Stabilization and Calibration of Permanent Magnets

Presented by
Steve Constantinides, Director of Technology
Arnold Magnetic Technologies

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- Dependable magnetic output is defined as all the flux desired, where you need it and over the full range of temperature of the application.
- To achieve these goals often requires pre-conditioning a magnet, so subsequent loss in flux is minimal, or in treating the magnet so that its output falls in a narrow range.

Definitions - 1

- Thermal Stabilization

  – The exposure of magnets to elevated (or, for ferrite, low) temperatures such that subsequent exposure to the same temperature results in negligible additional change in (flux) output

- Magnetic Calibration

  – The partial knockdown of each magnet within a batch of magnets such that the entire batch exhibits similar magnetic (flux) output

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- The reasons for performing these procedures are evident in the definitions.

- THERMAL STABILIZATION
  - Where magnets will be exposed to elevated temperatures, or low temperatures in the case of ferrites, as a pre-treatment to stabilize the magnet. This pre-treatment reduces in-use performance drop to a minimum.

- MAGNETIC CALIBRATION
  - Batches of magnets, either a single shipment, shipments over a few weeks or shipments over several years, should perform similarly. To do so requires conformance to an acceptable range of magnetic (flux) output.

- Generally accepted ranges in production output for a specific grade vary between +/-3 to +/-5% for Br and +/-7 to 10% for flux.

- When an application requires a tighter tolerance in output, it is necessary to perform some type of selection or treatment process. Because the materials are quite costly, a treatment process is most often more desirable than the selecting-and-rejecting alternative.

- Magnetic calibration can reduce the variation in flux output to as low as +/-1/2% though a range of +/-1.5% is more common.

- Magnetic calibration has the added benefit of being able to reduce out-of-spec high product to an acceptable output flux level.

Definitions - 2

- Reversible Magnetic (Flux) Output
  - That portion of the change in output due to the intrinsic characteristics of the material and is characterized by Reversible Temperature Coefficient of Induction

- Irreversible Magnetic (Flux) Output
  - Loss in output caused by exceeding critical operating parameters or by structural change in the magnetic material

- Stabilizing a magnet reduces or eliminates the irreversible portion of flux loss.
- The reversible portion is due to fundamental material characteristics defined by the material's Reversible Temperature Coefficient of Induction

Magnetic Calibration

- Magnetic Calibration is achieved by applying a reverse field to the magnet sufficient to reduce the (flux) output to an acceptable range.

  – This implies the magnet must be measured after the reverse field application

  – It may be necessary to repeat the field application and measurement multiple times

  – This process is often automated and controlled by sophisticated computer algorithms

