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HARD MAGNETIC MATERIALS

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Introduction

Permanent magnets are vital parts of a great variety of electrical and electronic equipment used by the Air Force, aloft or on the ground. Hundreds of magnets are used in a modern plane or missile, in communication and navigation equipment, in small motors and generators, in many measuring instruments, etc. The following is a selection of important Air Force applications of permanent magnets:

Moving coil instruments

Motors, generators (stator field)

Combustion engine ignition (magnets)

Relays

High frequency tubes (magnetron, traveling wave tube)

Load isolators

Biasing of ferrite cores

Loud speakers

Telephone receivers

Cathode ray tube biasing

Magnetostrictive devices (Sonar)

Magnetic drives

Magneto-hydrodynamic boundary layer control (nose cones)

If we consider their diversified functions, it becomes obvious that there is not one "best magnet material" but that quite different qualities are expected of magnets for various uses. An instrument magnet, for instance, must be highly insensitive to demagnetizing fields, temperature independent near room temperature, and not subject to aging. High power tube magnets have to operate at elevated temperatures and must produce high flux. Biasing magnets for ferrite cores must be electrical insulators. Magnets for speakers, motors and generators should have primarily high energy products, etc. Weight will be a prime consideration in airborne equipment; and low price non-strategic materials will further qualify a magnet where large quantities are required.

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These rather stringent requirements justify the considerable effort being expended both here and abroad to create improved permanent magnets. Noteworthy is the Air Force sponsorship, which has for years stimulated the permanent magnet research in American industry.

For a long time, permanent magnets were made of hardened steels, had low energy products, and unsatisfactory coercive forces. With the discovery of the first precipitating alloys of the Alnico-type in 1931 a rapid development of magnetic materials began which has not lost momentum. In recent years, better theoretical understanding has brought about the concept of fine particle magnets, which hold great promise for the future. The trend of the maximum energy products obtained in laboratory sample, shown in figure 1, illustrates these impressive achievements.

The Physical concepts of Permanent Magnets

In simple terms, the main purpose of a permanent magnet is to produce a magnetic flux as large as possible between its pole faces without the necessity for maintaining an exciting field. To best achieve this purpose, we need a material with a high saturation magnetization; we want to preserve a large fraction of the saturation, preferably 100 percent, as remanence when the magnetizing field is removed; and we want to protect this remanence against the adverse influence of demagnetizing fields (in other words, we need a high coercive force). Figure 2 is intended to recall some of the terms used in the description of permanent magnets.

The criterion "high saturation" serves mostly to pre-select potential magnet materials and is not too restrictive. There is little hope that materials can be tailor-made with saturation values significantly higher than those known. For a given basic material, however, we can do much about the other two factors, remanence and coercive force, by modifying the structure of the materials.

Magnetization reversal can basically happen by two processes: domain wall motion and rotation of all spins more or less simultaneously (figure 3). The first of these processes is the dominating one in all soft magnetic materials and also in the conventional permanent magnets.

The motion of domain walls requires only a little energy and thus yields a low coercive force. One way magnetically to harden magnet materials is to impede the wall motion by creating obstacles. This can be done by inducing random strains by strong deformation or thermal quenching or by precipitating non-magnetic inclusions. Magnet materials of this type range from simple martensitic carbon steels, which are now rarely used, through alloyed steels containing cobalt, chromium, tungsten, manganese and/or molybdenum, to alloys such as Cunife, Cunico, Vicalloy, and others in which iron is no longer the main constituent. The best magnetic properties achieved with steels were, perhaps, ${}_{B}H_{C}$ 250 oersted and $(BH)_{max} = 1 \times 10^{6}$ gauss-oersted, while the limits of alloys hardened by non-magnetic precipitates are nearer $H_{c} = 800$ oersted and $(BH)_{max} = 2 \times 10^{6}$ gauss-oersted. Some of these alloys are strongly anisotropic as a consequence of cold-rolling or drawing.

The second basic mechanism of magnetization change, simultaneous rotation of all spins in a domain, requires much higher energies than the shifting of domain walls. It is the process by which saturation is approached in an isotropic, polycrystalline

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ferromagnetic material at high field strengths and long after all wall motions have been completed. This suggests that, by eliminating all domain walls and relying solely on rotations, we could make a material in which the magnetization reversal would require very high fields--one of the fundamental properties a permanent magnet must have.

