# What is the Magnetic Hysteresis Loop

This **TECH**Note addresses the measurement of ferromagnetic materials in a closed circuit magnetometer. A detailed discussion of the origin of the magnetic field and explanations of other magnetometer types will be discussed separately.
-----------------------------------------------------------------

Physicists tell us that magnetism is one of four fundamental forces. The others are the weak and the strong atomic forces and the gravitational force. Magnetism is more accurately called the *electromagnetic* force and its origin is electric in nature – originating in the "spin" of electrons. In common parlance we refer to the electromagnetic force as simply the magnetic force and ascribe the source of this force to a magnetic field emanating from a magnet (or electromagnet).

We can't see magnetic fields but we can witness the effects of the presence of those fields such as watching the needle of a compass. As we rotate the compass the earth's magnetic field interacts with the magnetic needle of the compass causing a rotational force until the two fields are properly aligned.

When Benjamin Franklin attached a key to the string of his kite and flew the kite during a thunderstorm, it was in an attempt to answer questions about electricity. At that time, no one had a clear understanding of what lightning was or how to measure electricity. The invention of devices to observe, monitor and control electricity provided a path toward an easier life for the earth's citizens – even though we have never seen an electron we can measure its effects.

We have an analogous conundrum with magnetism – we cannot see it. But we can observe and measure it. And to a great extent we can control it and use magnetic fields to our advantage.

A magnetic field is a vector quantity in that it has both a magnitude and a direction – remember the compass needle aligning to the earth's magnetic field. When we measure a field we need to also establish the direction of the field.

There are many devices that can measure magnetic fields and the general name for these is "magnetometer". A hysteresigraph is one of these devices and is used to measure (quantify) the strength of a magnetic field emanating from a magnet sample. Other devices include vibrating sample magnetometers (VSM), SQUID magnetometers (semi-conducting quantum interference device), and pulse field magnetometers (PFM). Other devices such as gaussmeters and Helmholtz coils (with fluxmeters) only measure a subset of magnetic properties.

A hysteresigraph consists of a yoke structure, two electromagnets (connected in series), power supply for powering the electromagnets, two fluxmeters (or occasionally one fluxmeter and a Hall Effect gauss probe), a "search coil", control electronics and software for capturing the signals and producing data and chart output. A magnet is measured by placing it within the search coil and placing the coil (with the magnet) between the poles of the yoke structure, adjusting the position of the upper pole so it is in contact with the magnet (forming a closed circuit) and commencing the measurement.

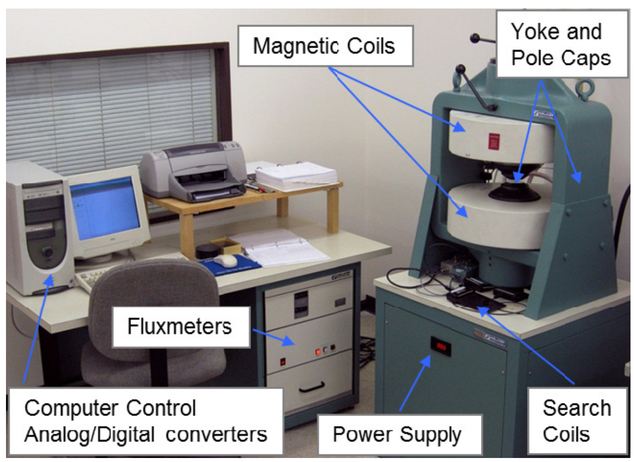


Figure 1: Hysteresigraph showing component parts

When the electromagnet (EM) is energized, a magnetic field is produced. This field has the effect of aligning magnetic domains within the sample through a process called *induction*. When the output of the search coil is monitored, we observe a field different than that created by the EM alone. Thus, we are measuring a combination (summing) of the applied field and the field induced in the sample, the magnetic induction. When we compare the magnitude of the applied EM field with the induced field (the induction), we can create a chart of the relationship – a hysteresis loop.

The reason we call it a *hysteresis* loop is there is work performed to rotate magnetic domains using the applied field and when H, the applied field, is returned to zero the induction does not return to zero – some or most of the induced field remains even in the absence of an externally applied field.