  – Output tolerance is limited by numerous factors such as magnet field measurement technique, speed of operation, ambient temperature controls, magnetic noise, variability of input material, etc
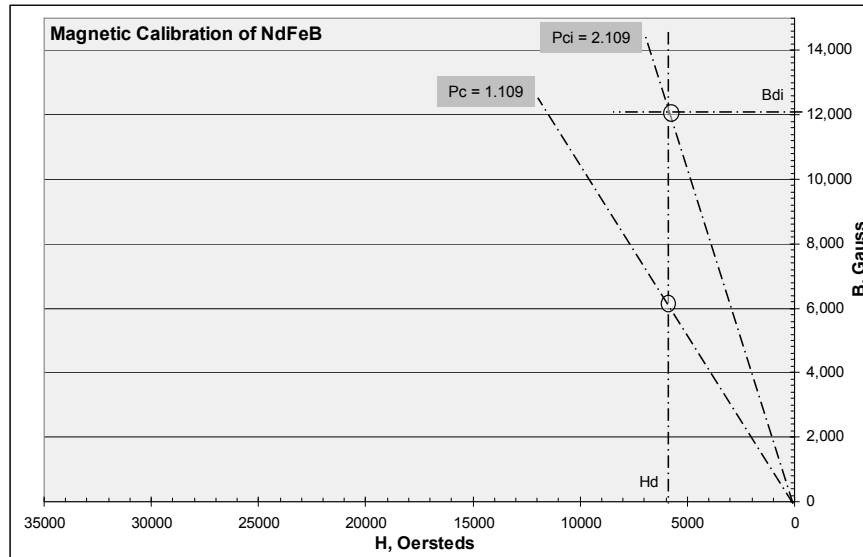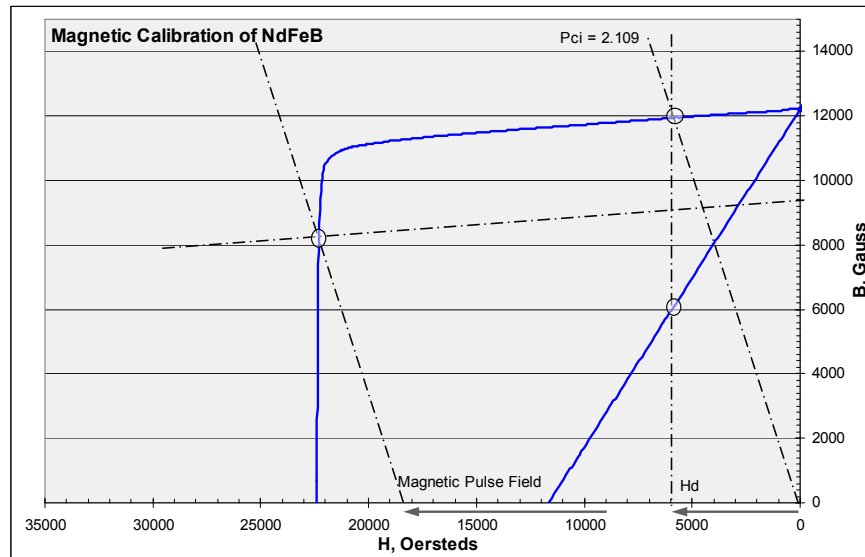
- Here we will build the explanation for how it works. We start by identifying a magnet, measuring it dimensionally, making select calculations and finally by performing a hysteresigraph measurement.

- The first measurements are for dimensions and Helmholtz flux.

- The first calculations are for Pc, Pci, Bdi and Hd.

- Pc stands for Permeance Coefficient. It is the slope of the dashed line, the value here is 1.109. While Pc is "dimensionless" in the cgs system, it is thought of as B/H and plotted as a value of B and H where B/H equals the slope.

- Pci is the Intrinsic Permeance Coefficient, abbreviated Pci and is 1+ Pc in the CGS system. Both B and H can be converted to SI units for slopes consistent with SI demagnetization graphs. It is represented by the second dashed line with a value of 2.109.

- These values can be represented on a blank hysteresigraph chart as shown here.
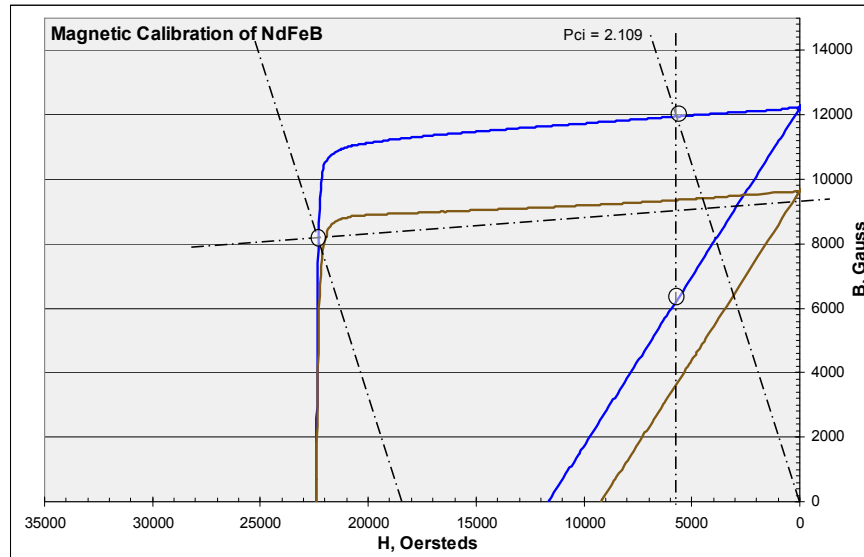
Method – 2