This concept (that the coercive force of a ferromagnetic powder aggregate increases with decreasing size of the particles which form the powder) is the basis for the modern fine particle magnets (figure 4). It was first noted by Gottschalk and since confirmed by many other workers on a variety of materials. This phenomenon is ascribed to the approach to a "single domain" particle behavior. When the particle diameter becomes comparable to the thickness of a Bloch wall, the formation of such a wall becomes energetically less favorable than the magnetization reversal by spin rotation; and, the particle tends always to remain one single magnetic domain. The coercive force which can be obtained with such powder magnets depends on the strength of the forces which bind the magnetization vector to certain favored directions within the particles. The origin of these forces can be the so-called crystal anisotropy in which the magnetization lies preferentially in certain directions of the crystal lattice or the shape anistropy for which the long axis is a magnetic preference direction in an elongated particle. Fine particle magnets based on either of these types of anisotropy have been produced. Two other possible ways to create a magnetic preference direction in particles by straining a highly magnetostrictive precipitate or by making use of the so-called exchange forces between the particle and on anti-ferromagnetic shell are being studied in different laboratories but have not yet been used for commercial magnets. To reach the highest possible remanence with any fine particle magnet, however, it is necessary to align the particles with their easy axes parallel to one another.

The best properties so far obtained for powder magnets in laboratory experiments are B_r = 4,800 gauss, $M^{H}C$ = 3,650 oersted, $(BH)_{max}$ = 5.4 x 10^6 gauss-oersted for manganese-bismuth (a material of no practical importance so far) and B_r = 10,800 gauss H_c = 950 $(BH)_{max}$ = 6.5 x 10^6 gauss-oersted for elongated iron-cobalt particle magnets. The theoretical limits lie much higher, for elongated iron-cobalt particle magnets, for instance, at B_r = 16,300 gauss H_c = 4,100 oersted and $(BH)_{max}$ = 50 x 10^6 gauss-oersted (4).

The highest energy products of all magnets where $(BH)_{max}$ = 12 x 10^6 gauss-oersted combined with H_c = 1,300 oersted and B_r = 12,000 gauss in the best laboratory samples, are obtained with alloys of the Alnico type. Their properties are determined by highly ferromagnetic precipitate in a weakly ferromagnetic matrix which exhibits also near single domain behavior. The structure is quite complicated, however, and not yet fully understood although much progress in this respect has been made in the last few years (8, 9). These alloys can be cast or sintered and a preferred orientation can be created by a proper field anneal. While they have excellent magnetic properties, Alnico magnets are expensive and contain large amounts of Co and Ni, materials of limited supply. This is true also for the ferrous-cobalt particle magnets (but not for some of the other powder magnets including those of iron), provided the matrix problem can be solved satisfactorily.

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The non-metallic ferrite magnets, of which only barium ferrite and, to a lesser degree, cobalt ferrite have technical importance, also owe their high coercive force to a fine subdivision of the material with high crystal anisotropy. However, they do not consist of genuine single-domain particles and domain walls do exist in them. The best reported values for ferrite magnets are $B_r = 4{,}000$ gauss, $H_c = 2{,}000$ oersted H $(BH)_{max} = 3.7 \times 10^6$ gauss-oersted. Barium ferrite, being made of inexpensive and non-critical raw materials, is today the most-used permanent magnet material in western Europe and in Russia, and will undoubtedly find an expanding market in this country as well.

Summary and Outlook

In figure 5, typical demagnetization curves are shown for most of the materials previously discussed. They are representative of what is at present commercially available.

If we try to envision the future development of permanent magnet materials, we can safely assume that the efforts will concentrate on single domain particle magnets in the wider sense. Of these the properties of barium ferrite are rather near their theoretical upper limits now and only incremental improvements can be expected here. Other ferrite compositions with higher saturation magnetization may be formed, however, and ferrites with higher Curie temperatures would be especially valuable for many Air Force uses which call for elevated operating temperatures.

Considerable improvement can still be expected of the Alnico materials; continuation of the research efforts to understand their precipitation mechanisms, their structure and its relation to the magnetic properties are pre-requisites for systematic material development. Air Force sponsored studies of the high temperature properties of a variety of permanent magnets have proved Alnico V and VI useful for application at operating temperatures above 500°C (10). Such investigations will also have to be continued and extended to materials not heretofore tested.

Elongated particle magnets need considerable improvement. New matrix materials, in addition to lead and plastics, should be found for the iron and iron-cobalt magnets, and methods devised for producing more uniform, near-cylindrical particles to permit a further increase of the maximum energy product.