The coils that are around the sample magnet will detect both the applied field and the induced field. The output of this "combined" field is call the "normal" or B versus H curve. If we separately measure the applied field, it is possible to subtract it from the combined field resulting in just the field contribution from the magnet, this being the intrinsic curve. Values on the intrinsic curve are called polarization (J) or magnetization (M).

The chart of the hysteresis loop (Figures 1) shows a horizontal axis representing the magnitude of the applied field, H. The vertical axis represents the magnitude of:

1) "B" - the combination of the applied field and the induced field ("normal" or B vs H curve) and
2) "J" – only the field contributed by the magnet.

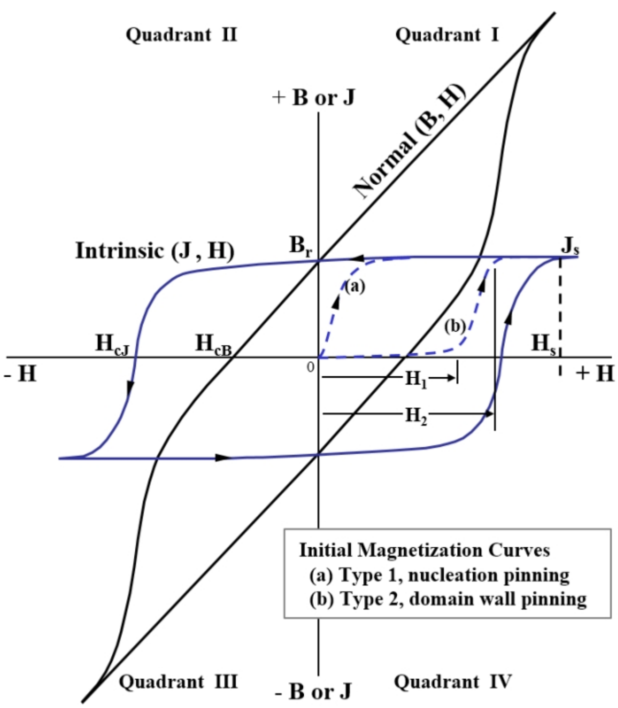



**Figure 1:** Complete normal and intrinsic hysteresis loops with key metrics identified [2]

The complete loop exists in four quadrants. For soft magnetic materials which normally cycle through a complete loop as they perform their function as a magnetic flux carrier, we are particularly interested in two views of the loop.

1) The first quadrant shows us how easy it is to induce a field in the soft magnetic material and what the maximum induction is.
2) The complete loop indicates to us how much energy it takes to force the material around the loop. This energy is proportional to and represented by the area within the (normal) loop. Low values of coercivity ($H_{cB}$) are desirable as that results in a reduced area within the loop.

For permanent magnets, we are interested in the first quadrant to learn how difficult it might be to magnetize the material to saturation. Saturation is achieved when the application of additional field strength results in no additional increase in magnetization. However, most of our interest lies in the second quadrant as shown in Figure 2.

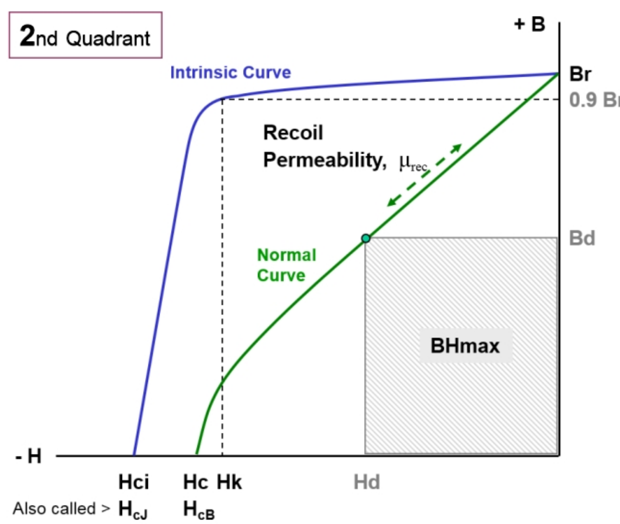



**Figure 2:** Typical 2nd quadrant of a hysteresis loop for a permanent magnet material

The top (blue) line is the 2nd quadrant intrinsic curve; the green line is the normal curve. In the cgs system, B, induction and J, polarization, are quantified in Gauss or in SI units of Tesla. Coercivity, the values of H, are quantified in oersted or in SI units of A/m (amperes per meter) or the more useful kA/m (kilo-amperes per meter).

