (ungapped) structure of the same shape, dimensions, and reluctance that would give the inductance equivalent to the gapped structure.

$\mu_r$  Relative permeability, the permeability of a material relative to that of free space.

$\mu_n$  Normal permeability, Figure 1.17d, the ratio of  $B/H$  at any point of the curve.

$\mu_{\max}$  Maximum permeability, Figure 1.17e, the slope of a straight line drawn from the origin tangent to the curve at its knee.

$\mu_p$  Pulse permeability, the ratio of peak  $B$  to peak  $H$  for unipolar excitation.

$\mu_m$  Material permeability, the slope of the magnetization curve measured at less than 50 G.

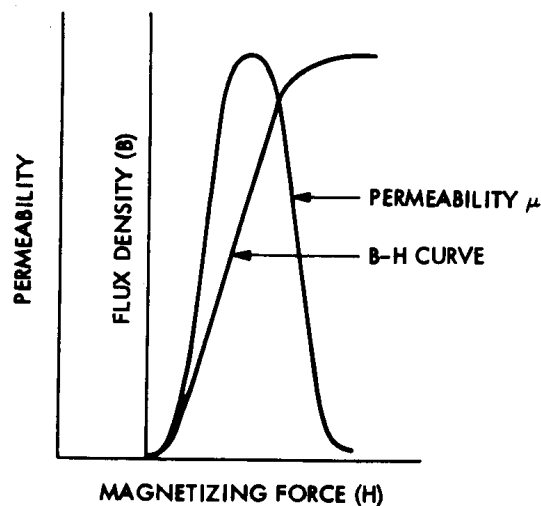


Figure 1.17a. Variation of  $\mu$  along the magnetization curve.

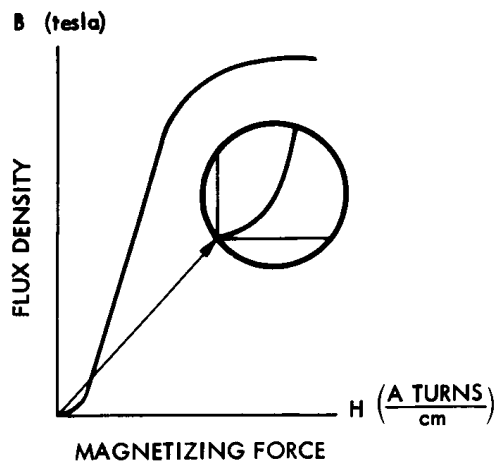


Figure 1.17b. Initial permeability.

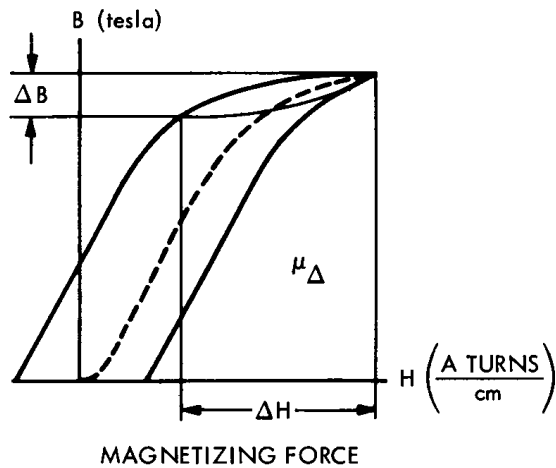


Figure 1.17c. Incremental permeability.

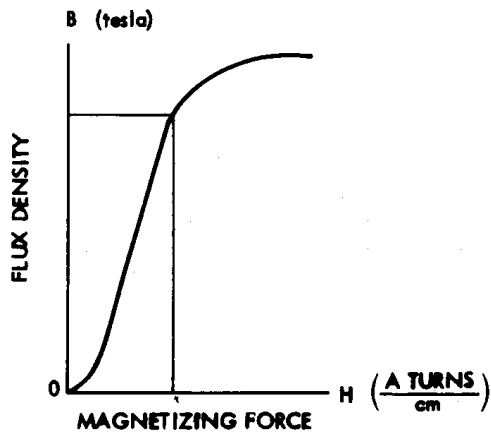


Figure 1.17d. Normal permeability.

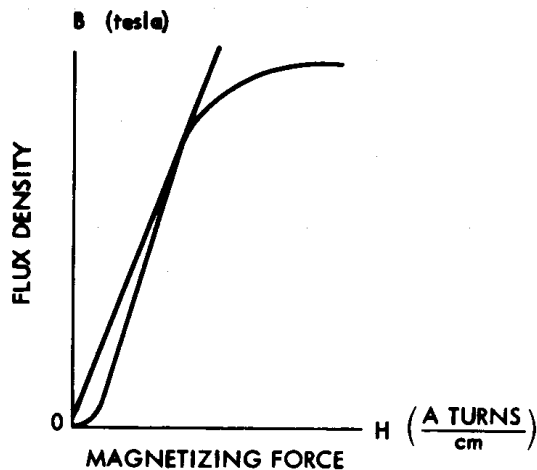


Figure 1.17e. Maximum permeability.

