Appendix B

Magnet Application Data

Nature of Magnetism

Magnetism is considered by some to be a mysterious phenomenon. This is not true, except insofar as the ultimate nature of gravity, electrostatic fields, matter, and radiation are also mysterious. All of these can, in fact, be described by means of mathematical expressions that predict their behavior and in this sense, are well understood.

In order to understand the magnetic behavior of materials, it is necessary to take a microscopic view of matter. A suitable starting point is the composition of the atom, which Bohr described as consisting of a heavy nucleus and a number of electrons moving around the nucleus in specific orbits (Figure B-1).

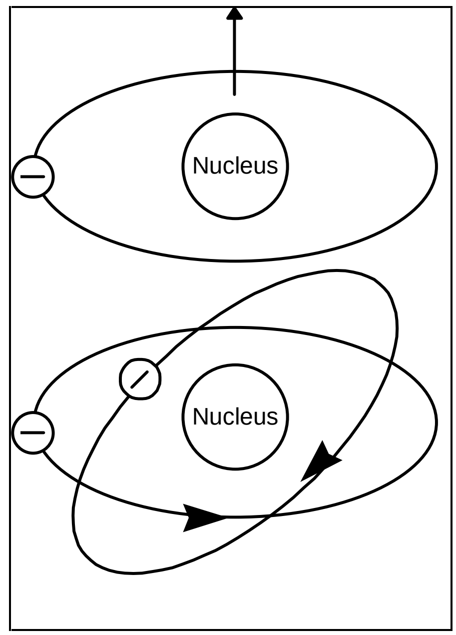

Figure B-1 Bohr's model of the atom

Closer investigation reveals that the atom of any substance experiences a torque when placed in a magnetic field; this is called a magnetic moment. The resultant magnetic moment of an atom depends upon three factors - the positive charge of the nucleus spinning on its axis, the negative charge of the electron spinning on its axis, and the effect of the electrons moving in their orbits. The magnetic moment of the spin and orbital motion of the electron far exceed that of the spinning nucleus. However, this magnetic moment can be affected by the presence of an adjacent atom. For simplicity, we chose the hydrogen atom. Accordingly, if two hydrogen atoms are combined to form a hydrogen molecule, it is found that the electron spins, the nucleus (proton) spins, and the orbital motions of the electrons of each atom oppose each other so that a resultant magnetic moment of zero should be expected. Although this is almost the case, experiment reveals that when a hydrogen molecule is exposed to a magnetizing force, there is a slight decrease in magnetic field as compared with free space. Materials in which this behavior manifests itself are called diamagnetic. Besides hydrogen, other materials possessing this characteristic include silver and copper.

Continuing further with the hydrogen molecule, assume it is made to lose an electron, thus yielding the hydrogen ion. Complete neutralization of the spin and orbital electron motions no longer takes place. In face, when a magnetic field is applied, the ion is so oriented that its net magnetic moment aligns itself with the field, thereby causing a slight increase in flux density. This behavior is described as paramagnetism and is the characteristic of such materials as aluminum and platinum.

So far, we have considered those elements whose magnetic properties differ only vary slightly from those of free space. As a matter of fact, the vast majority of materials fall within this category. However, there is one class of materials – principally iron, nickel, cobalt and many other alloys – for which the relative permeability is very many times greater than that of free space. These materials are called ferromagnetic and are of great importance in magnetic applications. The reason iron (and its alloys) is much more magnetic than other elements can be answered by the Domain theory of magnetism proposed by Weiss. Like all metals, iron is crystalline in structure with the atoms arranged in a space lattice. Domains are subcrystalline particles of varying sizes and shapes containing about 10^{15} atoms in a volume of approximately 10^{-9} cubic centimeters. The distinguishing feature of the domain is that the magnetic moments of its constituent atoms are all aligned in the same direction. Thus in a ferromagnetic material, not only must their exist a magnetic moment due to a non-neutralized spin of an electron in inner orbit, but also the resultant spin of all neighboring atoms in the domain must be parallel.

Domains act independently of each other, and for a specimen of unmagnetized iron these domains are aligned randomly so that the net magnetic moment is zero. Application of an external field of sufficient magnitude will cause the magnetic moments of all the domains to align themselves parallel to the external applied field. When this state is reached the iron is said to be saturated – there is no further increase in flux density over that of free space for further increases in magnetizing force.