The key figures of merit along the H-axis are:

- Coercivity, Hc or $H_{cB}$, is a measure of the magnitude of the externally applied field, H, sufficiently large to balance the field contributed by the magnet. When the $H_{cB}$ point is reached, there is zero net field (B~0), but the magnet is **not** demagnetized. When the H field is removed (returned to 0), the magnet's field is still present, rebounding to Br.
- Intrinsic coercivity, Hci or $H_{cJ}$, is a measure of the magnet's resistance to de-magnetization. When the intrinsic curve drops to meet the H-axis, about half the magnetic domains have reversed, resulting in approximately the same number pointing north up and north down and having almost no net external field. Further, when the H field is removed, the field from the magnet remains near zero (B~0).
- Hk is a calculated value, not a measured one. When a horizontal line is placed at a value of B equal to 0.9 times Br and extended to the left, it will intersect the intrinsic curve. When a vertical line is dropped from this intersection to the H-axis, that value of H is called Hk and indicates the magnitude of the demagnetizing field required to demagnetize the magnet by about 10%. In many regards this value is more important than $H_{cJ}$ since it indicates the onset of demagnetization. If Hk is divided by $H_{cJ}$, the quotient represents an indication of loop "squareness". A perfectly square loop will have a value of 1. High quality Neo and ferrite magnets typically have squareness values between 0.90 and 0.95. SmCo is slightly lower at 0.85 to 0.93.

For very high $H_{cJ}$ materials, it is possible that the Hk intersect will occur before the knee of the intrinsic curve resulting in an artificially low value of Hk and squareness. The IEC (International Electrotechnical Commission) task group 68 on magnetics has recently proposed a modification to Hk wherein instead of drawing a horizontal line at 0.9Br, the line would be drawn at the intrinsic recoil slope (= 1-recoil permeability, ~0.05). Instead of calling the value Hk, it is to be called Hd. The procedure for calculating the slope of the intrinsic recoil is described and the value of Hd only applies to Neo magnets. Hk is still a broadly used measure, but must be applied with an understanding of the intercept value as shown on $2^{nd}$ quadrant hysteresigraph loops.

The value of both the normal and the intrinsic curves at the intersection with the B-axis is called residual induction or residual polarization, represented by Br or Jr respectively. As a matter of convention it is usually referred to as Br. It represents the maximum value of magnetization provided by the magnet in **closed circuit** and without the application of an external field. (Recall that the hysteresigraph test is a closed circuit test). When this value of Br results from a magnet that is fully magnetized (saturated), it is the highest possible value of Br and can be called retentivity, though for the most part, we just call it Br.

The normal curve for Ferrite, SmCo and Neo magnets, when they are made with well-aligned powder, is close to a straight line between the B-axis and the intersection with the H-axis and we say that the materials are "straight line" materials. If the intrinsic curve is the reference for shape, then the materials are said to be "square loop". In either case, the slope of the normal curve from Br to the maximum energy point forms a slope approximating recoil permeability, $\mu_{rec}$. For ferrite, SmCo and Neo, the value of the slope ranges from 1.02 to 1.09 with the majority of values between 1.035 and 1.06.

The slope of the normal curve is non-linear for isotropic and for non-aligned materials. It is also non-linear for alnico, FeCrCo, Vicalloy and similar alloys.

The potential energy of a magnet is represented by the area between the B-axis and the normal hysteresis curve. In the second quadrant, for each point on the normal curve, there is a value of B and a value of H. When these values are multiplied together they produce an *energy product*. For one point on the normal curve, the product of B and H is a maximum and this point represents the maximum energy point - and the *maximum energy product* represented by BHmax or (BH)max in MGOe (mega-gauss-oersted) or kJ/m$^3$ in the SI system. The product of B and H represents the shaded area in Figure 2. In the cgs system where 1 gauss = 1 oersted, there is marvelous symmetry to hysteresis loops. The maximum energy point for straight line materials is approximately at the intersection of the normal curve and a permeance coefficient line with a slope of -1.08 – just slightly greater than the recoil permeability, but with a negative slope.