Magnetic Calibration of NdFeB

Pci = 2.109

(chart: B, Gauss on vertical axis from 0 to 14000; H, Oersteds on horizontal axis from 35000 to 0)

Magnetic Pulse Field

Hd

- Here the hysteresigraph data has been superimposed on the previously plotted points (or vice versa).

- We've also added a second Pci line shifted so that the origin is at a field of ~18,400 Oe. (This is really a negative value, -18,400, but the minus sign is frequently omitted).

- This provides an intersection with the intrinsic curve just above 8,100 gauss.

- If we follow back along the intrinsic recoil slope (recoil permeability – 1), we arrive at an estimated new residual induction of 9,400 gauss.

Method – 3

Magnetic Calibration of NdFeB   Pci = 2.109

(graph with axes: B, Gauss on vertical axis ranging 0 to 14000; H, Oersteds on horizontal axis ranging 35000 to 0)
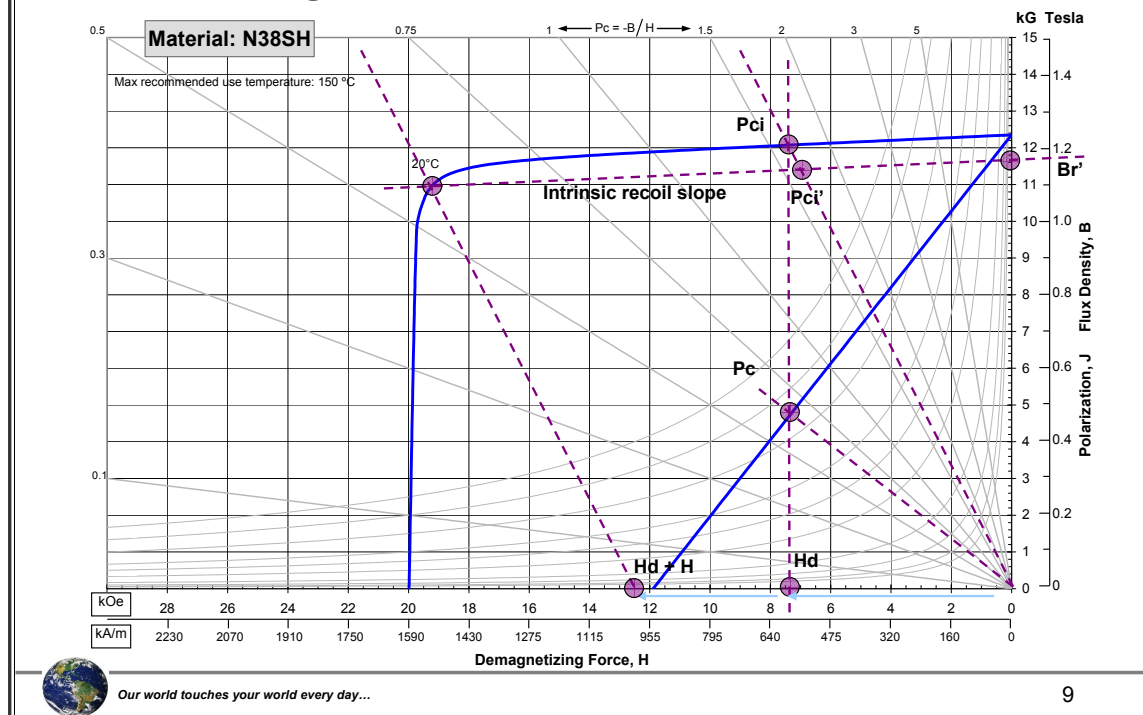
- After the magnet has been knocked down with a reverse field of 18,400 oersteds, it is re-measured in the hysteresigraph and plotted. It is represented here by the dark brown line and shows the measured Br to be 9,600 gauss.

