Hk: A Key Magnetic Figure of Merit

Abstract: The quality of permanent magnets is defined by several parameters such as B_R, H_{cJ}, $(BH)_{MAX}$, permeability (μ) and reversible temperature coefficients of induction $\alpha(B_R)$ and coercivity $\alpha(H_{cJ})$. Engineers designing devices for use at other than room temperature or in the presence of a demagnetizing field also use a characteristic describing the quality of the intrinsic curve. This calculated value, H_K, is too little understood and alternative definitions of curve quality are appearing.

THE PAST: Prior to the late 1950's commercial magnet materials fell into two general categories: magnet steels and alnico. When measured, the Normal and the Intrinsic curves were very similar and only the Normal curve was routinely utilized. Even for alnico 8 and 9, where moderate differences between the Normal and Intrinsic curves are evidenced, the Intrinsic curve is successfully ignored as the Normal curve provides for conservative calculations.

When ferrite magnets, also known as ferrite permanent magnets or ceramic magnets, were developed in the mid 1950's they began to dominate the market for permanent magnets due to their low material cost, adequate magnet properties and wide availability. By the mid 1960's ferrite magnets had made significant inroads into loudspeaker and motor applications. Ferrite magnets also have an interesting and useful characteristic: the Normal curve under most conditions is very close to a straight line in the second quadrant – at least to the maximum energy point. Due to this, ferrite became known as a "straight line" material. Engineers working with the Intrinsic curve, referred to ferrite magnets as a "square loop" material. Today, one can hear either expression used with regard to ferrite, SmCo and NdFeB magnets. The relevance is that as long as the operating point of the magnet remains within the linear portion of the Normal (or Intrinsic) curve, the magnet will suffer little to no irreversible loss in magnetic output.

That point on the Intrinsic or Normal curve where the straight line deviates to a curve is called the "knee". If the magnet were to operate below the knee, irreversible loss would occur. Motor designers were eager to push these magnets to their limits and also wished to know where approximately 10% knockdown would occur. This occurred primarily on the leading and trailing magnet edges which could beneficially reduce motor cogging. James Ireland[1] proposed a quantity he called H_X which was obtained from a horizontal line drawn at 0.8 x B_R with a vertical dropped to the H axis from the horizontal line's intersection with the Intrinsic curve (Figure 1). The value of H_K is also shown for comparison.

Later, authors adjusted the determination of H_X starting with a value of 0.9 • B_r. One such reference is Parker and Studders, *Permanent Magnets & Their Application*, in 1962 and 1964. Sixteen years later Rollin J. Parker wrote an updated text for the magnet industry, *Advances in Permanent Magnetism*[3], 1990, in which he too refers to this definition of H_X. Glenn R. Gaster of Indiana General (later at 3M Corporation) was a proponent of a quantity called H_X. However, he modified the definition as follows: the line drawn from the 0.9 • B_R point on the B axis was not a horizontal line, but sloped downwards to the left at the Intrinsic Recoil slope. Where it intersects the intrinsic curve, a vertical is dropped to the H axis. That value of H is called H_X (Figure 2).

Sometime prior to 1981 and continuing thereafter, several authors referred to the H_X value as H_K. One interpretation is that the "K" refers to "knee" of the intrinsic curve. These early writings referring to H_K include papers in the International Workshops on Rare Earth Magnets and Their Applications[5][6][7] (1981 and 1985) and the MMPA Permanent Magnet Guidelines[4] from 1988.

THE PRESENT: Despite an almost total lack of reference to H_K in textbooks on magnetism, it remains a useful quantification of intrinsic curve shape. An exception is *Magnetism II* [2] (du Tremolet de Lacheisserie, D. Gignoux and M. Schlenker) pp.13-14. They refer to H_K (in SI units it is $\mu_0 H_K$) as the "maximum working field… defined as the reverse field for which the magnetization is reduced by 10%." In 2008, Stan Trout wrote[8] that [H_K] may be "better than *Hci*", which, interpreted means it is more informative about showing when a magnet will start to suffer irreversible loss of flux.