The *straight line* nature of ferrite, SmCo and Neo permits an approximate value of maximum energy product, (BH)max, to be calculated from Br and Br calculated from (BH)max per the formula:

$(BH)max = Br^2 / (4 \cdot \mu_{rec}) \sim Br^2 / 4.2$

…and

$Br = ((BH)max \cdot 4 \cdot \mu_{rec})^{0.5}$

The energy in a magnet is not consumable like burning gasoline or using a battery. It is more like a spring wherein the spring can be compressed and released – used to store energy and then release it back. The temporary energy storage of the magnet is a function of its permeance coefficient (subject of a separate TECHNote) and is represented by the shaded area between the two operating points.

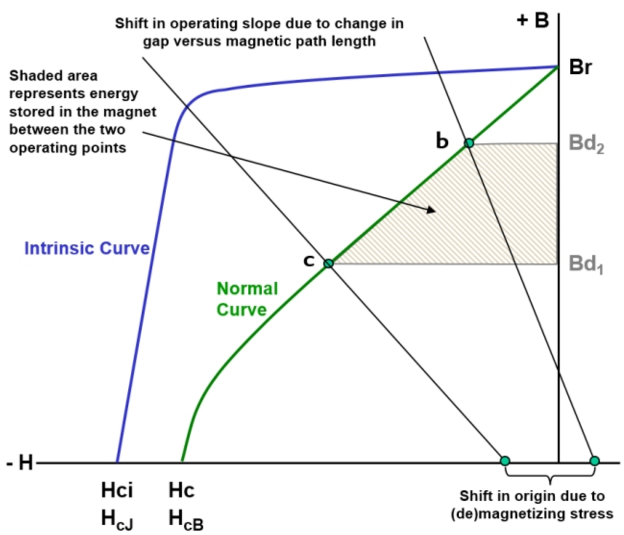



**Figure 3:** 2nd quadrant of a hysteresis loop showing change in potential energy as a function of operating points on the normal curve. [4, 5, 6]

The energy, represented by the shaded area can be calculated as [6]:

$$-\int_b^c B\,dH - \int_b^c H\,dB = -[BH]_b^c$$

Magnetic fields – the magnetic output – do not remain constant as temperature changes. So too, the hysteresis loops change with temperature. Accordingly, two of the key figures of merit, Br and $H_{cJ}$, also change with temperature and in a regular, predictable way. The average rate of change of Br as a function of temperature and between two specified temperatures is call the *reversible temperature coefficient of induction*. It has been represented by the Greek letter alpha (α) and more recently and per IEC definition, by α(Br).

The change in (**intrinsic**) coercivity as a function of temperature is called the *reversible temperature coefficient of coercivity* and has been represented in the past by the Greek letter beta (β). More recently and per IEC definition, it is represented by $\alpha(H_{cJ})$. Neither change is linear, so it is imperative to specify the temperature range over which the "average rate of change" applies. For Ferrite magnets this is usually, but not always, from 20 to 100 °C. SmCo is usually rated from 20 to 150 °C. Neo magnets are often rated from 20 to the recommended maximum use temperature.

The loop shape remains fairly consistent over these temperature ranges. However, anomalies to the loop may change in shape with change in temperature depending on the cause of the curve shape anomaly. The best quality materials avoid this complexity.

Measurement of magnets at other than room temperature can be performed in hysteresigraphs suitably equipped with heated poles or an "oven" insert; on a VSM with an attached oven; or on a SQUID magnetometer. Alnico and ferrite magnets are rather simple to measure as they can be magnetized to saturation by any of the measurement devices. Rare earth magnets require very high fields to saturate (fully magnetize) them so, when measured in a hysteresigraph or VSM, sample magnets are pre-magnetized in a high-field pulse magnetizer prior to placement in the magnetometer. SQUID magnetometers are capable of very high magnetizing fields so magnetization can be performed in-situ. Remember that VSM, SQUID and PFM measurements are not closed circuit.