- The net result is that this magnet, in free space, can be exposed to any field up to 18,400 and not see additional reduction in flux output – unless the operating conditions (permeance coefficient or temperature) are made worse.

- For this to work properly, the magnet must be fully magnetized (saturated) which develops full Br and full coercivity.

- Interestingly, calibration reduces Br, but has a negligible affect upon Hci.

Method Reviewed and Expanded

- In the next several slides, we'll start with a group of magnets and show what happens when the calibration method is applied

Demagnetization Due to Reverse Field

Material: N38SH

Max recommended use temperature: 150 °C

Pc = -B / H

20°C

Pci

Intrinsic recoil slope

Pci'

Br'

Pc

Hd + H

Hd

kG Tesla

Flux Density, B

Polarization, J

kOe

kA/m

Demagnetizing Force, H

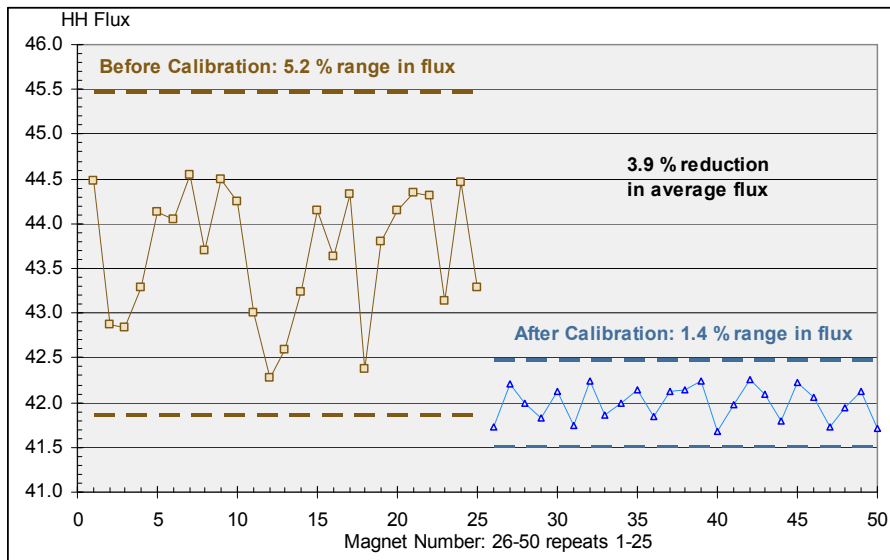Our world touches your world every day…

- Pc: The Permeance Coefficient is calculated. In our example it has a value (slope) of about 0.65. (We ignore the negative sign).

- Pci: The Intrinsic Permeance Coefficient is Pc + 1 or about 1.65. Where these Operating Lines intersect the Normal and the Intrinsic curves, we have the Normal and the Intrinsic Operating Points. The slope of the Pc and Pci lines are due strictly to the geometry of the magnet (or magnetic circuit).

- Hd: The internal (self) demagnetizing stress is approximately 7.3 kOe. Both the Normal and the Intrinsic Operating Points fall on the vertical line above this value.

- Hd + H: When an external field is applied, the magnitude of that field is added to the internal demag stress. Since the geometry of the magnet has not changed, the Pci slope remains unchanged. We draw a line with the same Pci slope but with the origin shifted to the Hd + H point on the H axis.

- The intersection of this new Pci line with the Intrinsic curve is intentionally selected for illustration here to be just over the knee of the curve.

- When a line is drawn from this point back to the B axis, it is drawn with a slope equal to the Recoil Permeability minus 1 (called Intrinsic Recoil slope). For Neo magnets, this Intrinsic Recoil Slope is typically ~0.05.