### 1.1.8 Magnetomotive Force (MMF) and Magnetizing Force ( $H$ )

There are two force functions commonly encountered in magnetics: magnetomotive force  $\text{mmf}$  and magnetizing force  $H$ . Magnetomotive force should not be confused with magnetizing force; the two are related as cause and effect. *Magnetomotive force* is given by the equation

$$\text{mmf} = 0.4\pi NI \quad [\text{gilberts}] \quad (1.20)$$

where  $N$  is the number of turns  
 $I$  is the current, amperes

whereas  $\text{mmf}$  is the force,  $H$  is a force field, or force per unit length:

$$H = \frac{\text{mmf}}{\text{MPL}} \left[ \frac{\text{gilberts}}{\text{cm}} = \text{oersteds} \right] \quad (1.21)$$

Substituting,

$$H = \frac{0.4\pi NI}{MPL} \quad [\text{oersteds}] \quad (1.22)$$

where MPL = magnetic path length, cm.

If the flux  $\phi$  is divided by the core area  $A_c$ , we get flux density  $B$  in lines per unit area:

$$B = \frac{\phi}{A_c} \quad (1.23)$$

The flux density  $B$  in a magnetic medium due to the existence of a magnetizing force field  $H$  depends on the permeability of the medium and the intensity of the magnetic field.

$$B = \mu H \quad [\text{gauss}] \quad (1.24)$$

The peak magnetizing current  $I_m$  for a wound core can be calculated from the following equation:

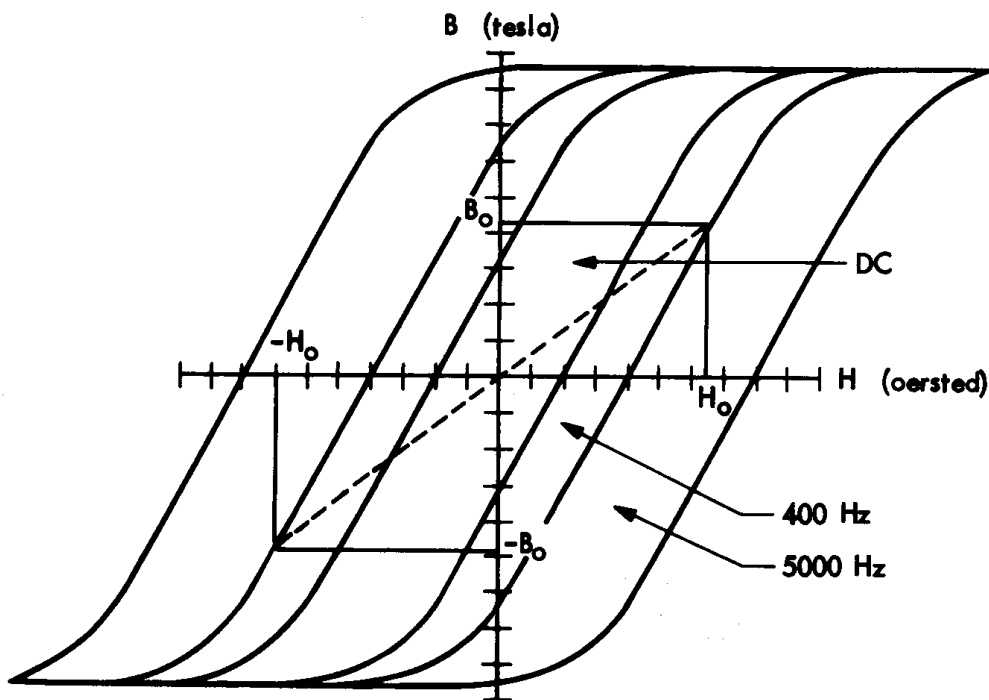


Figure 1.21. Typical  $B$ - $H$  loops result from operating at different frequencies.

$$I_m = \frac{H_0 \text{MPL}}{0.4\pi N} \quad (1.25)$$

where  $H_0$  is the field intensity at the peak operating point.

To determine the magnetizing force  $H_0$ , use the manufacturer's core loss curves at the appropriate frequency and operating flux density  $B_0$  as shown in Figure 1.21.