It is normal for a pre-pulsed magnet to "drop-back" slightly after the pulse as this is performed in open circuit conditions. Therefore, to ensure accurate measurement of properties, it is routine, after placing the search coil with magnet into the hysteresigraph, to apply a field in the first quadrant at the start of the test to re-magnetize those "easy-to-reverse" domains that spontaneously reversed in open circuit. During hysteresigraph testing, it can be instructional to observe the 1st quadrant to see how much field is recovered, that there is nil drift of fluxmeters, and that the magnet sample is saturated prior to 2nd quadrant ("demag") curve generation.

What about measurements using VSM or SQUID magnetometers?

Magnets have a self-demagnetizing stress built into them which is totally dependent upon the shape of the magnet, often called the length to diameter ratio (L/D) or equivalent length to equivalent diameter ratio (Le/De). The subject of demagnetizing factors: ballistic ($N_B$), magnetometric ($N_M$) and fluxmetric ($N_F$) is length and complicated. We mention them here as permeance coefficient, Pc, can be calculated form the demagnetizing factor:
Pc = 1 – (1 / N)

When testing a magnet in open circuit, the demagnetizing stress seen by the magnet is a combination of its own demagnetizing stress plus (or minus, depending on field directions) the applied field. Accuracy of the measurement depends upon accuracy of calculating the self-demagnetizing stress of the magnet. This is avoided in closed circuit testing.

PFM is also an open circuit test with the added complication that the pulsed fields which are sequentially applied with increasing magnitude create eddy currents in conductive magnets. Eddy currents create a magnetic field which impedes penetration of the magnet by the applied pulsed field. Both the self-demagnetizing stress and the eddy current effect must be accounted for in the software. The pulsed field test is not a true DC test.

Two example hysteresigraph plots are provided. The first of the following charts shows typical properties for a Neo magnet over a range of temperatures from -40 to 220 °C. The recommended maximum use temperature for this "UH grade" material is 180 °C.

The second chart is for a high quality SmCo magnet material, Recoma® R33E with recommended maximum use temperature of 350 °C.

Both materials start with very high coercivity, but the Neo material "loses" coercivity much faster than the SmCo material. The reversible temperature coefficients for the two materials are shown in the following table. Reversible temperature coefficients of induction for both neo and SmCo are quite linear from 20 to about 150 °C where neo induction begins

**Table 1:** Reversible temperature coefficients for one grade of Neo and one of SmCo in %/°C.

| Temperature | α(Br) | | α($H_{cJ}$) | |
|---|---|---|---|---|
| Range, 20 to | N40UH | R33E | N40UH | R33E |
| 100 °C | -0.12% | -0.035% | -0.489% | -0.260% |
| 180 °C | -0.12% | -0.035% | -0.465% | -0.254% |
| 200 °C | -0.13% | -0.035% | -0.449% | -0.250% |

dropping off more rapidly. SmCo continues quite linearly until well above 250 °C.

In addition to reversible temperature coefficients, there are maximum (and minimum) temperatures beyond which a ferro- and ferri-magnetic material loses most of its magnetic field. For all four of the widely available commercial alloys (alnico, ferrite, SmCo and Neo), the Curie temperature, Tc, is that temperature above which the material becomes paramagnetic – exhibiting only very weak magnetism. As this temperature is approached, induction drops off more quickly.

At roughly 140 Kelvin Neo undergoes a "spin reorientation" where instead of an easy axis there is a cone of magnetization. The result is a substantial reduction in magnetism below this temperature. Modifying the composition by substituting praseodymium for 80% or more of the neodymium eliminates the spin reorientation.