By definition H_K is always less than H_{cJ}. If one were to divide H_K by H_{cJ}, the resulting number represents a measure of how "square" the intrinsic curve is. For a perfectly square curve, this squareness ratio[7] would be 1. For high quality rare earth and ferrite magnets typical values range from 0.90 to 0.95.

THE FUTURE: Is the current definition of H_K adequate? One difficulty arises with very high coercivity materials such as the "EH" and "AH" grades of Neo with H_{cJ} values greater than 30,000 Oe (2390 kA/m). A recoil permeability slope of 1.05 produces an intrinsic recoil slope of 0.05. For example, for a B_R of 11,000 gauss, 0.9 • B_R = 9,900 gauss for a "drop" of 1,100 gauss. Calculating H = 1,100 / 0.05 = 22,000 oersted. What this indicates is that no matter how high H_{cJ} is, or otherwise how good the demagnetization curve is, H_K will have a maximum value of 22,000 Oe and the squareness ratio will be lower than expected. Even with a reduced recoil slope of 1.035, the maximum H_K is 31,400 Oe (2500 kA/m), not as high as some of the newer Neo grades.

M. Katter[9] has proposed a revision of the H_K definition to the IEC (International Electrotechnical Committee), an international standards organization. Katter's revised definition (Figure 3) requires analysis and plotting only slightly more difficult than the traditional H_K method while retaining the primary purpose: identifying the value of H where the knee occurs. In fact, with some amplification it is what Glenn Gaster had proposed some 23+ years ago. It also allows for variable sensitivity by specifying how much lower than the Intrinsic curve the new line will be drawn (Figure 3). Note also, that the frequently observed minor drop in induction as the curve moves away from the B axis is ignored in the recoil slope calculation resulting in a more accurate assessment of squareness.

Method: One calculates the slope of the intrinsic curve between points A and B. A is located at H=20% of H_{cJ} and B is located at H=70% of H_{cJ}. Then a parallel line is plotted at a defined percentage lower than points A and B. In the example shown here, lines are drawn at 95% and at 90% of the intrinsic curve. The values of H at the intersections would be referred to as H_{R95} and H_{R90} respectively. This procedure can be performed automatically when making hysteresigraph measurements or manually with a calculator and straight edge on a printed demagnetization curve.

This method also accommodates the slight shifts in recoil slope that take place at elevated temperatures, producing a better estimate of H_R at high temperature. Like the standard H_K calculation, it places a greater performance burden on lower B_R materials: 90% of a smaller B_r produces a smaller drop in either the horizontal or the recoil slope lines used to obtain H_K or H_R. One alternative is to calculate a fixed drop, say 0.2 Tesla. The resulting intersection point could then be called $H_{R0.2}$.

Whatever is finally decided it seems that curve shape and the describing value will finally see the respect it deserves.

Author's notes

Since this was written in 2009, the IEC has accepted a definition of H_K similar to that proposed by M. Katter, but only applicable to NdFeB magnets with H_{cJ} greater than 400 kA/m (5000 Oe). The value of H_K is instead called H_{Dx} where "x" represents the percentage reduction on the B axis. For example H_{D10} represents the value of H_D with a line drawn parallel to the intrinsic recoil slope and starting on the B axis at a point 10% below B_R, i.e. 0.9•B_R.

This change is encompassed in the latest revision of IEC 60404-8-1:2015[10], Magnetic materials - Part 8-1: Specifications for individual materials - Magnetically hard materials, available from https://webstore.iec.ch/publication/22009.

Symbols for key magnetic parameters continue to represent a challenge so here are a few equivalent symbols for selected parameters. The subscripting is often ignored so as to simplify writing and typing of the symbols. The subscripted letters are almost always capital letters so they are easily legible. The symbols are generally italicized. For additional information the reader is directed to ASTM A340[11] and NIST Guide to the use of SI[12]. Be sure to read the latest edition of ASTM A340 as it is undergoing continual updating to be made consistent with IEC and industry usage. The first abbreviation shown has, until recently, been the most common; the last abbreviation for each is most consistent with SI and what industry seems to be moving toward.