Attempts should also be made to produce elongated particles of other materials, possibly combining the action of crystal and shape anisotropy by making single crystal particles whose long axis will coincide with a direction of minimal magneto-crystalline energy. A recent publication reported that it is also possible to produce oxide-covered particles which derive their coercive force from the shell while the metal core provides the remanence.

For fine particle magnets based on crystal anisotropy, manganese-aluminum is a material most worthy of intensive study (11). Investigation of other known or heretofore not produced magnetic intermetallic compounds may well bring about new promising materials with high crystal anisotropy, sufficiently high saturation and Curie point, and good environmental stability.

Finally, pursuit of the concept of exchange coupling between an antiferromagnetic layer and a ferromagnetic particle of film may eventually lead to the development of practical magnets of unidirectional behavior (ref. 12).

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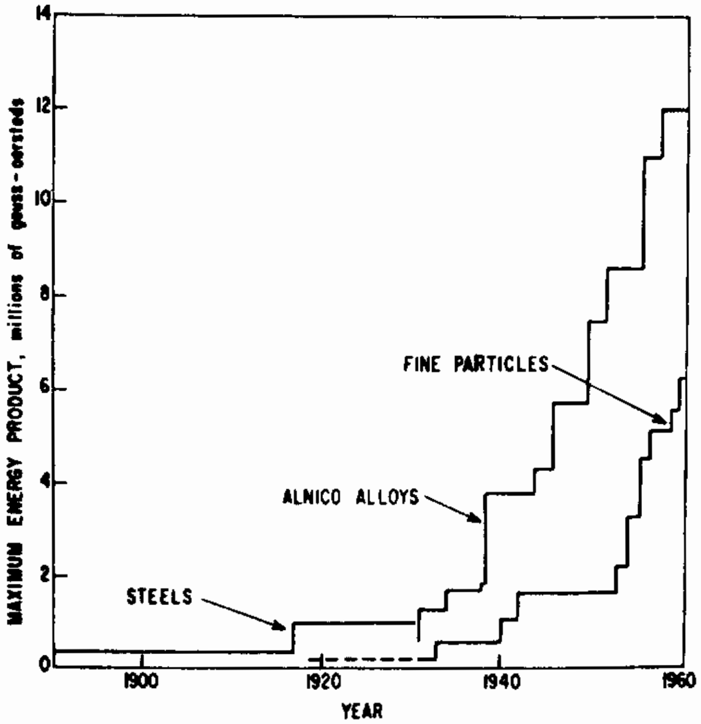

Figure 1. Progress in Permanent Magnet Development (From Ref. 4)