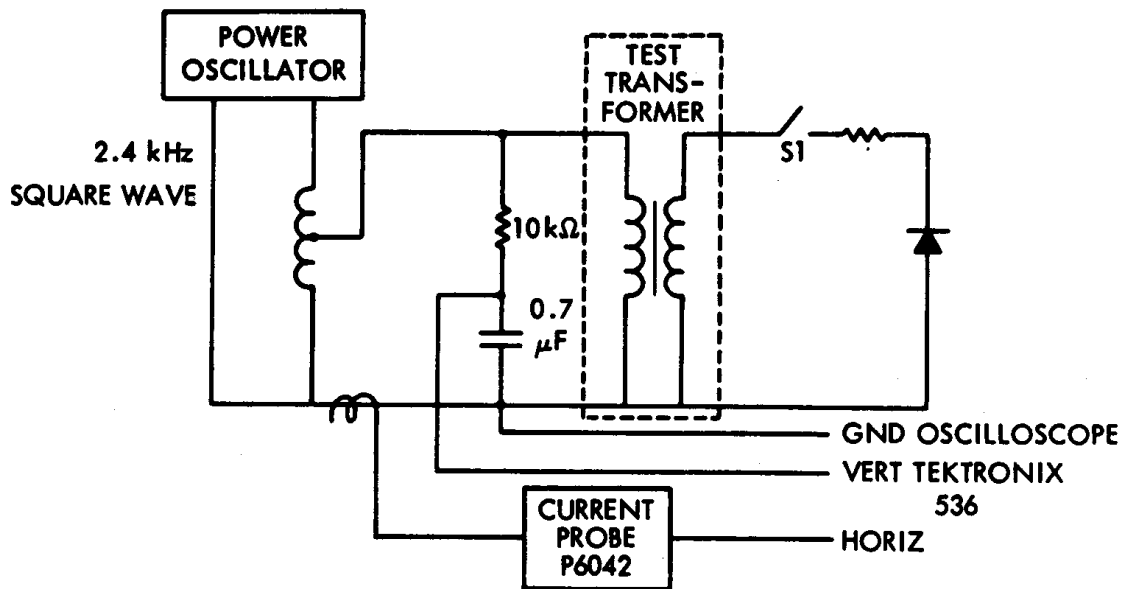


Figure 1.29. Dynamic  $B$ - $H$  loop test fixture.

### 1.2.4 The Test Setup

The test fixture schematically illustrated in Figure 1.29 was built to effect comparison of dynamic  $B$ - $H$  loop characteristics of various core materials. Cores were fabricated from various core materials in the basic core configuration designated No. 52029 for toroidal cores manufactured by Magnetics Inc. The materials used were those most likely to be of interest to designers of inverter or converter transformers. Test conditions are listed in Table 1.2.

Winding data were derived from the following:

$$N = \frac{V \times 10^4}{4.0 B_m f A_c} \quad (1.35)$$

Table 1.2. Materials and test conditions

Core type*	Material	$B_m, T$	$N_T$	Frequency, kHz	$l_m, cm$
52029 (2A)	Orthonol	1.45	54	2.4	9.47
52029 (2D)	Sq. Permalloy	0.75	54	2.4	9.47
52029 (2F)	Supermalloy	0.75	54	2.4	9.47
52029 (2H)	48 Alloy	1.15	54	2.4	9.47
52029 (2H)	Magnesil	1.6	54	2.4	9.47

\*Magnetics Inc. toroidal cores.



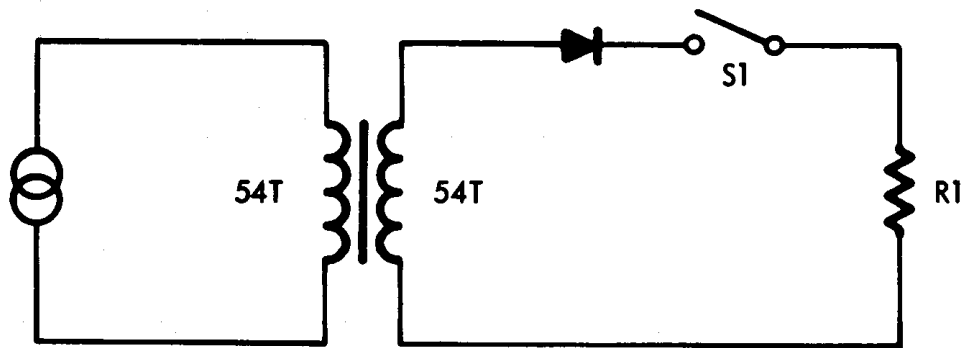


Figure 1.30. Implementing dc unbalance.

The test transformer represented in Figure 1.30 consists of 54-turn primary and secondary windings, with square wave excitation on the primary. Normally switch S1 is open. With switch S1 closed, the secondary current is rectified by the diode to produce a dc bias in the secondary winding.