In the case of pure iron, if the external field is reduced to zero, it will be found that the magnetic moments will return to the randomly ordered condition (if a slight demagnetizing force is present). Materials with this property are referred to as magnetically soft and used in electromagnets. In the case of the permanent magnet materials, it is found that the magnetic moments will strongly resist being realigned in a random fashion. These materials are referred to as being magnetically hard.

Locked-in Domains

It is a common fallacy that a permanent magnet supports a magnetic field external to itself by means of the expenditure of some internal energy, that it is similar to a battery having a limited period of diminishing usefulness, or in the extreme case, similar to an electronic light bulb, whose usefulness comes to a definite and abrupt ending. Such is not the case.

The ability of a permanent magnet to support an external magnetic field results from locked-in positions of small magnetic domains within the magnet itself. These locked-in positions, once established by initial magnetization, are held until acted upon by forces exceeding these locked-in forces. The energy involved in the repeated performance of various functions generally associated with the permanent magnet comes not from within the magnet, but from external sources; the magnet merely acting as an intermediary or transducer in converting this external energy to some other useful form. For example, when magnets are used in a generator, the driving motor furnishes the initial mechanical energy. The resulting electrical energy does not come from the magnet.

Magnetized permanent magnets differ from batteries and radioactive materials since they are potential energy sources and consequently do not run down. Thus, the magnetic field surrounding the magnet does not require energy to maintain it and there is no theoretical reason for a permanent magnet to continually lose strength.

Material Characteristics

The original magnets were lodestones, an iron oxide magnetized by lightning. Lodestones were used as early as 2700 BC by the Chinese for compasses. Until 1600 when Gilbert did the first theoretical study of magnetism, lodestones were considered to be magic. Gilbert developed methods of making magnets from iron and established that the earth itself was a magnet.

In the latter part of the 19^{th} Century, the first materials developed specifically for permanent magnets came into use. Early magnet materials, chrome, cobalt, and tungsten steels were relatively unstable metallurgically and magnetically. In 1932, the Japanese announced that excellent properties were obtained from an aluminum-nickel-iron alloy. This material became subject to intensive investigation. The ultimate result of these investigations was the development of an aluminum-nickel-cobalt alloy (Alnico) which had high metallurgical and magnetic stability.

Alnico

Alnico magnets are made by pressing metal powders into approximately the desired shape and then sintering at elevated temperatures. Small grain structures result, providing magnet materials with more uniform flux distribution and superior mechanical properties. Alnico is well-suited to the mass production of small magnets with intricate shapes.

Indox ®

Indox magnets are chemically inert with the composition MO-$Fe_2 0_3$ (M representing barium, strontium, lead or a combination thereof). They are formed by compaction and sintering, are hard and brittle but can be ground, usually with diamond wheels, to obtain closer tolerances than those maintained in the as-pressed condition.

Indox magnets are poor conductors of heat and electricity. Shock, stress and vibration will not affect their magnetic characteristics. An Indox magnet will by physically destroyed before any change in characteristics is noted. Figure B-2 summarizes Indox properties.

Figure B-2 Typical Indox Properties

Indox	B_r (Kilogauss)	H_c (Oersted)	$(B_dH_d)_{MAX}$ (Mega-Gauss-Oersted)
1	2.2	1825	1.0
2	2.9	2450	1.8
3	3.35	2350	2.6
4	2.55	2300	1.5
4-HR	2.85	2600	1.9
5	3.8	2525	3.4
6	3.3	2800	2.45
7	3.45	3250	2.8
8	3.85	3050	3.5

Lodex ®

Lodex is a family of single domain, fine particle magnet materials that can be pressed or extruded to form a finished magnet. Domain-sized particles and binder are mixed in power form and then pressed to final shape. Lodex lends itself to small and intrically-shaped permanent magnets. The magnetic properties of Lodex are summarized in Figure B-3.

Figure B-3 Typical Lodex Properties

Lodex	B_r (Kilogauss)	H_c (Oersted)	$(B_dH_d)_{MAX}$ (Mega-Gauss-Oersted)
30	4.0	1250	1.68
31	6.25	1140	3.4
32	7.3	940	3.4
33	8.0	860	3.2
36	3.4	1220	1.45
37	5.5	1000	2.1
38	6.2	840	2.2

Rare Earth

Rare Earth magnets are composed of elements including Erbium, Gadolinium, Terbium, Dysprosium, Holmium and Samarium in combination with Cobalt.

These magnets are fabricated by pressing small particles of rare earth cobalt powder properly aligned (by the influence of a magnetic field), then sintering to high densities and heat treating to optimize properties. Rare earth magnets feature very high peak energy products, but their relatively high costs generally limit them to applications where small size, high magnetic strength and/or high resistance to demagnetizing fields are important. The magnetic properties of rare earth magnets are summarized in Figure B-4.