- Br = B_R = Residual induction and is equal to J_R (residual polarization) and M_R (residual magnetization).
- Hc = Hcb = H_{cB} = coercivity or normal coercivity or coercive field strength. "b" or "B" are probably used as the H_{cB} point is on the normal or "B versus H" curve.
- Hci = iHc = Hcj = H_{cJ} = intrinsic coercivity, a measure of a magnet's resistance to

demagnetization. The “I” or “J” are probably used as this point is on the Intrinsic curve also called the polarization (J) curve.

- BHmax = (BH)max = $(BH)_{MAX}$ = maximum energy product. Every point on the normal curve has a value of B and a corresponding value of H. There is a product of B•H for every point on the curve. The point where the product of B•H is maximum is called the maximum energy point and the value of B•H at this point is the maximum energy product. (You may have noticed that typing the parentheses for $(BH)_{MAX}$ avoids autocorrecting the two sequential capital letters).
- $\mu_{(REC)}$ = Recoil permeability is measured on the normal curve. When referring to the corresponding slope on the intrinsic curve it is called the intrinsic recoil permeability. In the cgs-Gaussian system where 1 gauss equals 1 oersted, the intrinsic recoil equals the normal recoil minus 1. For example, a typical rare earth magnet might have a $\mu_{(REC)}$ = 1.05 and the Intrinsic $\mu_{(REC)}$ = 0.05.
- Pc = P_C = Permeance coefficient. This is a calculated value dependent upon the dimensions of the magnet - for our purposes as shown on the demagnetization charts the magnet is assumed in open circuit. It is also dependent upon the magnetic material though the material affects are usually ignored for “straight line” materials (ferrite, SmCo and NdFeB). The two most often used calculations are based either on the Evershed polar model (N_B, ballistic demagnetizing factor) or on Joseph’s uniform material (magnetometric, N_M or fluxmetric, N_F, demagnetizing factor). In the cgs-Gaussian system, the intrinsic permeance coefficient, $P_{CI} = P_C+1$.
- H_K, other than as discussed herein is the symbol used to represent a magnetic material’s anisotropy field, a theoretical number representing the maximum potential intrinsic coercivity. In practice, magnetic materials achieve a small fraction of this potential.

References:

(1) J. R. Ireland, *Ceramic Permanent-Magnet Motors*, McGraw-Hill (1968), pp. 41-43

(2) E. du Tremolet de Lacheisserie, D. Gignoux, M. Schlenker, *Magnetism II – Materials & Applications*, Kluwer Academic Publishers (2002), pp. 13-14

(3) R.J. Parker, *Advances in Permanent Magnetism*, Wiley Interscience (1990), p. 40

(4) Magnetic Material Producers Association, *Permanent Magnet Guidelines (PMG-88)*, (1988) pp. 10-11

(5) H.F. Mildrum, G.A. Graves, Z.A. Abdelnour, *Engineering Properties of High Energy Product Sintered Rare Earth-Cobalt Permanent Magnets*, Proceedings of the Fifth International Workshop on Rare Earth-Cobalt Permanent Magnets and Their Applications, University of Dayton (1981) pp. 313-333

(6) D.L. Martin, *Permanent Magnet Characterization Measurements*, *Engineering Properties of High Energy Product Sintered Rare Earth-Cobalt Permanent Magnets*, Proceedings of the Fifth International Workshop on Rare Earth-Cobalt Permanent Magnets and Their Applications, University of Dayton (1981) pp. 371-404

(7) D.L. Martin, H. F. Mildrum, S.R. Trout, *Squareness Ratio for Various Rare Earth Permanent Magnets*, Proceedings of the Eighth International Workshop on Rare Earth-Cobalt Permanent Magnets and Their Applications, University of Dayton (1981) pp. 269-278

(8) S.R. Trout, *Permanent Magnet Figures of Merit: We need a better story*, SMMA Fall Technical Conference (2008) slides 8-9

(9) M. Katter, IEC correspondence

(10) IEC Standard 60404-8-1:2015, International Electrotechnical Commission, https://webstore.iec.ch/publication/22009

(11) ASTM A340 – 15, Standard Terminology of Symbols and Definitions Relating to Magnetic Testing