Cores were fabricated from each of the materials by winding a ribbon of the same thickness on a mandrel of a given diameter. Ribbon termination was effected by welding in the conventional manner. The cores were vacuum impregnated, baked, and finished as usual.

Figures 1.31–1.35 show the dynamic  $B$ - $H$  loops obtained for various core materials.

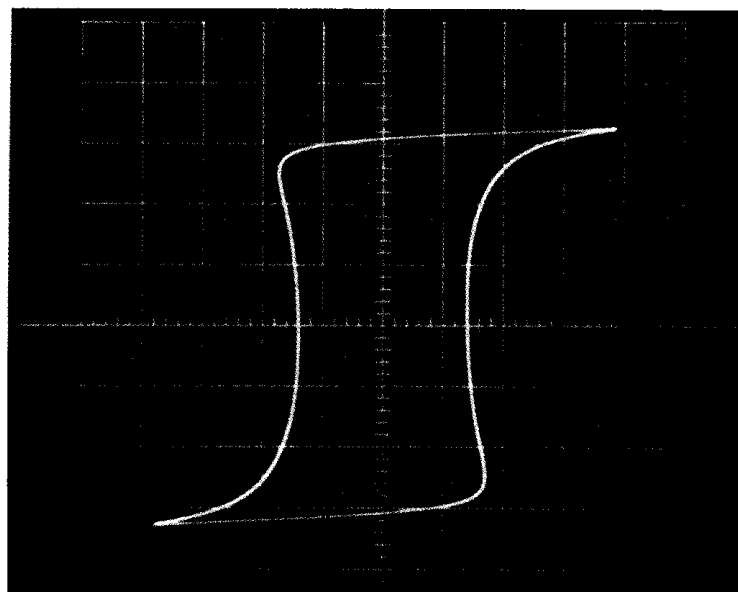


Figure 1.31. Magnesil (K)  $B$ - $H$  loop.

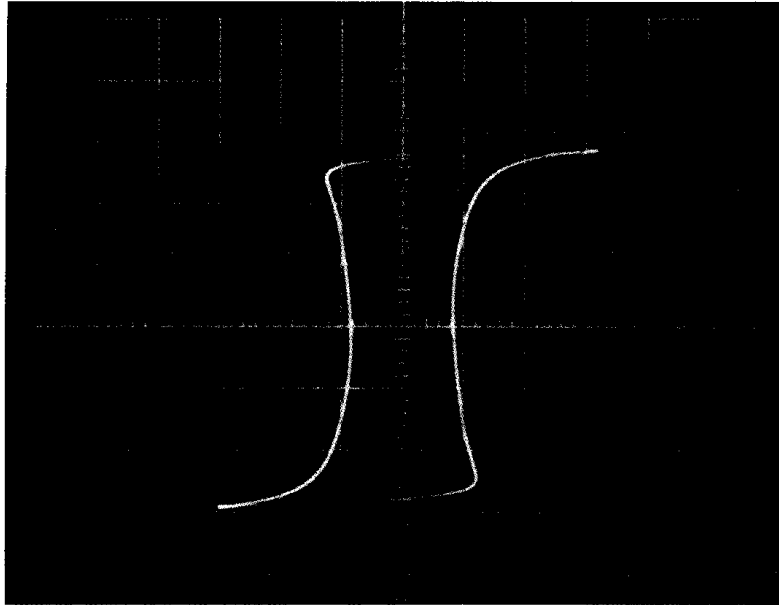


Figure 1.32. Orthonol (A)  $B$ - $H$  loop.