Figure B-4 Typical Rare Earth Properties

Rare Earth	B_r (Kilogauss)	H_c (Oersted)	$(B_dH_d)_{MAX}$ (Mega-Gauss-Oersted)
Hicorex 90A	8200	7500	16.0
Hicorex 90B	7500	8200	18.0
Hicorex 92	6000	5500	9.0
Hicorex 93	7000	6000	12.0
Hicorex 96A	10250	9500	26.0
Hicorex 99C	10600	6000	27.0
Incor 16	8100	7900	16.0

Factors influencing permanent magnet strength

Permanent magnets are truly permanent – they do not wear out. However, various factors, such as time, temperature and external fields, can produce changes in the strength of a permanent magnet. These factors should be considered when selecting a magnetic material.

Time

In the older permanent magnet materials, such as cobalt-steel, some metallurgical changes take place as a function of time. If such a magnet is magnetized before these changes have stabilized, flux changes will occur. (This effect can be reduced to a negligible factor by artificial aging.) In the magnet materials such as Alnico or Ceramic, metallurgical changes do not take place in any measurable degree at room temperature.

A freshly magnetized permanent magnet will lose a minor percentage of its flux, as function of time. This loss of flux can be essentially eliminated by a partial demagnetization of the charged magnet in the amount of 7% to 15%. This is most conveniently accomplished by an AC field. The AC field should be in the same direction as the magnetizing field. It should be reduced to zero gradually, either by withdrawing the magnet with power on, or by reducing the AC voltage to zero with a variable auto-transformer.

Temperature

Temperature effects fall into three categories: Metallurgical, Irreversible and Reversible.

Metallurgical changes may be caused by exposure to too high a temperature. Such flux changes are not recoverable by remagnetization. The approximate maximum temperatures which can be used without experiencing metallurgical changes range from 100°C for Lodex to 1080°C for the ceramics. Figure B-5 shows the maximum temperature for typical magnet materials. The effect of metallurgical changes, if present, can be avoided only by long-term exposure of the magnet to the temperature involved, prior to magnetizing.

Figure B-5 Maximum temperature without metallurgical changes

Material	Temperature (°C)	Curie Temperature (± 10°C)
Lodex	100	780
Hicorex	250	700
Incor	250	700
Barium Ferrite	400	450

Irreversible losses are defined as partial demagnetization of the magnet, caused by exposure to high or low temperatures. Such losses are recoverable by remagnetization, and are reduced or eliminated by magnet stabilization.

The ideal method for stabilizing magnets against temperature-induced irreversible losses, is installing them in the magnetic circuit (or assembly) for which they are intended, magnetize, then subject the assemblies to several temperature cycles which they are expected to experience in service.

The magnetized assembly may be partially demagnetized by means of an AC field, following the procedure described in **Time**. A rule of thumb to follow is determining by experiment that temperature cycling will cause X% flux loss, then the AC field should be such as to cause a 2X% flux loss, to properly stabilize against temperature.

Reversible changes in flux can occur with temperature. For example, if any ceramic grades are heated 1°C above ambient temperature, they will lose 0.19% flux. However, this will be spontaneously regained upon the magnet's cooling back to ambient temperature. The Alnico materials have reversible variations on the order of 1/10 as great as ceramics, depending upon the material and the operating point on the demagnetization curve. Reversible variations are not eliminated by stabilization treatments. However, use of proper temperature composition material in parallel with the magnet will reduce the effect to a negligible factor. Among others, household watt-hour meter magnets and speedometer magnets are temperature compensated in this manner.

Reluctance changes

If a magnet is magnetized in a magnetic circuit and subsequently subjected to permeance changes (such as changes in air gap dimensions or open-circuiting of the magnet) it may be found that a partial demagnetization of the magnet has occurred. Whether or not such a loss is experienced depends upon material properties and upon the extent of the permeance change.

Stabilization against such change is accomplished either by subjecting the magnet several times to reluctance changes after magnetizing, or by use of the previously described AC field.

Contacting the magnets with ferro-magnetic material (screw drivers, pliers and the like), at points other than the poles, can cause an appreciable drop in flux at the poles. It is difficult to stabilize against this type of abuse. The remedy is to avoid such practices.