(12) *Guide for the Use of the International System of Units (SI)*, NIST Special Publication 811, 2008 edition; A. Thompson, B.N. Taylor; http://physics.nist.gov/cuu/pdf/sp811.pdf

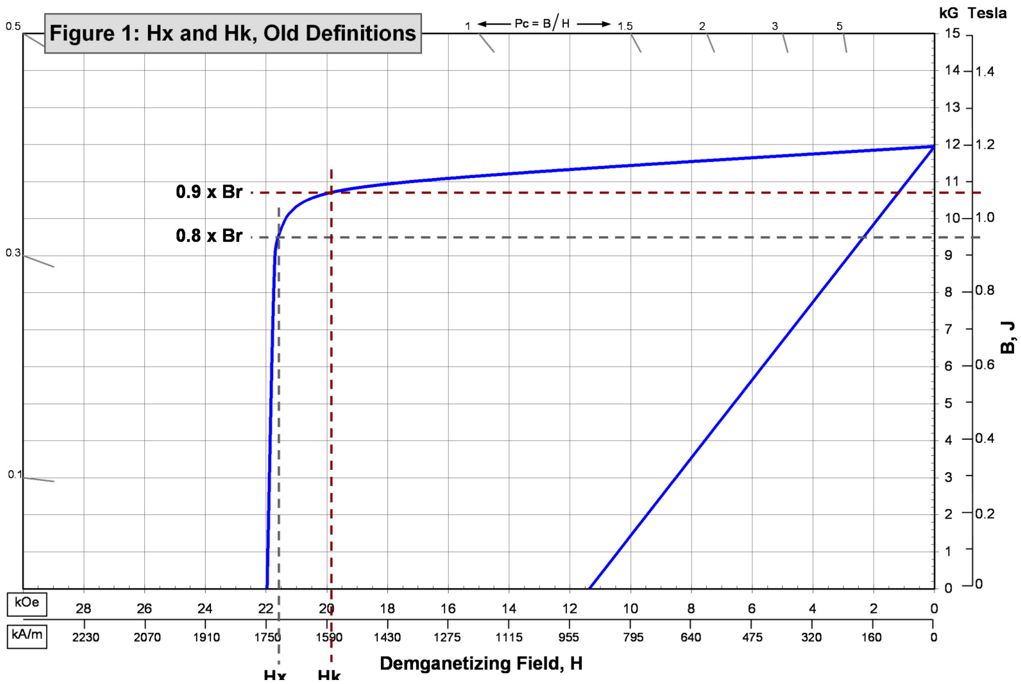

Figure 1: Original definitions of Hk and of Hx as proposed by James Ireland.