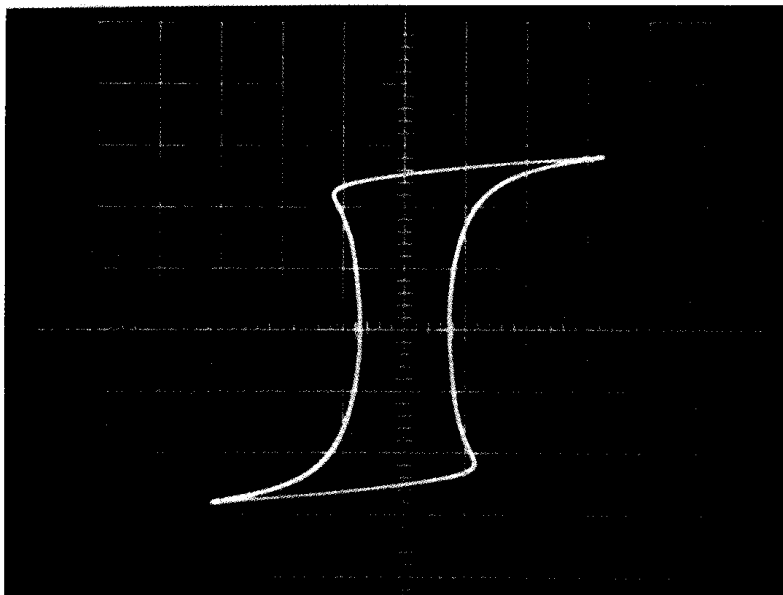
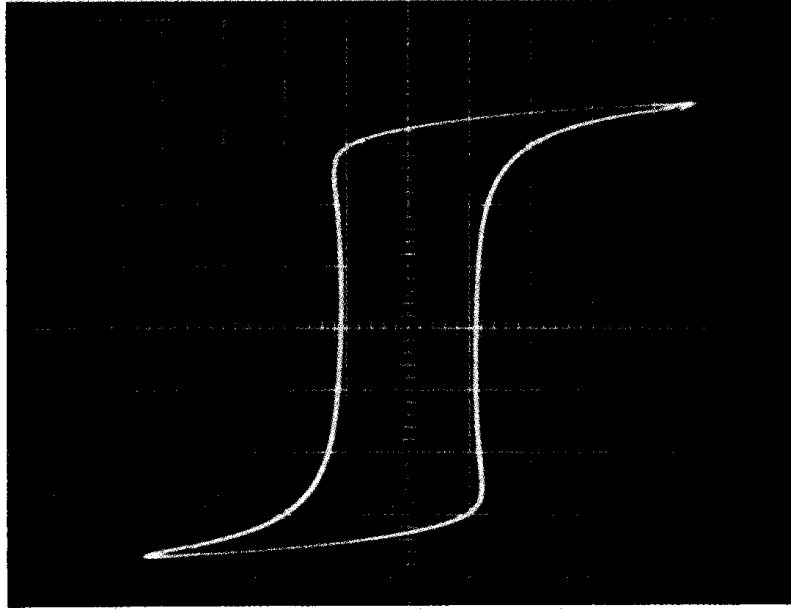


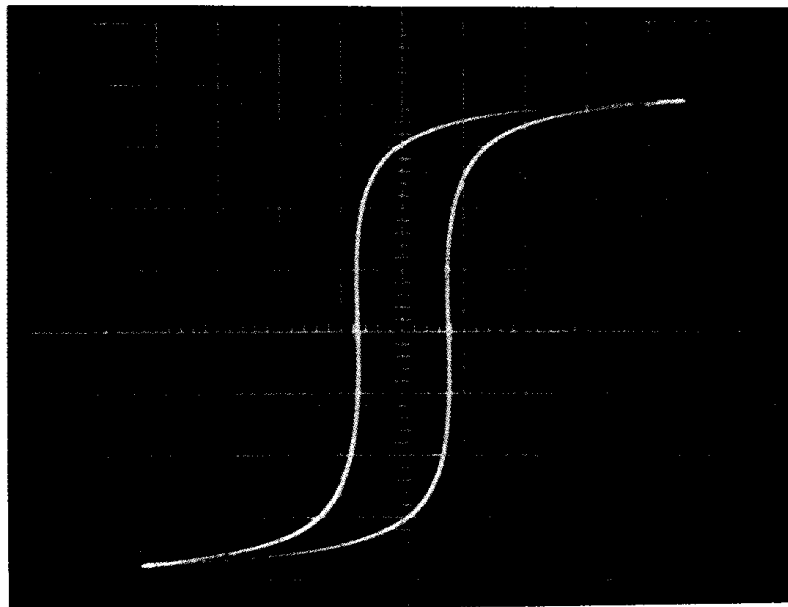
Figure 1.33. 48 Alloy (H)  $B$ - $H$  loop.

Figure 1.36 shows a composite of all the  $B$ - $H$  loops. In each of these, switch S1 was in the open position, so there was no dc bias applied to the core and windings.

Figures 1.37-1.41 show the dynamic  $B$ - $H$  loop patterns obtained for various core materials when the test conditions included a sequence in which switch S1 was open, then closed, and then opened. It is apparent from these data that with a small amount of dc bias the minor dynamic  $B$ - $H$  loop can traverse the major  $B$ - $H$  loop from saturation to saturation. Note that after the dc bias has



