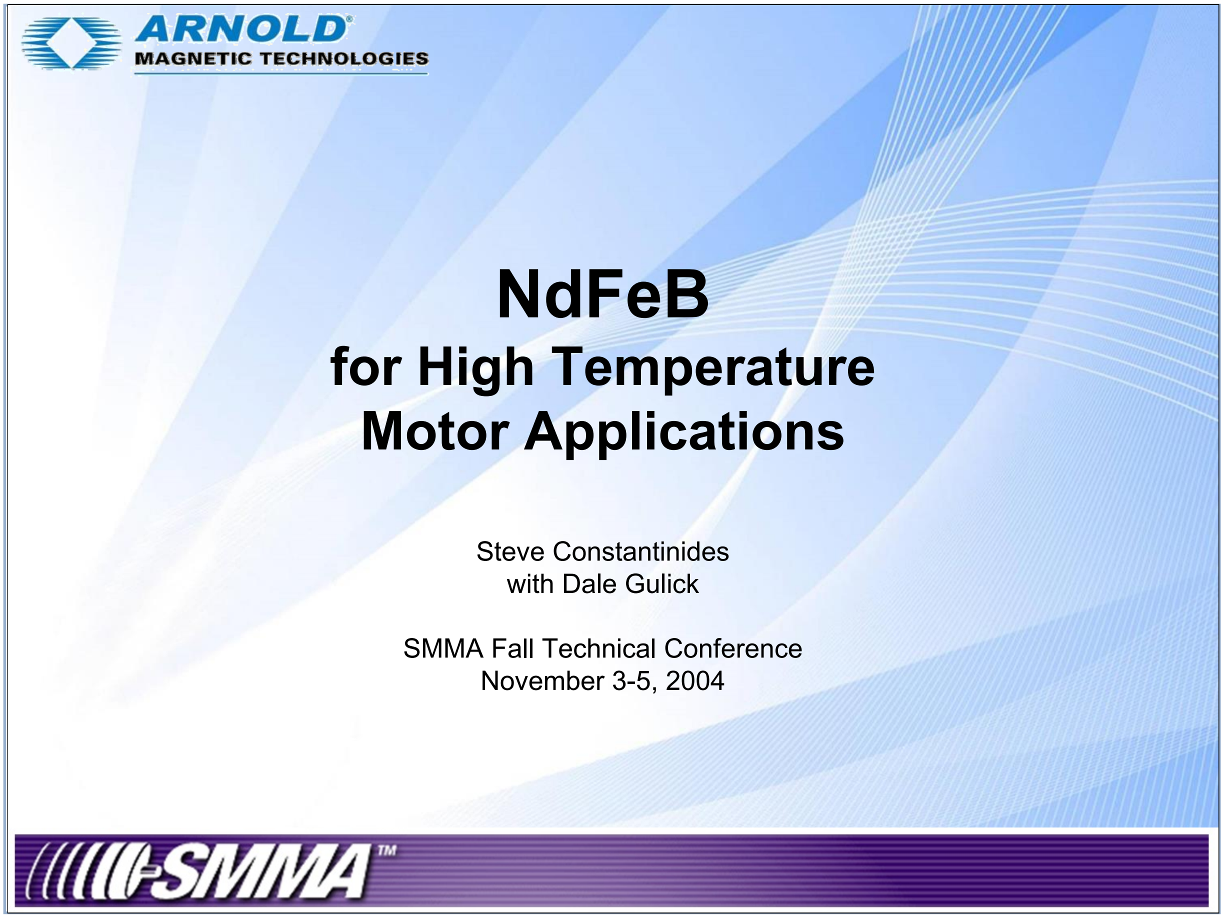
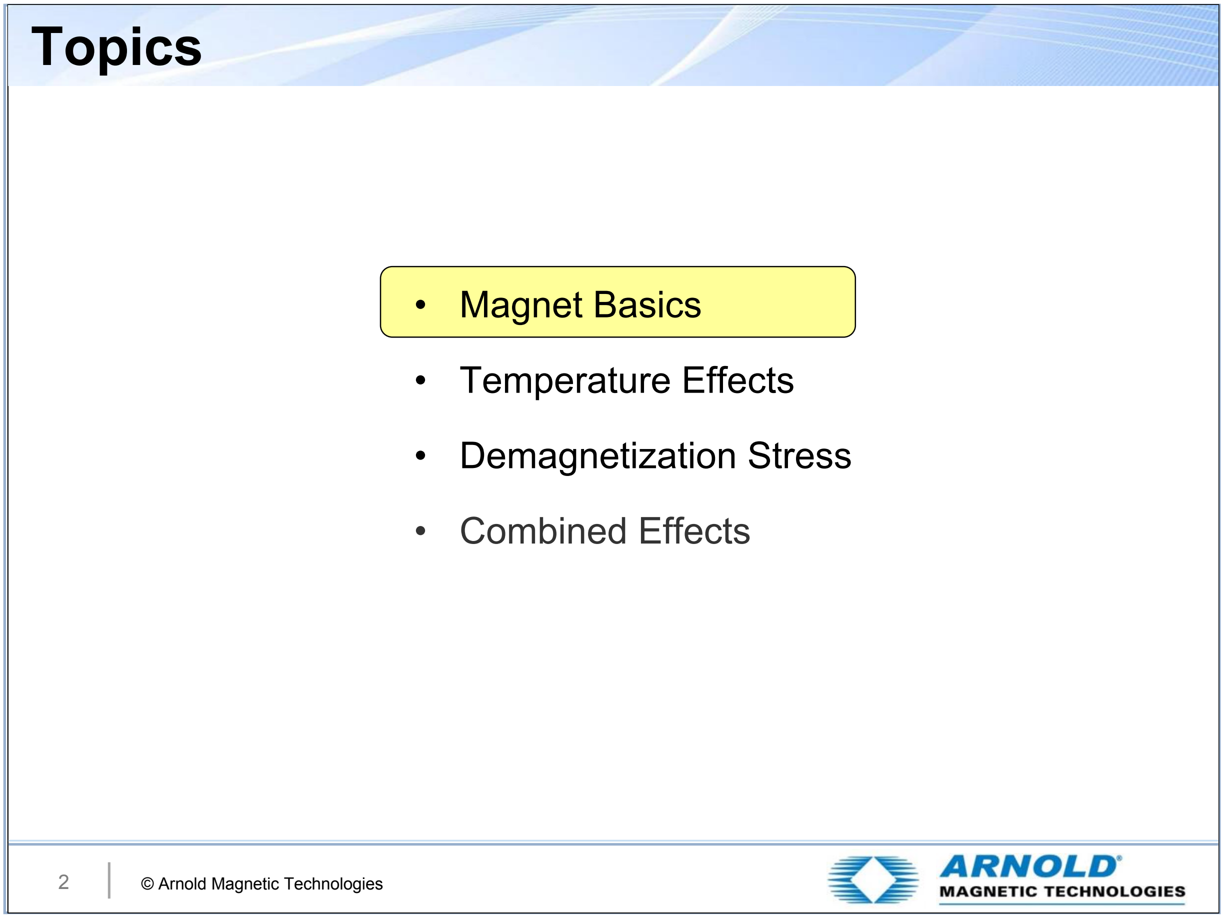


