Temperature Effects on Magnetic Output

All of the commonly available permanent magnet materials experience either reversible or permanent changes in magnetic output as a result of exposure to temperatures above or below room temperature. We will start by defining the types of changes, examine how each of the materials behaves and then make some performance comparisons between materials.

There are three types of loss in magnetic output defined as follows:

- **Reversible:** Flux output increases or decreases as temperature changes. When the temperature returns to room temperature, the original flux output is observed. That is, there has been no permanent change in the flux output of the magnet.
- **Irreversible, Recoverable:** With temperature change, a critical operating parameter has been exceeded resulting in the magnet being partially demagnetized. However, when re-magnetized, essentially all the original flux is again observed.
- **Irreversible, Unrecoverable:** The magnet has been exposed to conditions that resulted in a degrading structural change. While this degradation is often the result of corrosion, it can also be caused by microstructural changes due to exposure to extreme temperatures.

Permanent magnets have a small number of important characteristics that define the materials' performance and capabilities. Among these are Br, Hc (or H_{cB}), Hci (or H_{cJ}), Hk, and μ_r (recoil permeability). Each of these is indicated in the second quadrant of the Hysteresis loop in Figure 1.

Changes in temperature affect both flux output, which is proportional to Br, and resistance to demagnetization, which is proportional to Hci. The amount to which these change is called the reversible temperature coefficient of induction (Br) or the reversible temperature coefficient of coercivity (Hci). These have been referred to as α (alpha) and β (beta) respectively. Modern usage and IEC (International Electrotechnical Commission) terminology is $\alpha(B_r)$ and $\alpha(H_{cJ})$.

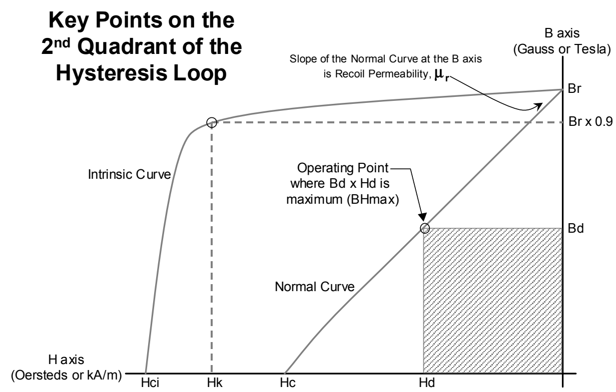

Figure 1. Key Points on the Demagnetization Curve (Second Quadrant of a Hysteresis Loop).

The accompanying table presents key temperature related characteristics for common permanent magnet materials. Note the sign of the reversible temperature coefficients. A negative value indicates a loss of Br or Hci with an increase in temperature.

MATERIAL	Reversible Temperature Coefficients, %/°C		Curie Temperature Tc, °C
	Induction (Br), α	Coercivity (Hci), β	
Alnico 5	-0.02	+0.01	900
Alnico 8	-0.02	+0.01	860
Sm_2Co_{17}	-0.03	-0.20	800
$SmCo_5$	-0.045	-0.40	700
NdFeB, Bonded MQP-C (15% Co)	-0.07	-0.40	470
NdFeB, Sintered 40 MGOe (0% Co)	-0.11	-0.60	310
Ferrite 8	-0.20	+0.27	450
Plastiform 2401 Ferrite-Neo Hybrid	-0.14	-0.04	N/A

Note also, that ferrite has a large positive reversible coefficient of coercivity. That means as temperature is reduced, intrinsic coercivity decreases resulting in a knee developing in the normal curve. In Figure 2 we see how Br and

Hci change as a function of temperature for Ceramic 5 and we see the dramatic effect of the development of this knee.

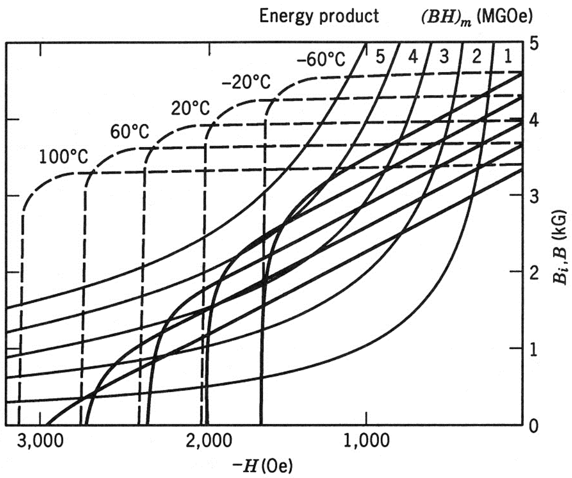

Figure 2. The effect of temperature on the intrinsic and normal curves for ferrite (Ceramic) 5.