**Figure 1.34.** Sq. Permalloy (P) *B-H* loop.



**Figure 1.35.** Supermalloy (F) *B-H* loop.

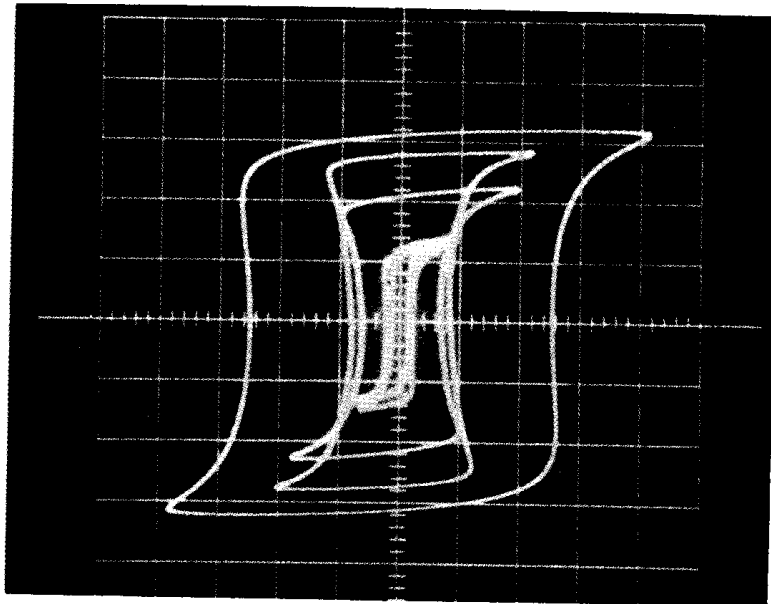


Figure 1.36. Composite 52029 (2K), (A), (H), (P), and (F)  $B$ - $H$  loops.

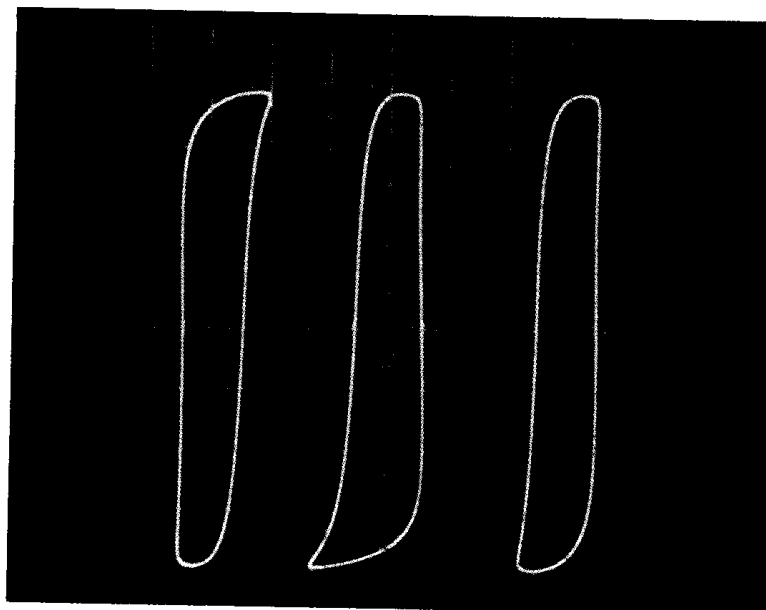
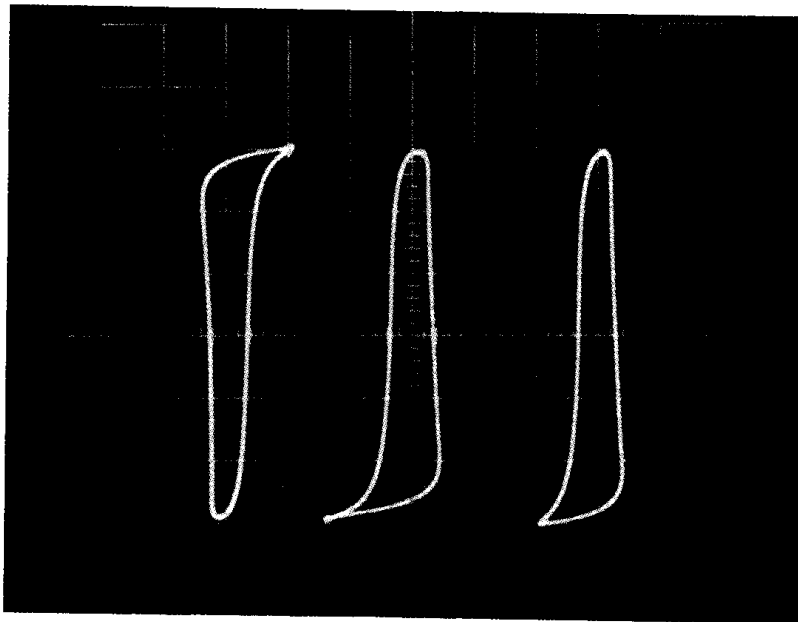
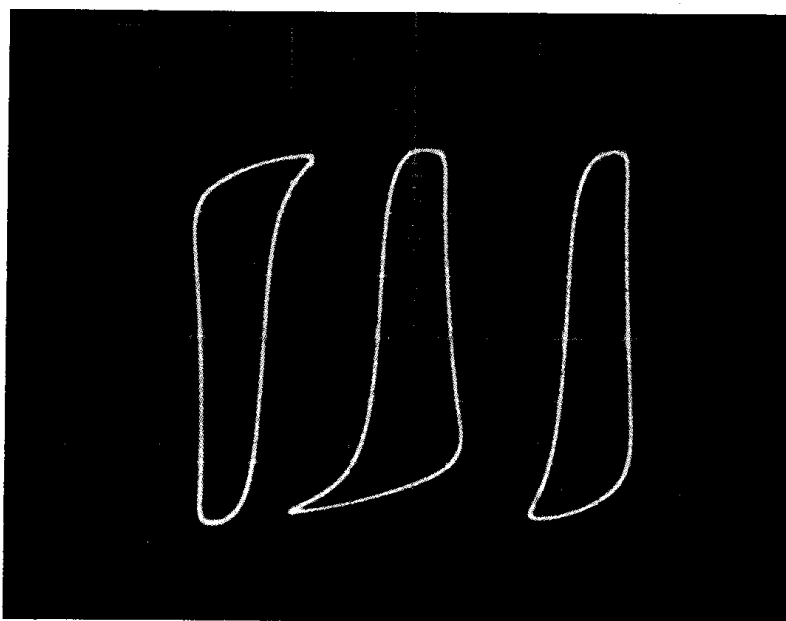