NdFeB
for High Temperature Motor Applications

Steve Constantinides
with Dale Gulick

SMMA Fall Technical Conference
November 3-5, 2004

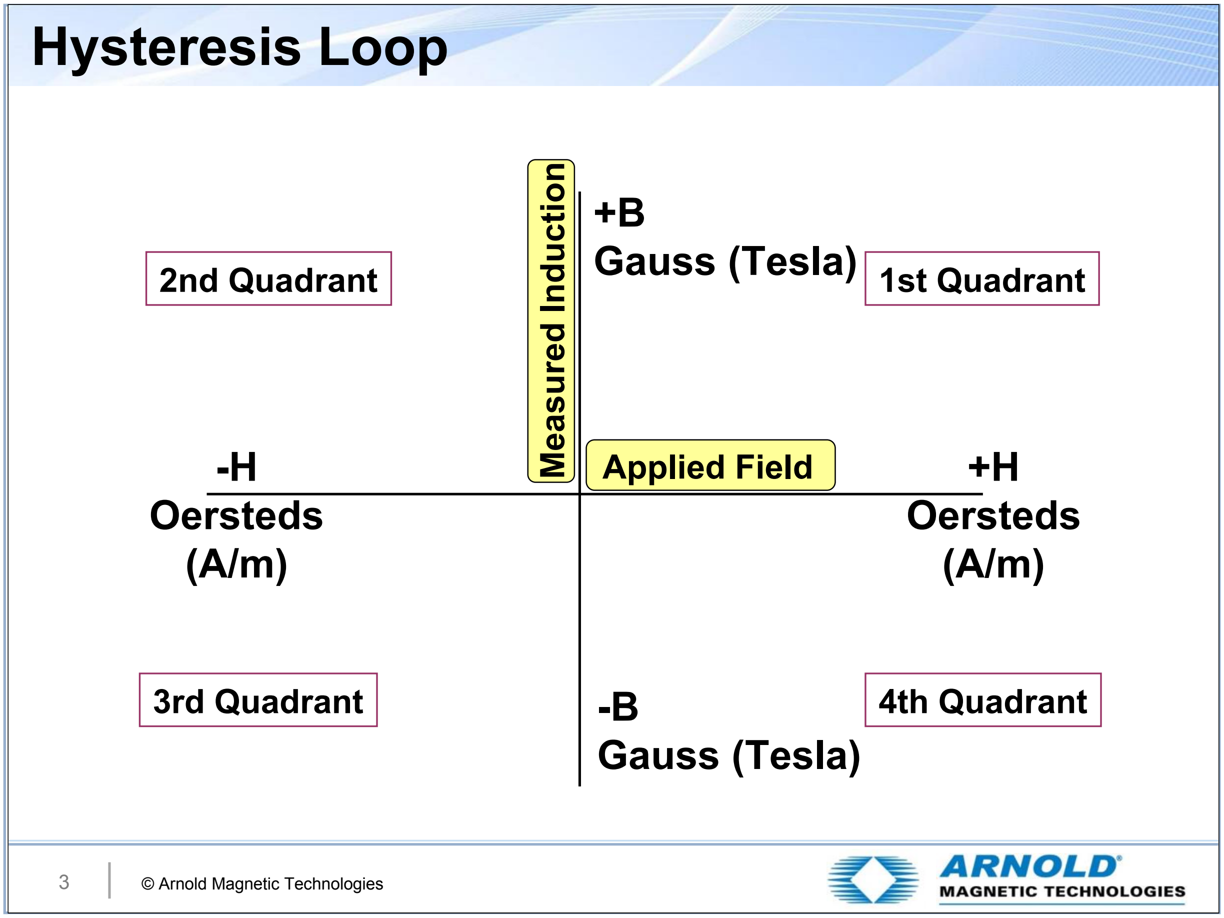


Topics

- Magnet Basics
- Temperature Effects
- Demagnetization Stress
- Combined Effects

- To understand what happens to a magnet at elevated temperature, or in the presence of a