- Br': Where this line intersects the B axis we have a new Residual Induction point.

- Pci': Where the recoil line intersects the Pci line, we have a new Intrinsic Operating Point. Note that the Hd value for this point is lower than the original value. That is, when a magnet becomes partially demagnetized, the internal demagnetizing force is also reduced.

Result of Calibration Treatment

Material: N38SH — Max recommended use temperature: 150 °C
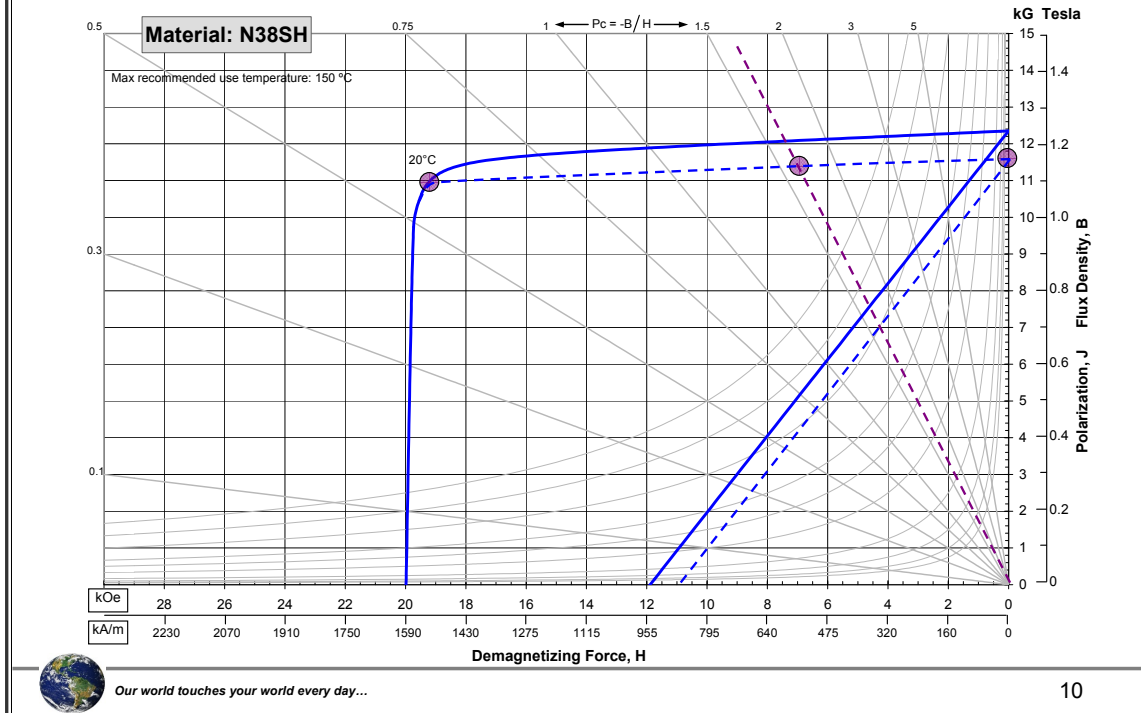
- As a result of the Calibration treatment, the material will exhibit a new demagnetization curve represented by the dashed line.

- The hysteresis loop below the intersection of the dashed line and the intrinsic curve continues to follow the original hysteresis loop to the Hci point.