Adverse fields

If a magnet or magnet assembly is subjected to an adverse magnetic field, a partial demagnetization may result, depending upon material properties and the intensity and direction of the adverse field. Proper stabilization consists of subjecting the magnet or assembly to a DC or AC demagnetizing field of the same magnitude as it is expected to encounter in service. The direction should be the same as that of the anticipated demagnetizing field.

Shock, stress and vibration

The effects of shock, stress and vibration (below destructive limits) on most permanent magnet materials are so minor than little consideration need by given to them. Proper stabilization as described in any of the preceding paragraphs will also stabilize against shock and vibration.

Radiation

The effects of radiation on permanent magnet materials varies widely by material classes. Current experiments indicate that all permanent magnet materials of a commercial nature can withstand irradiation to 3×10^{17} neutrons per cm^2 (neutron energies greater than 0.5EV), without flux changes. A majority of the commercial materials (including Alnico and Ceramic) can withstand 2×10^{18} neutron per cm^2 exposure without flux changes, and show only minor changes (less than 10%) when the radiation level is increased to 3×10^{13} neutrons per cm^2.

Radiation, like thermal demagnetization, is not applicable to calibration. Some evidence indicates that secondary exposure to high neutron densities that caused initial flux changes resulted in only negligible additional flux changes. This would indicate that stabilization of radiation effects by initial exposure is possible.

Handling of Permanent Magnets

In many instances, the permanent magnet remembers what was done to it or what environment it was exposed to. Adverse factors affecting permanent magnets must be acknowledged and techniques applied to minimize or eliminate these conditions. The design, manufacture, handling and processing of permanent magnets is based on adequate control of this sequence to insure optimum performance in the final application. Improper handling has resulted in poor, or completely sub-standard, performance.

Unmagnetized magnets

From the standpoint of ease in shipping, handling and storage, the unmagnetized magnet is preferred. Special problems of knockdown, iron chip pickup, and special instructions on handling to personnel are eliminated.

To insure magnetic quality, the permanent magnet supplier has to test the magnet in a fully magnetized condition. After this inspection, the magnet is demagnetized prior to shipment.

The benefit of purchasing, shipping and processing of unmagnetized magnets are many. A few of the problem areas that can be eliminated or minimized are:

- Keepers are not required
- Proximity effects of other permanent magnets may be ignored
- Proximity of strong AC or DC fields pose no problem
- Physical shock or vibration for critical applications may be ignored
- Shape problems of self-magnetization are not applicable
- Physical handling problems are considerably alleviated
- Storage and shipment problems are minimized

A final step must be performed to an unmagnetized permanent magnet: magnetizing and inspecting the functional magnetic field of the permanent magnet after assembly. Adequate means for saturation and control of the magnetizing process for the permanent magnet is needed. In some cases, stabilization must be included for temperature, AC or DC electric fields and/or other effects.

Magnetized permanent magnets

If a permanent magnet is purchased magnetized, what does or can occur magnetically must be realized. The concept of magnetic behavior, or operating slope for maximum magnet efficiency must be recognized. The accrued factor of self-demagnetization, or **built-in** stabilization, must be evaluated. The problem of in plant processing cannot be overlooked. Also, the problem of shipping a number of magnetized magnets and their attractive forces, along with temperature extremes, must be considered.

This magnetized condition, and its associated problems, can be alleviated by specifying that keepers be attached. A keeper is simply one or more pieces of ferrous material usually placed across the gap of a magnetized permanent magnet. The use of a keeper reduces stray leakage fields for better handling and less magnetic interaction among magnets.

Personnel who handle magnetized magnets and assemblies should receive special instructions. This details what should or should not be done to the magnetized assemblies. As an example, the dropping of a permanent magnet structure may alter the gap dimensions. This could occur without any visible damage to the structure, but would necessitate demagnetizing the permanent magnet, reworking the structure, and remagnetization. In many cases, the removal of a magnetized permanent magnet from its structure will degrade the performance, resulting in a **knockdown** of the permanent magnet, a condition remedied only by remagnetization.

The previous discussion for the two states of a permanent magnet – magnetized or not magnetized – are, of necessity, quite general. The user will have specific problems, which in many cases will require a unique procedure. This information should be obtained from the supplier.

Magnetization

Basically, magnetization requires subjecting the magnet to an uni-directional magnetic field of proper strength and direction. A power source with some type of control and a magnetizing fixture are the important elements. There are many ways to produce the magnetizing field required to magnetize magnets, magnet circuits or assemblies. These may range from a simple solenoid to an elaborate water-cooled one-half cycle pulsed transformer magnetization system. An evaluation of the best approach considers such factors as magnet material and shape, type of assembly, and production processes. In fact, many magnet designs and/or assembly processes are influenced by the availability of proper magnetizing equipment.