reverse magnetic field or a combination, it is necessary to understand the basics of magnetism.

- The first section will cover some of the more important magnetic characteristics.



Hysteresis Loop

Measured Induction

+B
Gauss (Tesla)

2nd Quadrant

1st Quadrant

-H
Oersteds
(A/m)

Applied Field

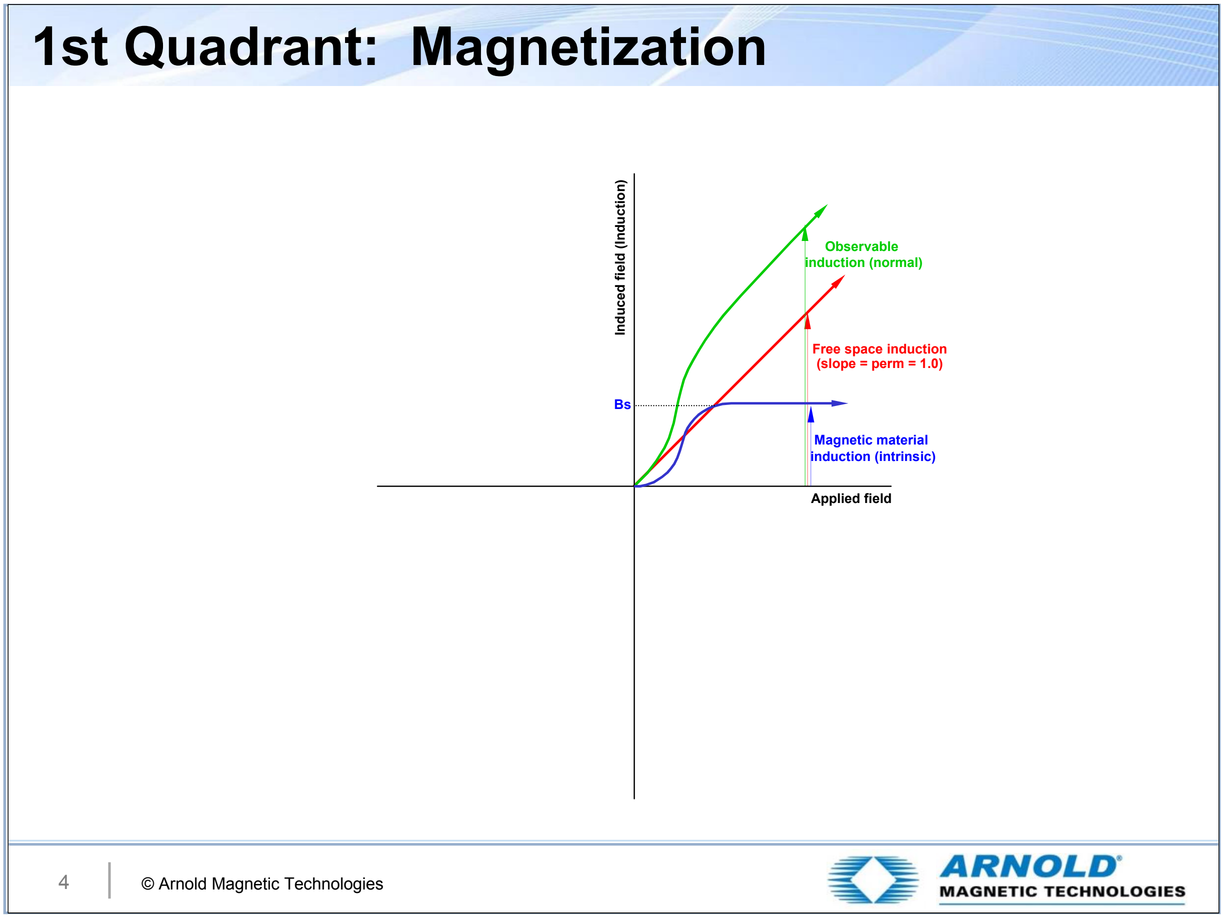
+H
Oersteds
(A/m)