Comparison of Before to After Calibration

- In this example, 25 magnets were calibrated to a tighter distribution.
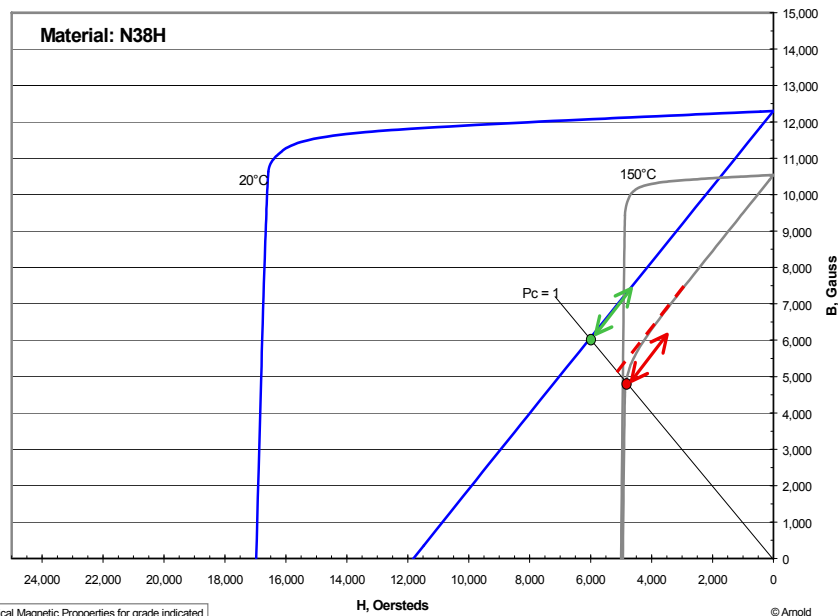- Dashed lines are + and – 2.5 standard deviations (98.8% limits).

Thermal Stabilization

- Thermal Stabilization is achieved by exposing a magnet or an assembly containing one or more magnets to temperatures at or slightly above the most extreme temperature expected in the application

- The length of time for exposure is dependent upon material and may also be affected by crystallization of plastics, curing of coatings or adhesives.
  - Exposure times are generally 1 to 2 hours with some situations requiring 8 or more hours treatment
  - Treatment temperature is usually 5 to 15 °C greater than the application extreme temperature

- Magnetic and Thermal treatments affect materials differently
  - While the treatments are not analogous of each other, a combination of magnetic and thermal knockdown can be used to achieve thermal stabilization – as long as the thermal treatment is performed last.

- The treatment temperature and exposure time is most often selected due to risk assessment.
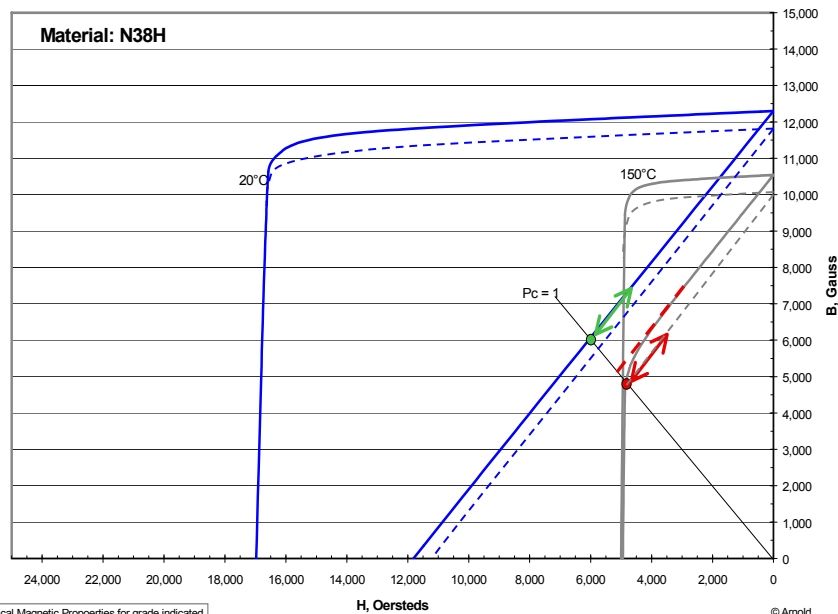
Demagnetization Due to Temperature

Material: N38H

- When no external magnetic field is applied, we can use either the Intrinsic or the Normal curve to show the affects of temperature - - more often the Normal curve is used.