Permanent magnet method

A permanent magnet may providing the necessary magnetizing field. However, this method is used only for small, simple shaped magnets. This method, while inexpensive and requiring no power source, is generally unacceptable. This is due to the possibility of inadequate magnetizing field strength, difficulty of removing the magnetized magnet from the magnetizer, distortion of the magnetizing field (caused when the magnet is removed) and the fact that magnetic particles attracted to the magnetizer are difficult to remove.

Electro-coil method

DC coils with or without iron cores and water cooling can be used to produce magnetizing fields. This method is probably the most common approach to general magnetization. Normally the magnetizers are used in an intermittent basis. Coils with steel cores are used with a rectified AC power source. These units are adaptable for the simple-shaped permanent magnet including rods, bars, and U-shaped configuration. Their major disadvantages are the difficulty in obtaining proper magnetizing field direction in complicated magnet designs and the relatively slow magnetization rate due to coil inductance.

Capacitor discharge method

This approach uses the energy stored in a capacitor bank. Since magnetization is essentially instantaneous, a magnetizer system is only required to supply the proper value of magnetizing pulse for a very short interval of time. The amplitude is dependent upon that required to saturate the magnet and the duration that is necessary to overcome the eddy current and hysteresis effects of the pulse of the magnet, its associated circuitry and the magnetizing system itself. Capacitor discharge units can also be used with high current pulse transformers.

The advantage of capacitor discharge systems is the energy can be put into the storage system (capacitors) at a relatively slow rate so that the power demand is low. However, this means that charging or reset time could be an undesirable factor in fast repetitive operations.

One-half cycle method

The one-half cycle magnetizer is a half-wave rectifier connected between an AC source and the magnetizing coil. Control circuitry assures a unidirectional high current pulse of one or more cycles. Proper phasing controls the energy of the magnetizing pulse. The one-half cycle magnetization system is ideal when used with a properly designed pulse transformer and matched magnetizing fixture. Extremely fast magnetizing cycles are possible because, at least in theory, it is possible to magnetize once every cycle. However, magnet handling consideration and coil and fixture heating are the limiting factors. With the practical adaptation of this type of system, the magnetization operation is no longer a bottleneck. Ingenious air and water cooling of the magnetizing fixtures, pulse transformers, and other parts of circuitry have led to high operational rates.

Testing systems

There are many ways to test permanent magnets. A flux sensing device combined with a readout method is required. Each application must be evaluated to determine what approach best fits the situation. Flux meter and ballistic galvanometer equipment have been used for many years. The magnetometer, permeameter, coercimeter, and gauss meter all plan an important role in determining and evaluating magnetic characteristics of permanent magnets, especially for engineering design evaluation.

The introduction of stable, sensitive, commercially-available Hall probes has made possible magnet production testing that is accurate, fast and reliable. The simplest form of a Hall probe is the Calibrated Hall Element discussed in Chapter 3. These probes, when energized with a constant control current or voltage, give a voltage output proportional to the strength of magnetic field. Consequently, the Hall probe with voltage sensor relays or readout devices is the heart of modern permanent magnet testing. Experience indicates that properly designed test systems can give results approximating laboratory accuracy.

It is important to obtain absolute values of magnetic parameters for engineering evaluation to prove the design. In this case, equipment is calibrated to give this information. Generally, however, production testing of permanent magnets is done on a comparative basis.

A reference magnet that gives known performance is used. The testing method and circuit is designed to be equivalent, as far as the magnet is concerned, to actual operating conditions. Normally, it is not necessary in production testing to investigate the entire demagnetization curve. Most production tests are designed to indicate the magnet’s quality at its operating condition.

Calibration systems

On occasion, consideration must be given to calibrating magnets or magnet assemblies. The decrease in the range of flux variation from magnet to magnet will result in an end product having greater performance uniformity. A careful analysis of all the factors will indicate if calibration should be considered.

It is first necessary to determine the strength of the magnet or magnets in the assembly. A comparison with the required level and the allowable variation will indicate if calibration is necessary. If so, the unit is demagnetized to the prescribed level of flux output. This is done by controlled demagnetizing pulses that partially demagnetize the magnet, thus decreasing the flux output.

AC fields and capacitor discharge systems having manual or automatic controls are also being used successfully in calibrating systems. These and even electro-coil methods have been used in laboratory work. The one-half cycle system will give the fastest rate for volume calibration of permanent magnets. Circuitry has been developed that will precisely control the synchronization and phasing of ignitron tubes to give fast, repetitive and controllable calibrating pulses.