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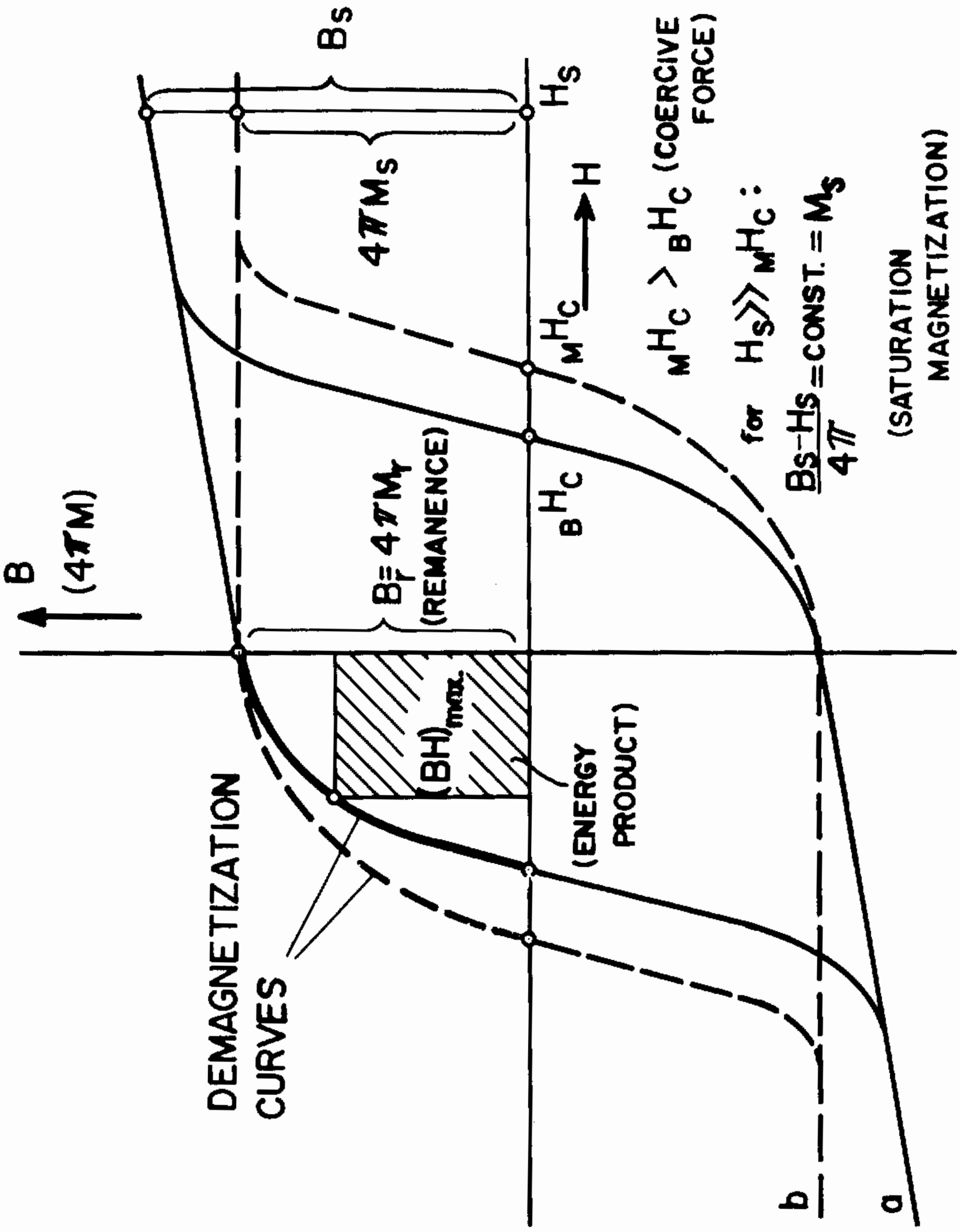

Figure 2. Terms Used in the Description of Permanent Magnets

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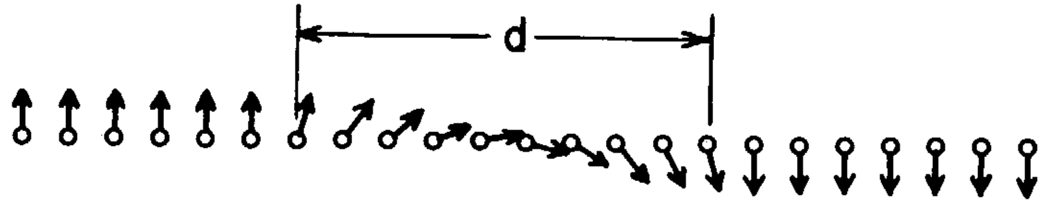
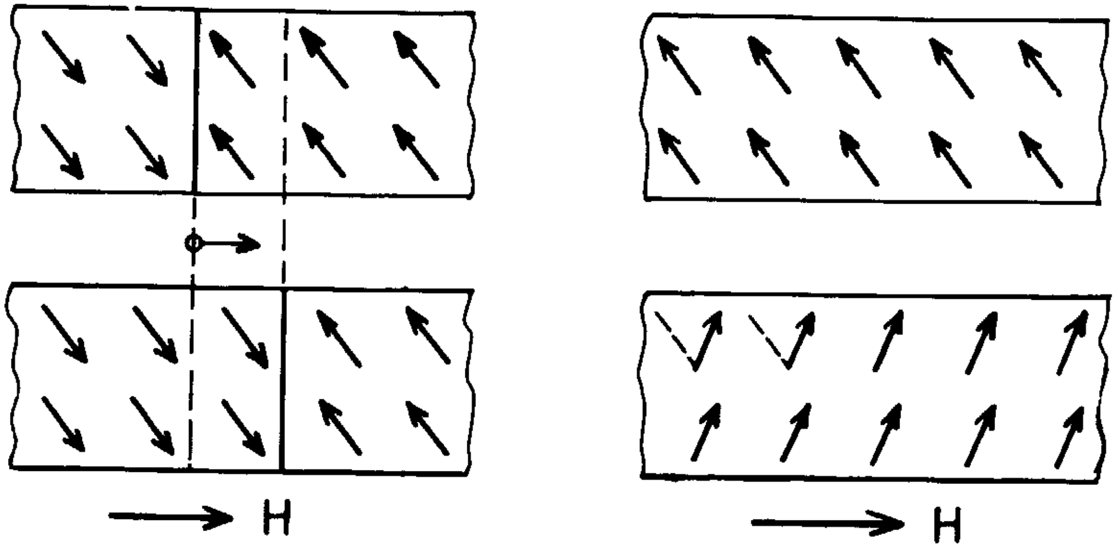