The change in Br and Hci as a function of temperature is not linear. The numbers presented in the above table are typical averages for the change over a temperature range from 20 to approximately 120ºC. Strictly speaking, when presenting these values, one should specify the temperature range over which the average has been calculated. This is increasingly important as use-temperature deviates significantly from 20ºC such as in cryogenic applications (see TECHNote 0302) or in high temperature automotive, aerospace, commercial and industrial applications where 180ºC or higher is common.

Irreversible-Recoverable loss occurs when the combination of: temperature extreme, Hci, reversible temperature coefficient and applied demagnetizing field exceeds the magnet's ability to remain fully magnetized. This occurs when the magnet in the application is at an operating point past the knee of the curve. (See TECHNote 0301 for the effect of reverse magnetic fields).

Magnetic circuit designers use Hk (or a similar value Hx) in combination with the reversible temperature coefficient of coercivity to determine the maximum operating temperature for a material. Or, in reverse, determine the minimum acceptable Hk value at the maximum operating temperature and calculate the required room-temperature values. Equations relating reversible temperature coefficients, Br and Hci are as follows.

Where:

- T = desired temperature (ºC)
- $Br\ (T)$ = Br at temperature T
- Br_{RT} = Br at room temperature (23 ºC used here)
- $Hci\ (T)$ = Hci adjusted for temperature
- Hci_{RT} = Hci specification for room temperature (23 °C used here)
- *Tc_{Br} and Tc_{Hci} = reversible temperature coefficients for Br and Hci in %/ºC*

$$Tc_{Br}\ \%/^{\circ}\mathrm{C} = \frac{Br\ (T)\ -\ Br_{RT}}{(T-23) * \ Br_{RT}} * 100$$

$$Br\ (T) = \ Br_{RT}\left(1 + \frac{Tc_{Br}\ (T-23)}{100}\right)$$

$$Br_{RT} = \frac{Br\ (T)}{\left(1 + \frac{Tc_{Br}\ (T-23)}{100}\right)}$$

$$Tc_{Hci}\ \%/^{\circ}\mathrm{C} = \frac{Hci\ (T)\ -\ Hci_{RT}}{(T-23) * \ Hci_{RT}} * 100$$

$$Hci\ (T) = Hci_{RT}\left(1 + \frac{Tc_{Hci}\ (T-23)}{100}\right)$$

$$Hci_{RT} = \frac{Hci\ (T)}{\left(1 + \frac{Tc_{Hci}\ (T-23)}{100}\right)}$$

The shape of the intrinsic curve stays very much the same as both Br and Hci change. When one knows the difference between Hci and Hk at room temperature, this same difference can be applied at higher and lower temperatures to approximate Hk at any temperature within the range covered by the reversible temperature coefficient. Therefore, the room temperature Hk can be estimated from the Hk determined at elevated temperature. By example: From the design calculations, there is a required Bd of 9,500 Gauss in a magnetic circuit with a Pci of 2.5 and a 2 kOe reverse field. Maximum temperature of the application is 120 ºC. The objective is to calculate the minimum room temperature characteristics: Br, Hci and Hk. These values may be calculated from the equations above. One assumption is that, for a typical NdFeB material, there is a 1,500 Oe difference between Hk and Hci. This value can be adjusted based upon actual product data. The inset table provides the results of the calculations.

	23ºC	120ºC
Br	11,825	10,560
Bdi	10645	9,500
Hci	17,945	7,500
Hk	16,450	6,000

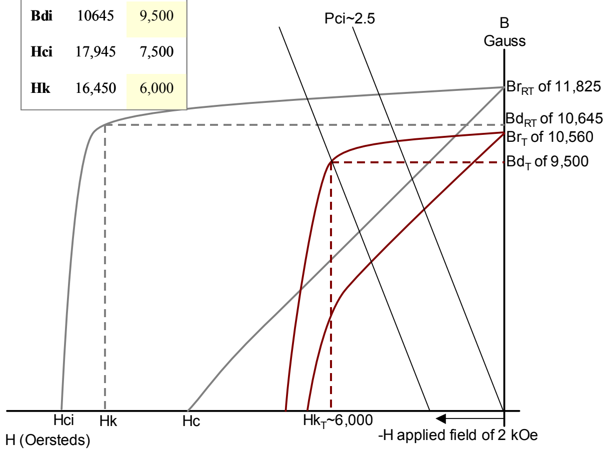

Figure 3. Calculating room temperature properties from high temperature requirements.