3rd Quadrant

4th Quadrant

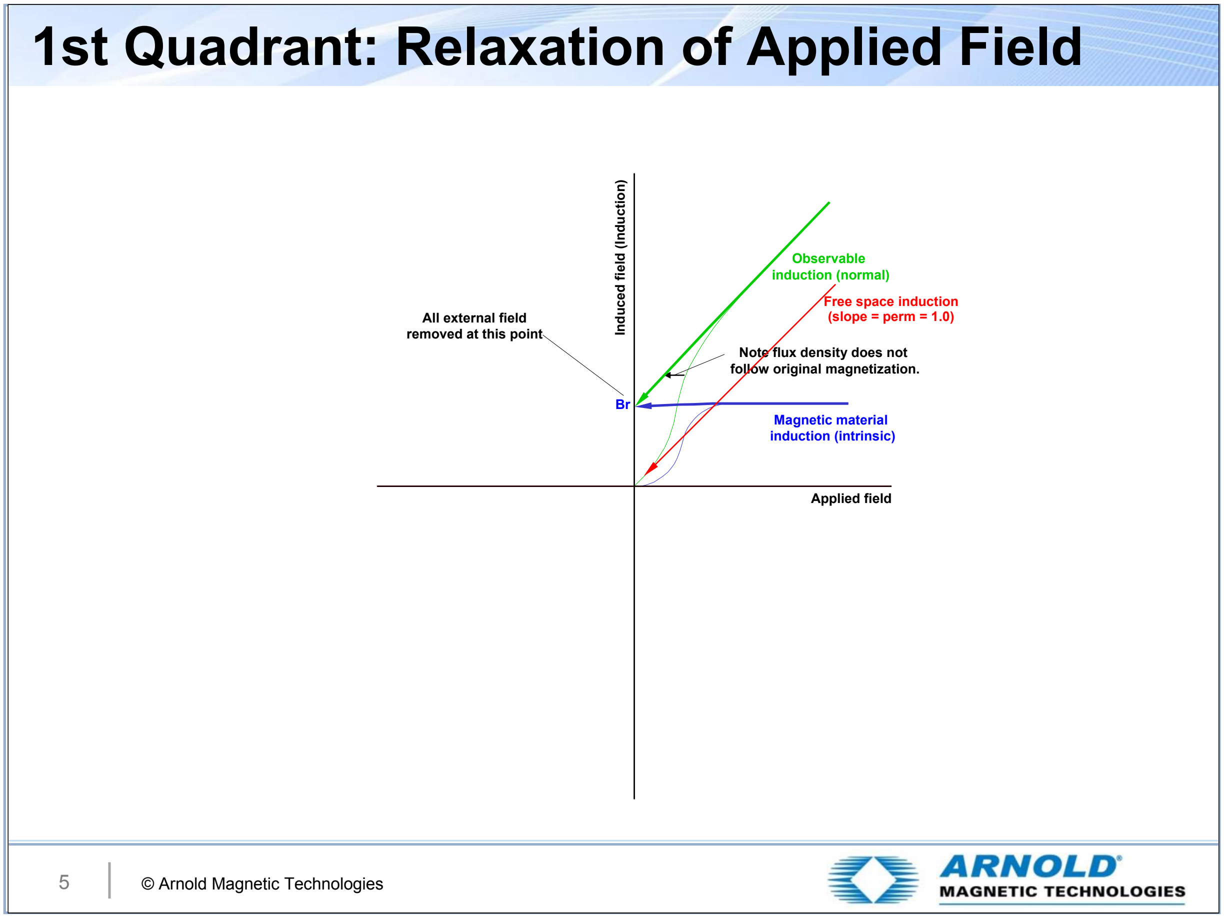
-B
Gauss (Tesla)