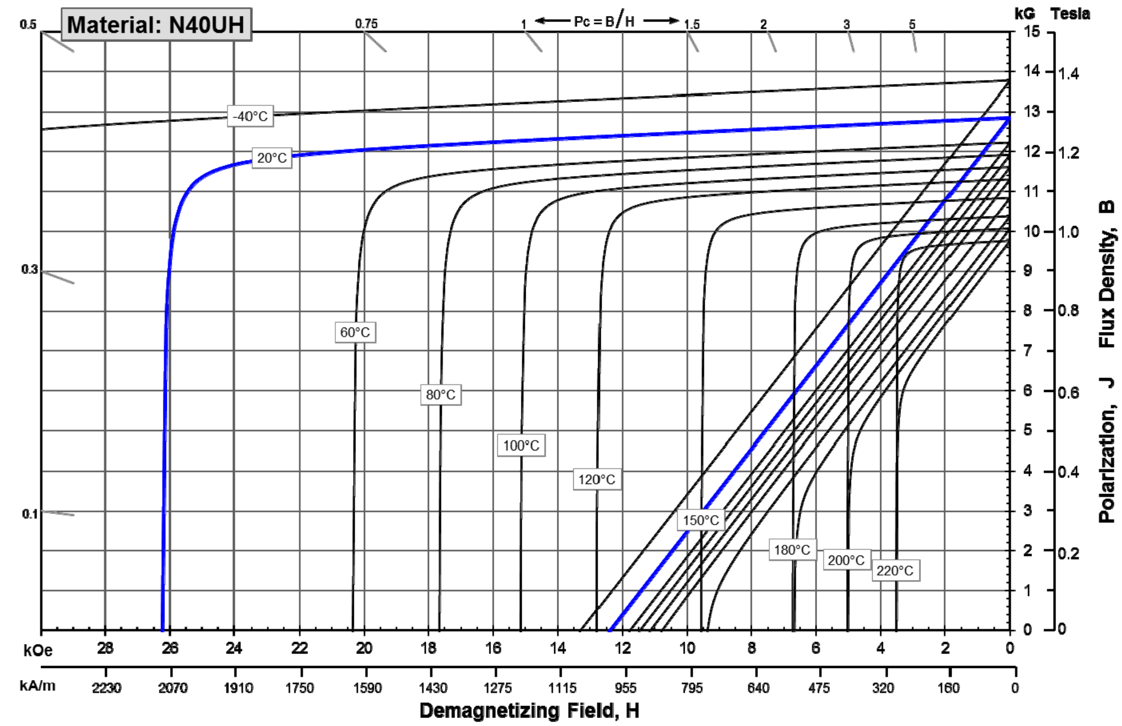
Ferrite magnets (ferri-magnetic) experience an increase of coercivity as temperature. However, at lower temperatures (intrinsic) coercivity becomes sufficiently low to permit easy demagnetization in applications. A practical low temperature limit for standard ferrites is -40 °C and for La-Co ferrites it is about -60 °C.

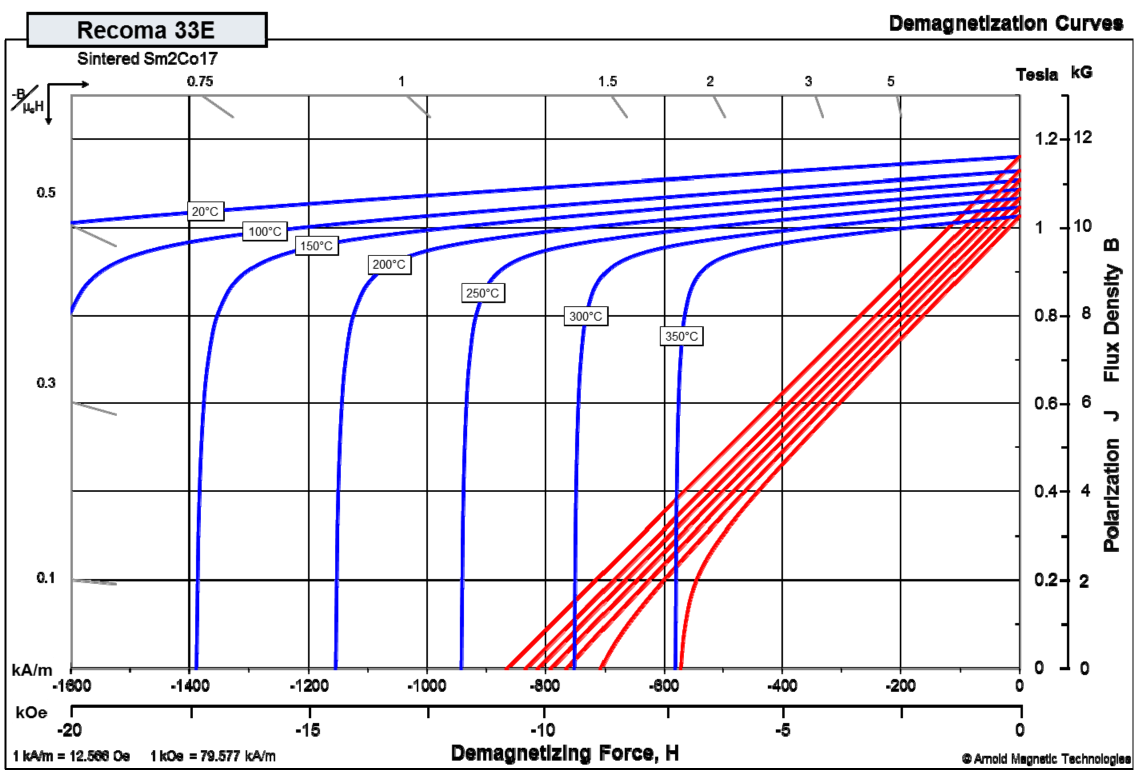
**Table V-2. Temperature Characteristics Comparison**