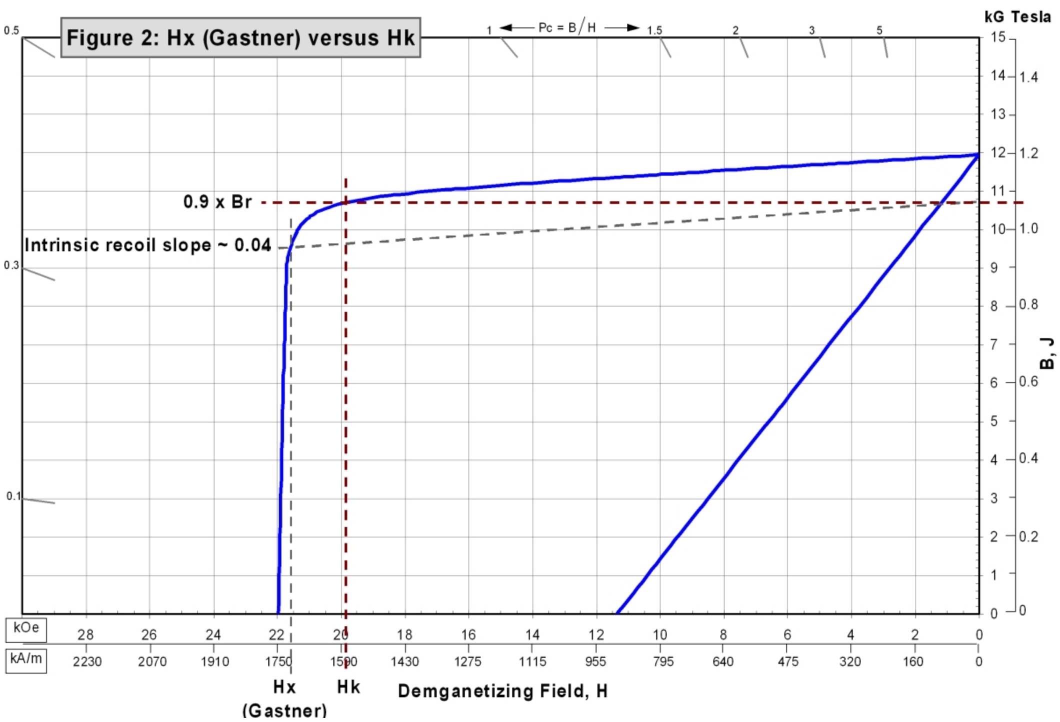

Figure 2: The generally accepted form of Hk shown in contrast to Hx as proposed by Glenn Gaster in 1986 and 1987.

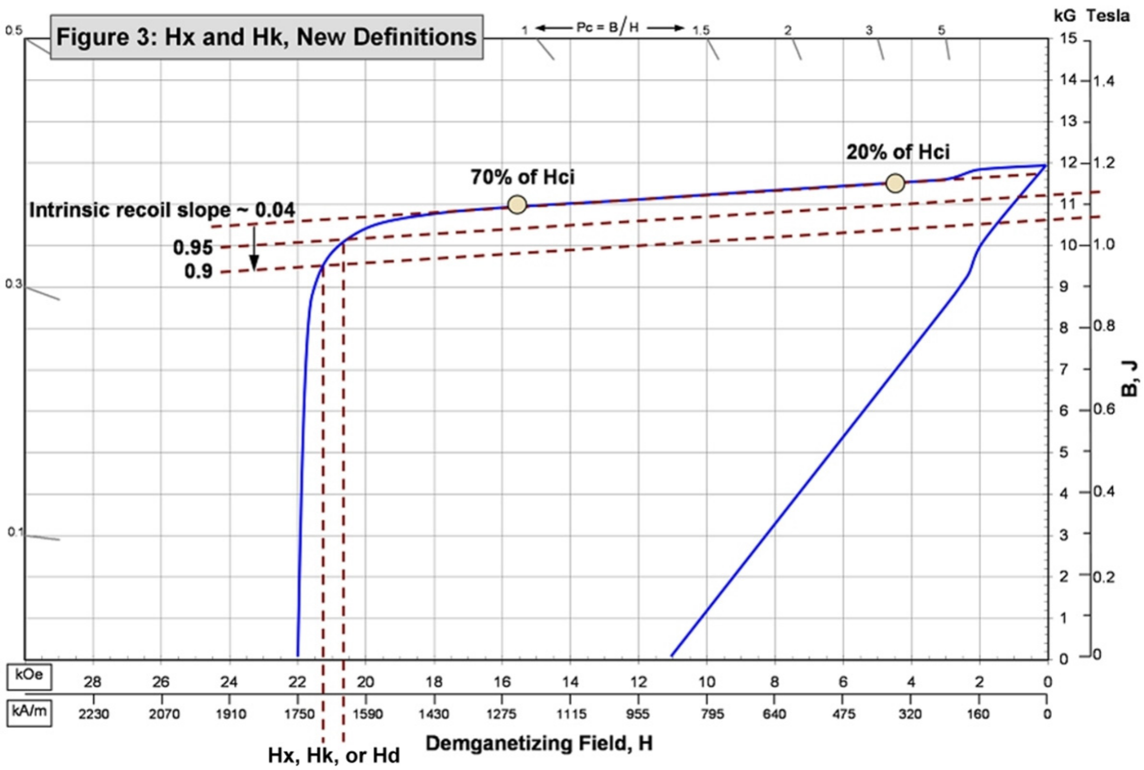

Figure 3: Hd (or Hr as proposed by M. Katter). The proposed complete term would be "Hd, 0.95", "Hd, 0.90" or similar with the number representing the offset of the dashed line.

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