SPINS IN A DOMAIN WALL



(a) DOMAIN WALL MOTION

(b) UNIFORM SPIN ROTATION

Figure 3. Processes of Magnetization Reversal

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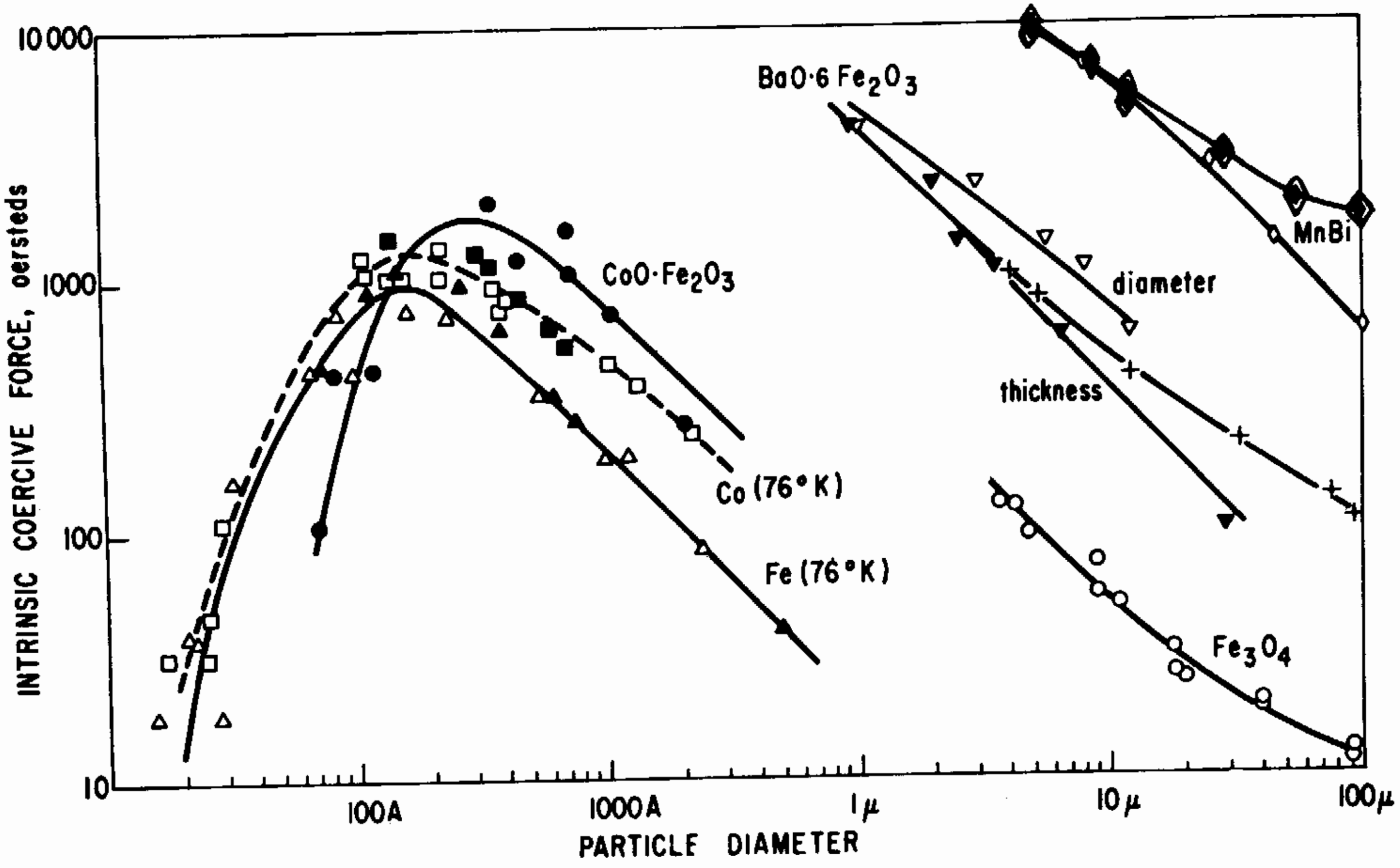