| Magnet Material | Curie Temperature °C | $B_r$ Reversible Coefficient %/°C | Hci Reversible Coefficient %/°C | Max. Service Temperature °C |
|---|---|---|---|---|
| Alnico 5 | 720 | –0.02 | –0.03 | 525 |
| Ferrite | 450 | –0.20 | 0.40 | 800 |
| $SmCo_5$ | 725 | –0.04 | –0.30 | 250 |
| $Sm(Co,Cu,Fe,Zr)_{7.5}$ | 825 | –0.035 | –0.30 | 300 |
| NdFeB | 310 | –0.12 | –0.60 | 150 |

Table V-2 is from reference 7, page 23. See manufacture specifications for more detail.


Material: N40UH
Pc = B/H
0.5
0.75
1
1.5
2
3
5
0.3
0.1
kG
Tesla
-40°C
20°C
60°C
80°C
100°C
120°C
150°C
180°C
200°C
220°C
Polarization, J Flux Density, B
kOe
kA/m
Demagnetizing Field, H
1 kA/m = 12.566 Oe 1 kOe = 79.577 kA/m


Recoma 33E
Sintered Sm2Co17
Demagnetization Curves
0.75
1
1.5
2
3
5
0.5
0.3
0.1
Tesla
kG
20°C
100°C
150°C
200°C
250°C
300°C
350°C
Polarization J Flux Density B
kA/m
kOe
Demagnetizing Force, H
1 kA/m = 12.566 Oe 1 kOe = 79.577 kA/m
© Arnold Magnetic Technologies

References:


1. B.D. Cullity and C.D. Graham; *Introduction to Magnetic Materials, 2nd Ed.*, IEEE Press and John Wiley & Sons, Princeton, NJ; 2009
2. F. Fiorillo; *Measurement and Characterization of Magnetic Materials*, Elsevier Academic Press; 2004
3. ASTM; *A977M − 07 (Reapproved 2013) - Standard Test Method for Magnetic Properties of High-Coercivity Permanent Magnet Materials Using Hysteresigraphs*, ASTM International, West Conshohocken, Pennsylvania USA
4. R. J. Parker; *Advances in Permanent Magnetism*, John Wiley & Sons, New York; 1990, pp. 141-143
5. P. Campbell; *Permanent Magnet Materials and Their Application*, Cambridge University Press; 1994, pp.16-17
6. P. Campbell; Comments on Energy Stored in Permanent Magnets, IEEE Transactions on Magnetics, Vol. 36, No. 1, January 2000
7. MMPA; PMG-88, Permanent Magnet Guidelines, MMPA; 1988; p.7-11; download from: *www.smma.org/pdf/permanent-magnet-guideline.pdf*
8. J.M.D. Coey; Magnetism and Magnetic Materials, Cambridge University Press; 2009; p.7-9
9. D. Jiles; Introduction to Magnetism and Magnetic Materials, 2nd Ed, Taylor & Francis; 1998; p.92-95


ARNOLD® MAGNETIC TECHNOLOGIES

770 Linden Avenue • Rochester • NY 14625 USA
800-593-9127 • (+1) 585-385-9010 • Fax: (+1) 585-385-9017
E-mail: infoNA@arnoldmagnetics.com

**www.arnoldmagnetics.com**