Figure 1.37. Magnesil (K)  $B$ - $H$  loop with and without dc bias.



**Figure 1.38.** Orthonol (A)  $B$ - $H$  loop with and without dc bias.



**Figure 1.39.** 48 Alloy (H)  $B$ - $H$  loop with and without dc bias.

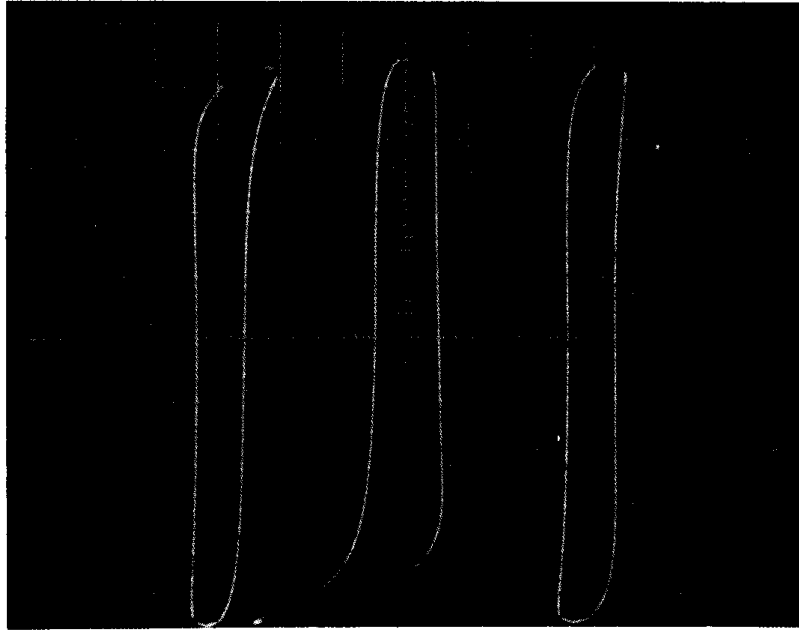


Figure 1.40. Sq. Permalloy (P)  $B-H$  loop with and without dc bias.