- We describe the hysteresis “loop” on a grid with X and Y axes except that we call the horizontal axis the “H” axis measured in Oersteds (or kA/m); the vertical axis is the “B” axis measured in Gauss (or Tesla, T).
- The H axis represents the magnitude of an externally applied field to the magnet material. The B axis represents the magnetic output either of the magnet or the combination of the magnet and the applied field.
- Note: in air, one Gauss = one Oersted. The distinction is that Oersted refers to applied field and Gauss to the measured, resultant (induced) field.
- The grid is divided into quadrants. The first quadrant is often referred to as the magnetizing quadrant, and the second is often referred to as the demagnetizing quadrant.



1st Quadrant: Magnetization

- As an external field is applied to our sample, the "B" measurement increases corresponding to the applied field.
- As the external field increases, the magnet starts to contribute to the output. That is, a field is induced in the magnet.
- When the magnet is saturated, the increase in B is once again equal to the increase in H.



1st Quadrant: Relaxation of Applied Field

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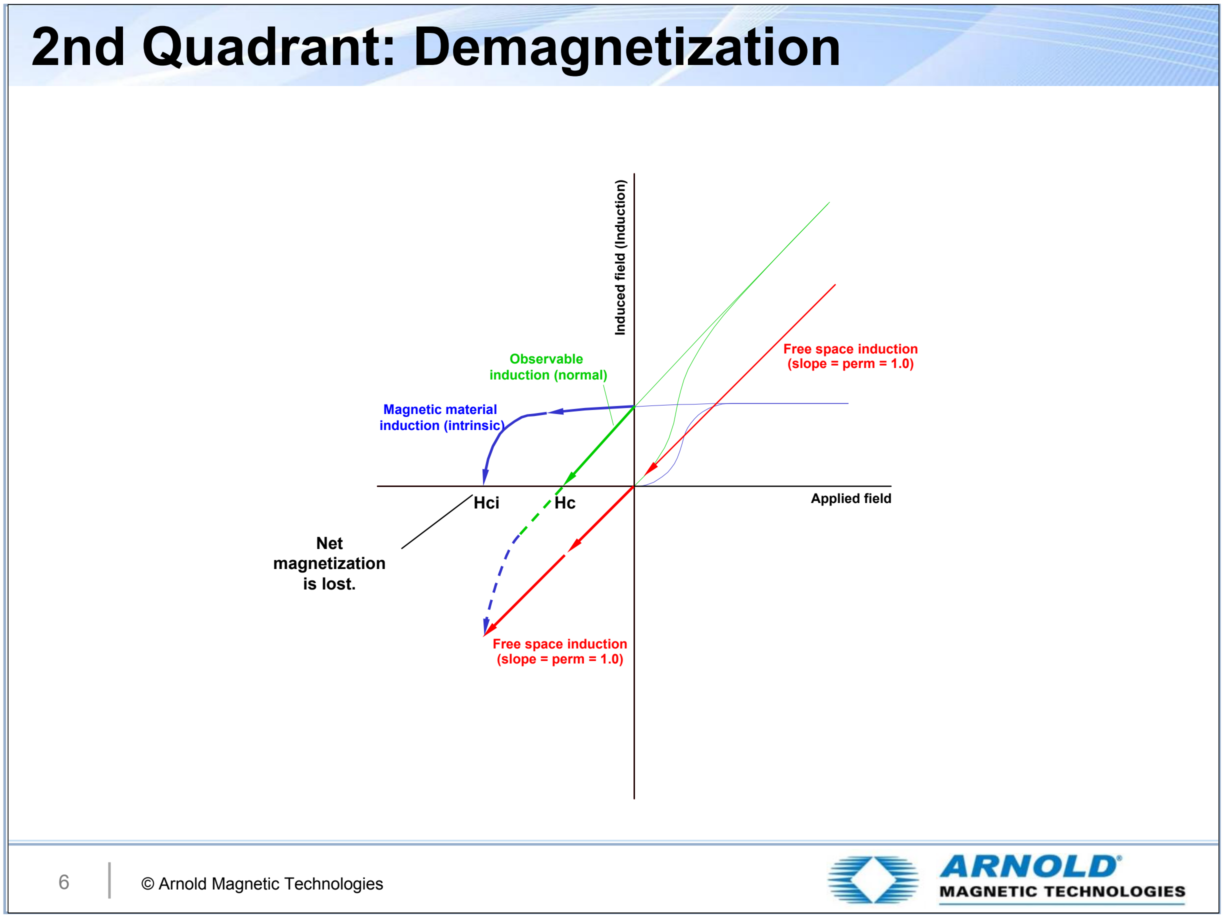
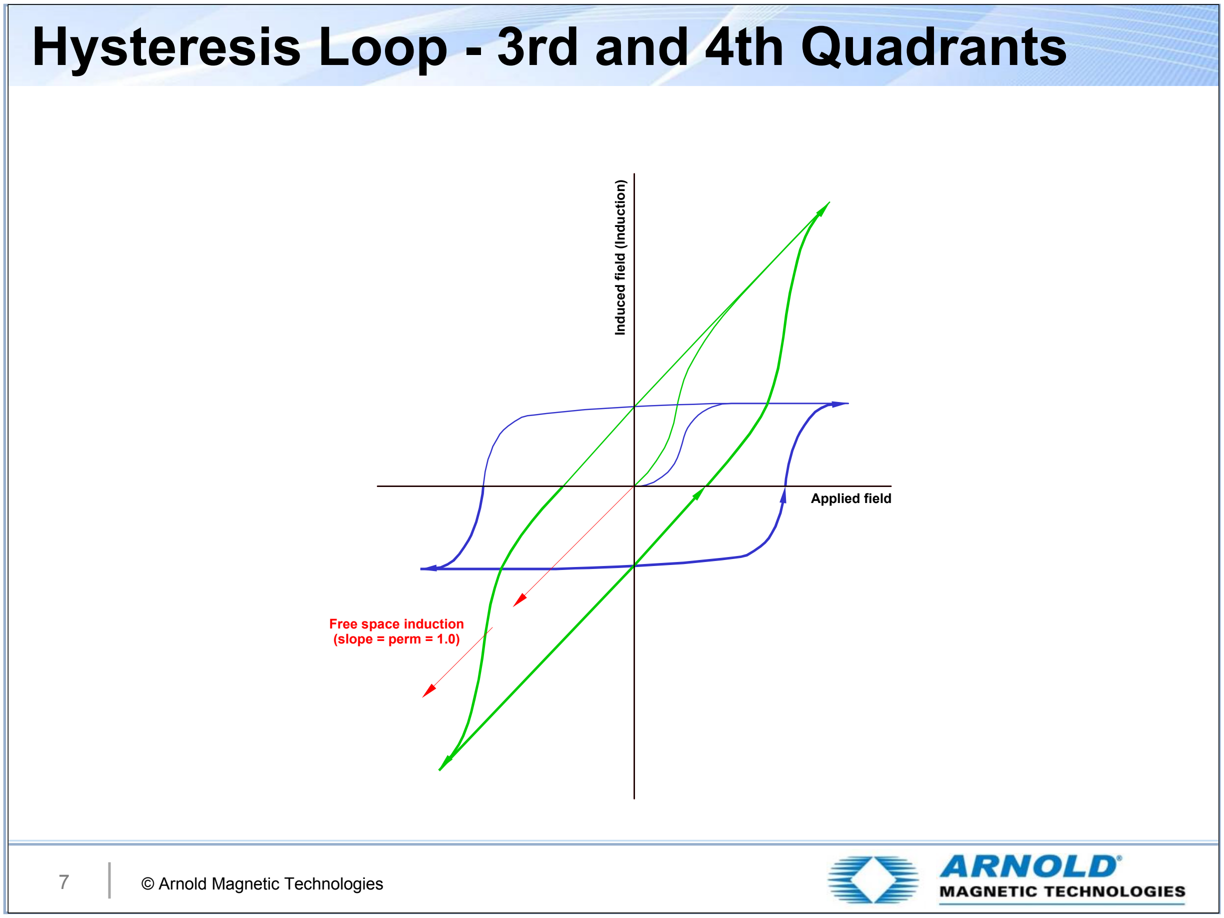
- As the H field is reduced, B also falls.
- The value of B where H=0 is called residual induction, Br.
- Two curves may be seen here: the normal (green) and the intrinsic (blue).
- The normal curve represents the measured, combined B value of both the applied field and that contributed by the magnetic material.
- The intrinsic curve is the calculated output due only to the magnet and is obtained by subtracting H from B.