- If, for example, a Pc = 1 line is drawn on this plot of N38H NdFeB, the intersection with the Normal curves for 20 and 150 degrees would represent the Operating Points at each of those temperatures. They are indicated by the small green and red circles.

- In the application, when the Pc increases above 1, we see the Operating Point for 20 degrees move back and forth at the slope of Recoil Permeability, approximately along the Normal curve.

- At 150 degrees, however, the Operating Point moves along a line at a slope of the Recoil Permeability which is substantially below the Normal curve.

- There has been Irreversible Loss in magnetic output due to "exceeding the Knee" of the Normal curve.

- If, after exposure to 150 degrees, the magnet is cooled to room temperature and re-measured, it will exhibit properties similar to the dashed blue lines.

- When the magnet is heated and measured at 150 degrees, the curve will look like the dashed gray lines.

- However, after the first drop from the solid blue to the dashed blue and gray lines, additional losses due to exposure to temperatures at or below 150 degrees will be negligible.

- (The exception to this is structural change over time due to metallurgical transformation or structural change through corrosion).
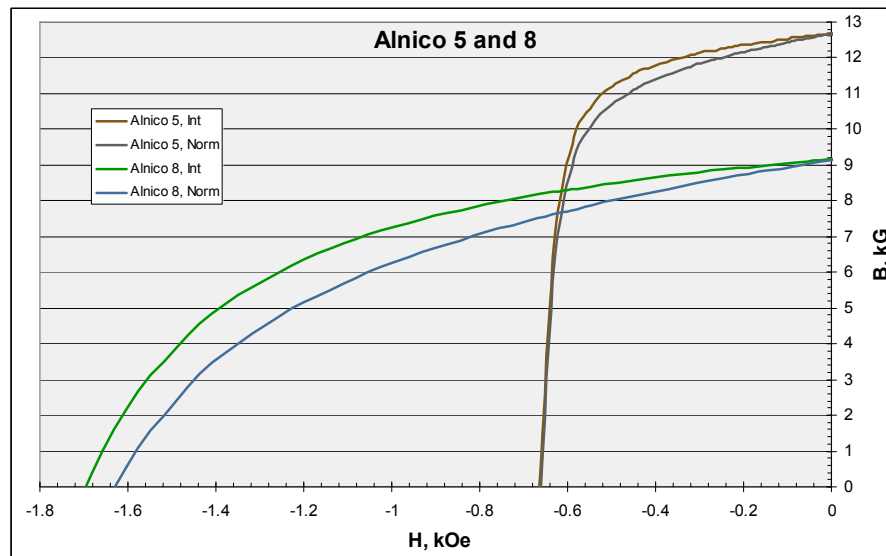
Method

- Magnets (Individual)
    - Open Circuit
    - On ferromagnetic substrate
- Assemblies
    - Held in fixture or supported on a non-magnetic substrate

- Individual magnets are magnetized to saturation then placed on either a non-magnetic or a ferromagnetic substrate.

- In either case, spacing between magnets must be controlled and consistent.

- For (near) open circuit treatment magnets must be spaced far enough apart so they have minimal affect upon neighboring magnets. Spacing is typically 3 to 5 times the largest magnet dimension.

- It is impractical to space magnets so that nil affect is present in which case the distance is approximately 20 times the largest magnet dimension.

- The interior of the treatment oven should be constructed of non-magnetic stainless steel (300 series). Racks should also be non-magnetic stainless.

- When testing is performed by placing magnets on a ferromagnetic substrate, it is necessary to use material of consistent magnetic properties and size, especially thickness.

- To prevent damage (chipping) of the magnets a pad is frequently used between the substrate and the magnets. The pad thickness will affect the permeance coefficient and the degree of stabilization so must be selected carefully and remain consistent through all testing.