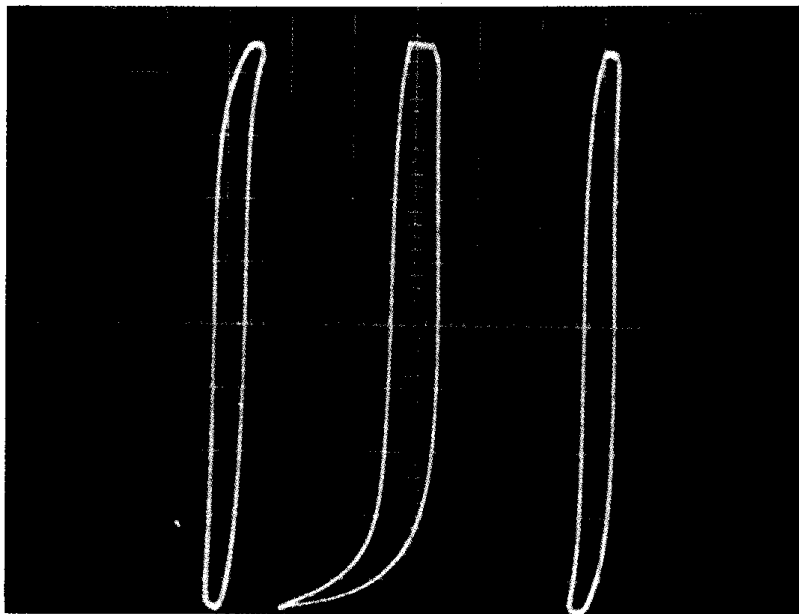


Figure 1.41. Supermalloy (F)  $B-H$  loop with and without dc bias.

removed the minor  $B$ - $H$  loops remained shifted to one side or the other. Because of the ac coupling of the integrator to the oscilloscope, the photographs in these figures do not present a complete picture of what really happens during the flux swing.

### 1.2.5 Core Saturation Theory

The domain theory of the nature of magnetism is based on the assumption that all magnetic materials consist of individual molecular magnets. These minute magnets are capable of movement within the material. When a magnetic material is in its unmagnetized state, the individual magnetic particles are arranged at random and effectively neutralize each other. An example of this is shown in Figure 1.42, where the tiny magnetic particles are arranged in a disorganized manner. (The north poles are represented by the darkened ends of the magnetic particles.) When a material is magnetized, the individual particles are aligned or oriented in a definite direction (Figure 1.43).

The degree of magnetization of a material depends on the degree of alignment of the particles. The external magnetizing force can continue to affect the material up to the point of saturation, the point at which essentially all of the domains are lined up in the same direction.

In a typical toroidal core, the effective air gap is less than  $10^{-6}$  cm. Such a gap is negligible in comparison to the ratio of mean length to permeability. If the toroid were subjected to a strong magnetic field (enough to saturate), essentially all of the domains would line up in the same direction. If suddenly the field were removed at  $B_m$ , the domains would remain lined up and be magnetized along that axis. The amount of flux density that remains is called the *residual flux*,  $B_r$ . The result of this effect was shown earlier in Figures 1.37-1.41.

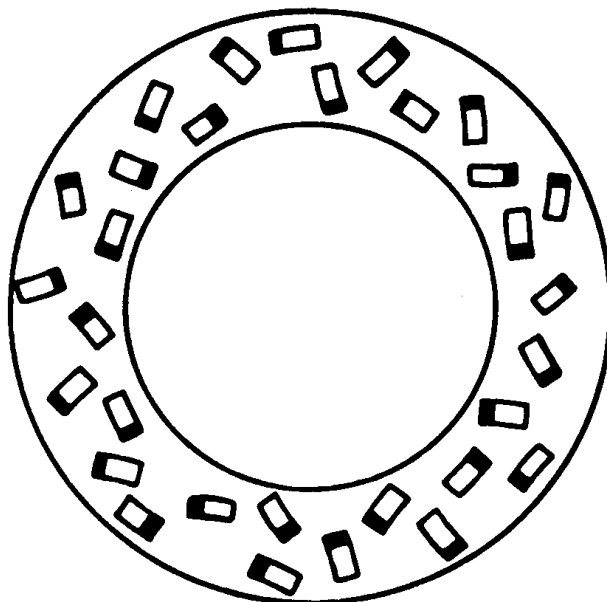


Figure 1.42. Unmagnetized material.

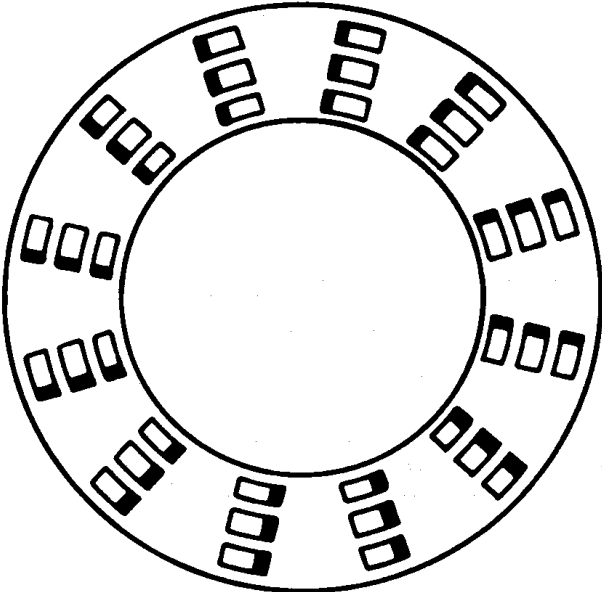


Figure 1.43. Magnetized material.