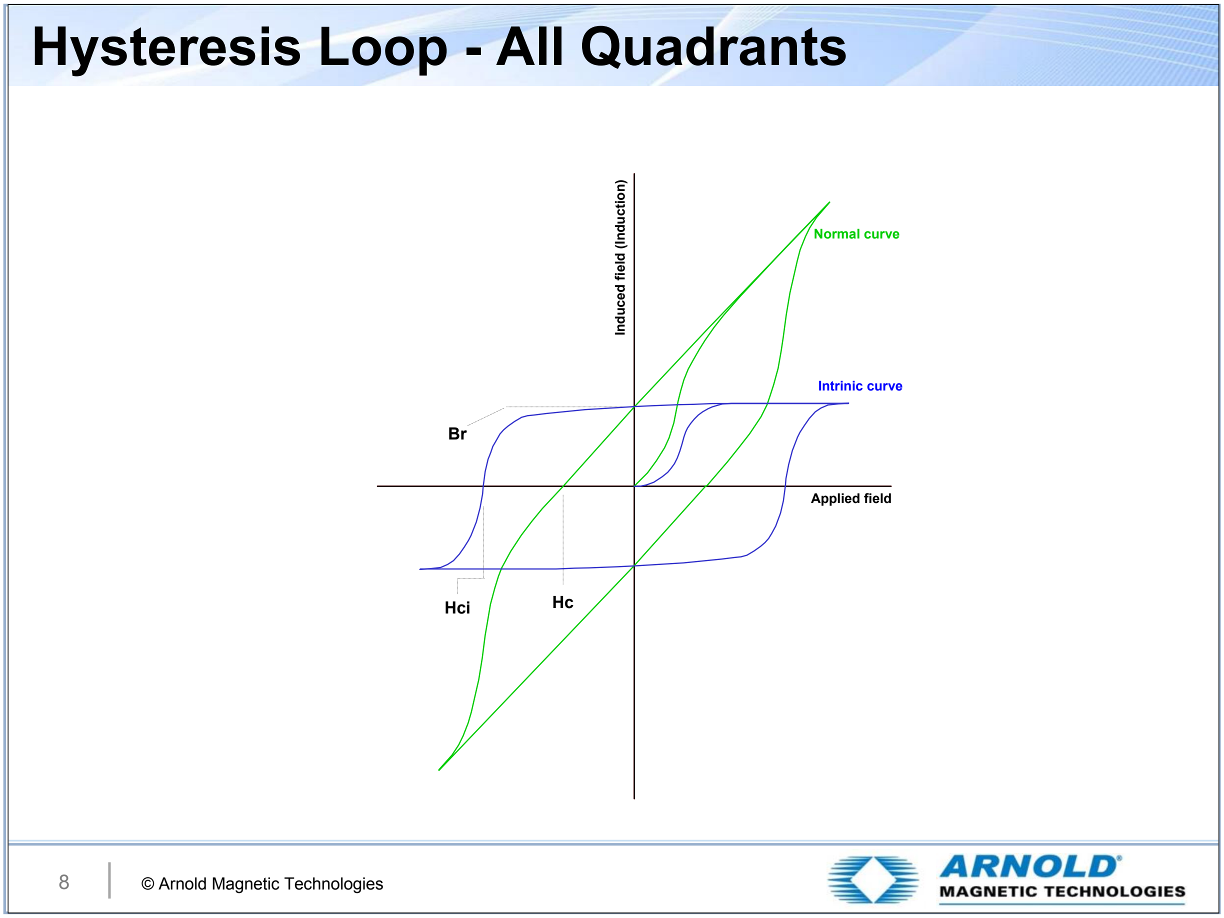
2nd Quadrant: Demagnetization

- If the external field is now applied in the opposite direction, the value of B will become smaller. At first, only a small reduction is noted.
- When there is sudden and substantial reduction in the magnet's field compared to the change in applied demagnetizing field, we say that the we have exceeded the second quadrant knee of the material.
- There are two very important points here.
  - Hc or H_{cB}, coercive force: When the magnet reaches this condition, it has no observable (external) field because the applied field H (= Hc) is balanced out by the flux M of the magnet material. Because they are in the opposite direction, the net observable induction B is equal to zero.
  - Hci or H_{cJ}, intrinsic coercivity: As the applied H is increased, past the "knee" of the intrinsic curve, the net magnetization of the material, M, reaches zero. This is the Hci, or intrinsic coercive force.