Comparison of Performance

The two highest energy product permanent magnet materials are NdFeB and SmCo. Of the two, NdFeB is generally less expensive by weight and, at room temperature, on a per unit flux output basis. However, at elevated temperatures, SmCo outperforms NdFeB. Our objective here is to identify at what temperature SmCo outperforms NdFeB on an absolute basis. The design engineer can then obtain relative pricing and arrive at a practical decision regarding the material of choice.

There are many grades of NdFeB with energy products ranging from under 30 to over 50 MGOe. Intrinsic coercivity (Hci) also varies greatly from less than 12,000 oersteds to over 30,000. The reversible temperature coefficient of coercivity for NdFeB is between -0.45 and -0.65 depending upon grade. To perform satisfactorily at elevated temperatures, room temperature Hci must be high. To achieve high temperature capability, various materials are added to the base NdFeB alloy, including one or more of dysprosium, terbium, cobalt, niobium, copper, gallium and selected other transition metals. They all have a dilutive effect, reducing Br and energy product.

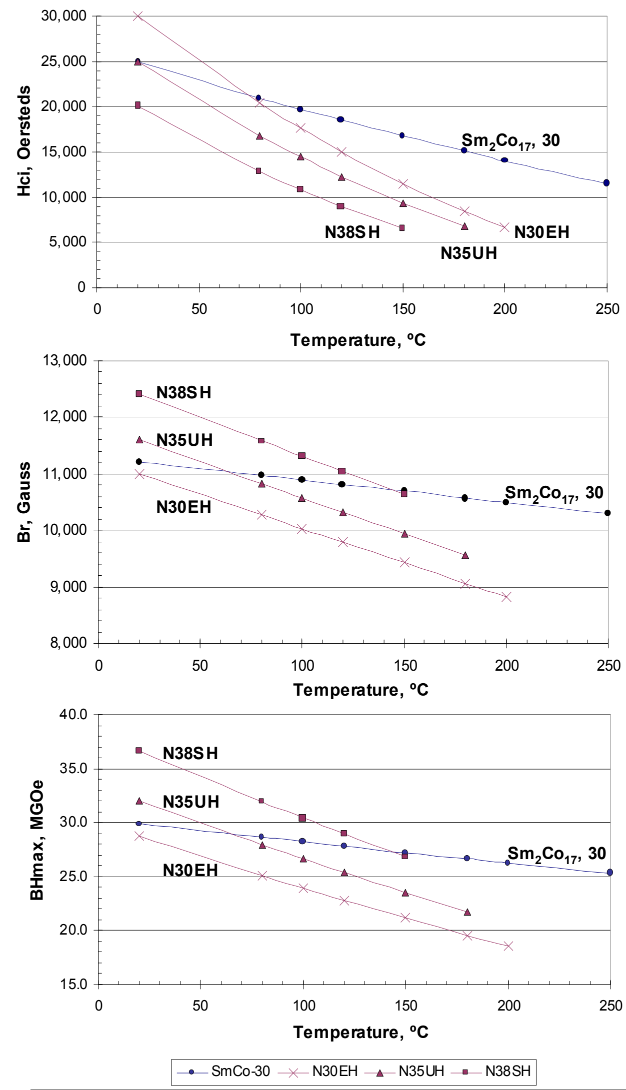

Figure 4. Comparison of SmCo and NdFeB magnetic properties from 20 to 250ºC

Examples of applications requiring high temperature performance include devices in the engine compartment of automobiles. Even in commercial and industrial motors rated for performance at 120ºC, an Hk in excess of 18,000 oersteds is often required. To achieve this Hk, an Hci of 20,000 oersteds or more is necessary.

Using Figure 4 and published specifications for NdFeB one can see that above 180ºC the material of choice is SmCo. NdFeB has a superior price/performance ratio below about 120ºC. It is the range from 120 to 180ºC that poses a challenge for the designer. Considerations include: material price, availability of the shape and size magnet for the application, physical requirements in assembly and in the application, assembly processes, corrosion resistance, coating options, rapid delivery of samples during the design phase and dependable supply of consistent quality in quantities required in production.

In the top chart of Figure 4, we note that the Hci of SmCo at 150ºC is substantially higher than that of the best NdFeB grade. Second quadrant loop squareness varies substantially from supplier-to-supplier. Loop “squareness” of higher quality SmCo magnets approaches that of high quality NdFeB magnets. For less than optimum quality materials a more useful value for comparison might be Hk or Hx.

The material of choice is also highly dependent upon the permeance coefficient, reverse magnetic fields in the application and the cost of materials. We’ve presented the basics for comparing magnetic properties, but a thorough design discussion is beyond the scope of this TECHNote.

For assistance with material selection in a specific design, please contact one of our experienced Applications Engineers.

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