- Testing of assemblies is usually accomplished by supporting the assembly by a mechanical member, not by the magnets. Assemblies demonstrate their own operating characteristics of permeance coefficient requiring wide spacing between assemblies or one-per-oven treatment. Testing is almost always, but not necessarily, performed in the absence of adjacent ferromagnetic materials.

- Whatever test conditions are finally agreed to between supplier and customer, appropriate in-use evaluation should be performed (repeatability testing) and the procedures "locked-down."
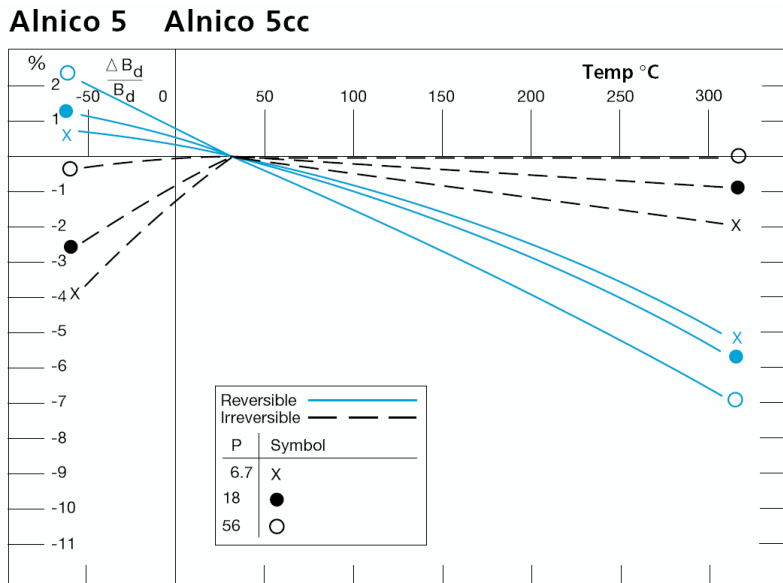
The Special Case of Alnico

Alnico 5 and 8

Legend:
- Alnico 5, Int
- Alnico 5, Norm
- Alnico 8, Int
- Alnico 8, Norm

Y-axis: B, kG (0 to 13)
X-axis: H, kOe (-1.8 to 0)

- HcB and HcJ is almost the same for Alnico 5 and the values are fairly close even for alnico 8.

- Worded differently, the Normal and Intrinsic curves are similar.

- It has been the ordinary case to ignore the Intrinsic curve and make all measurements and calculations based on the Normal curve.

- Since alnico is not a square loop (or straight line) material, exposure to any demagnetizing field will result in both reversible AND irreversible loss.

- Arnold has for decades presented both quantities in its product literature as follows.

Change in Alnico Flux with Temperature

Alnico 5   Alnico 5cc

%

$\triangle B_d / B_d$

Temp °C

-50   0   50   100   150   200   250   300

2
1
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11

Reversible ——
Irreversible — — —

P	Symbol
6.7	X
18	●
56	○

- Once a temperature is selected and a permeance coefficient known, the chart can be consulted.
- Following down from the specified temperature, one can read both the percentage irreversible loss and the percentage reversible loss.
- Subsequent exposure to this same temperature will result in only the reversible loss.
- The example permeance coefficients are high at 6.7, 18 and 56 since alnico's are generally used at high Pc's.
- For example, a magnet with Pc = 6.7 and exposure to temperature = 300 degrees C: irreversible loss is 2% (-0.007% per °C) and reversible loss is 5% (-0.018% per °C).

Thank you !
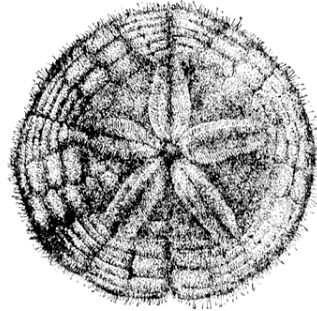
FEA from Permanent Magnet Motor Technology: Design and Applications, Jacek Gieras and Mitchell Wing, p.200