Figure 4. Relation Between Coercive Force and Diameter of Fine Particles with High Crystal Anisotropy (From Ref. 4)

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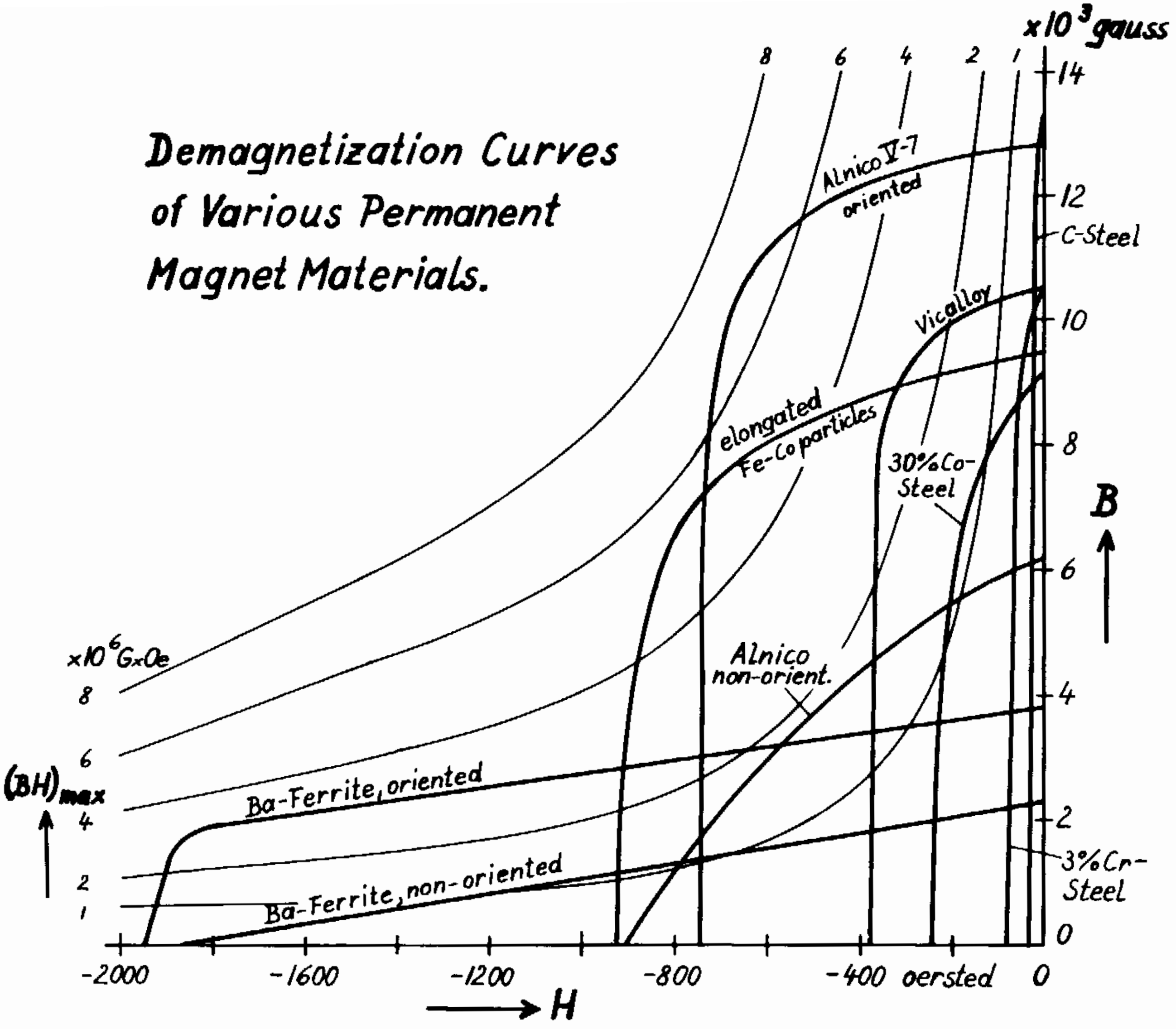

Figure 5. Demagnetization Curves of a Representative Selection of Commercially Available Magnet Materials

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