Magnetic materials

Most permanent magnet materials commercially available today have been available for many years. These basic materials have become identified with a standard name and number identifiable throughout the permanent magnet industry.

MMPA Standard 0100-66 that is published by the Magnetic Materials Producers Association, Chicago, lists commercially available permanent magnet materials. The publication presents nominal chemical composition and typical magnetic properties. A material specification submitted to any permanent magnet manufacturer need only designate the name - Alnico 5, Ceramic 1, Cunife, Sintered Alnico 2, etc. - in order to specify a particular permanent magnet material. The same MMPA Standard has been accepted by the Department of Defense in place of Military Specification QQ-M-60 for Permanent Magnet Materials.

Magnetic characteristics

In general, every cross section of an ideal magnet in a fixed gap circuit should operate at the maximum energy point shown in Figure B-6. In practice, this is usually not the case. In a good design, the majority of the magnet materials operate in the vicinity of the maximum energy point - Point 2, on the knee of the B-H curve. Small variations in B_r and H_c from magnet to magnet will have little or no effect upon the output of the magnet and its circuit.

If the magnet is operating above the knee of the B-H curve (Point 1), variations in B_r would affect the output, but variations in H_c would not. If the magnet is operating below the knee of the curve (Point 3), the opposite is true. If one of these conditions applies, the magnet manufacturer may modify processing to favor that condition so that magnet performance in the customer's product will be improved. Consequently, to achieve a satisfactory product, it is sufficient to tie down only those parameters that apply to a given magnetic circuit.

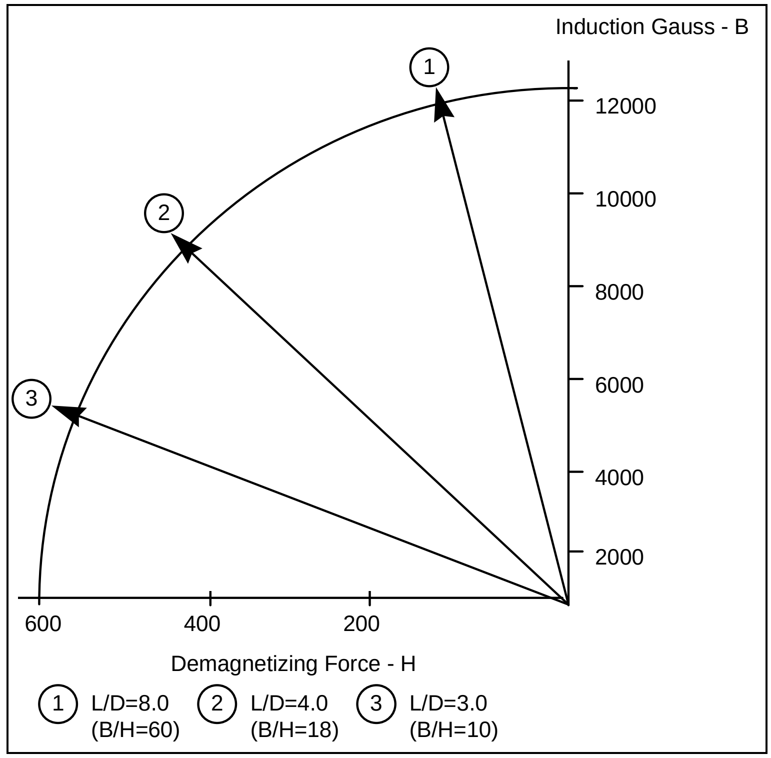

Figure B-6 Demagnetizing curve Alnico 5

Practical magnet specifications

As opposed to the sophisticated magnet theory and other magnet design principles that are of importance mainly to magnet manufacturers, practical magnet specifications involves a basic knowledge of magnet materials, magnetic characteristics, magnet test procedures, and factors that affect flux produced by a magnet. A disciplined application of these considerations simplifies correct magnet specification.

A user-formulated specification that is too light may require the magnet manufacturer to provide extra manufacturing, testing and quality control operations. In many cases, magnets perfectly suitable for the end product may be scrapped because of unrealistic specification. As a result, specifying too tightly increases the magnet’s cost.

On the other hand, a loose specification (or no specification) could allow the shipment of almost any magnet grade. Such a situation would not be desirable for either user or supplier. In addition to magnetic properties, specifications on surface finishes or physical dimensions are important.