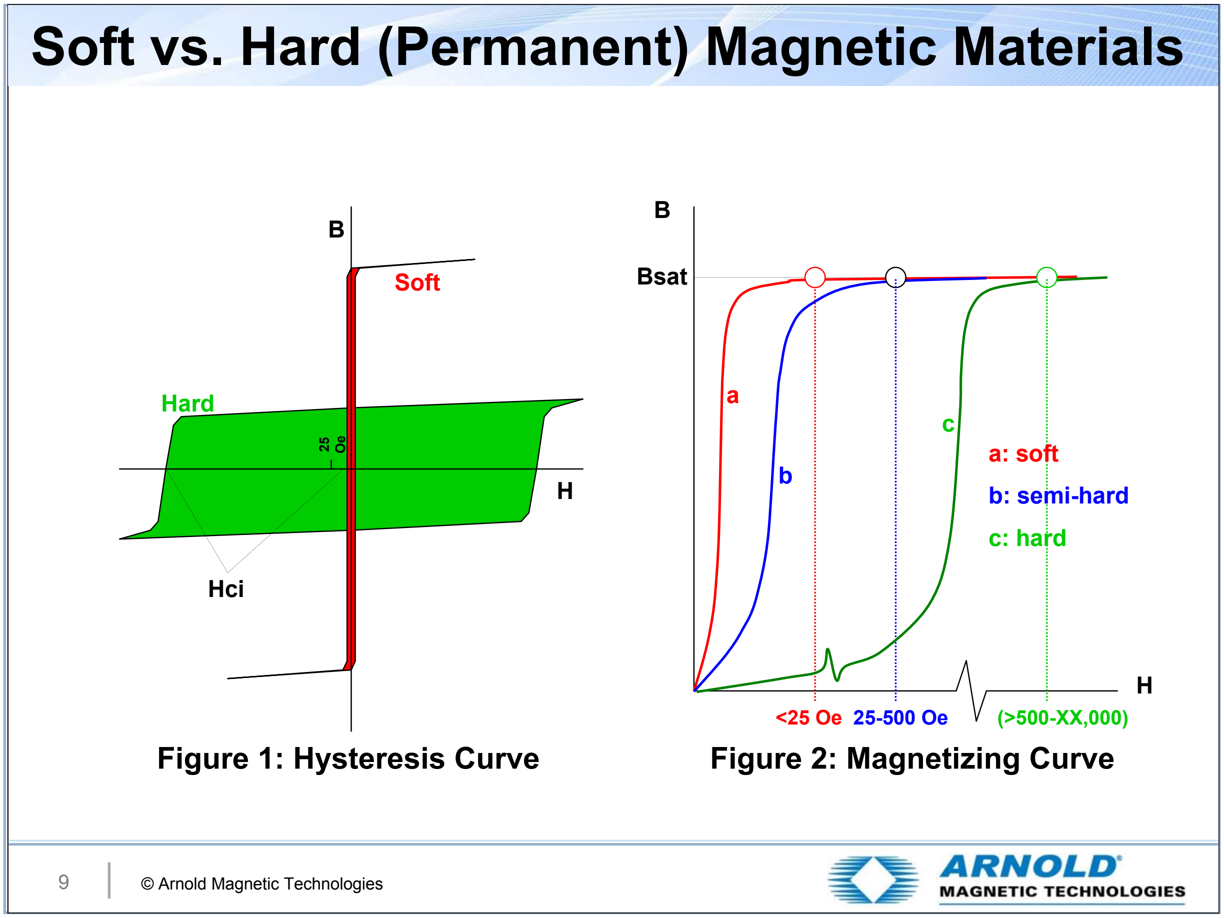
Hysteresis Loop - 3rd and 4th Quadrants

- The applied field can be increased until the magnet’s field has been fully reversed, in the third quadrant.
- If we then remove the applied field, the hysteresis loop returns to H=0 and with a negative value for Br.
- Applying a positive field, we move through the fourth quadrant and intercept the initial curve at saturation in the first quadrant.
- The third and fourth quadrants are essentially the same as the first and second quadrants, except they are in the opposite polarity.
- The entire curve is the “hysteresis loop”.



Hysteresis Loop - All Quadrants

- This chart displays the two types of hysteresis loops for a permanent magnet material: the Normal Curve and the Intrinsic Curve.
- At every point the two hysteresis loops will differ by the value of H: (B = Bi + H). In the first quadrant B = Bi +(+ H) or B=Bi +H. In the second quadrant B=Bi+(-H) or B=Bi-H. If you have one curve (e.g., B vs. H), you can calculate the other (e.g., Bi vs. H)
- The hysteresis curve shown is typical of a “straight line demagnetization” material, a.k.a., “square loop” material. “Straight line” refers to the normal curve’s linear response in the second quadrant. ”Square loop” describes the knee shape of the intrinsic curve.
- This behavior is typical of ferrite and rare-earth magnets (NdFeB and SmCo). For Alnico and Iron Chrome Cobalt, the intrinsic curve is very similar to the normal curve. They are so similar on these alloys that the Hci is approximately the same as the Hc.
- Bonded rare earth magnets exhibit a hysteresis loop somewhat less than “straight line.”



Soft vs. Hard (Permanent) Magnetic Materials

Figure 1: Hysteresis Curve

Figure 2: Magnetizing Curve

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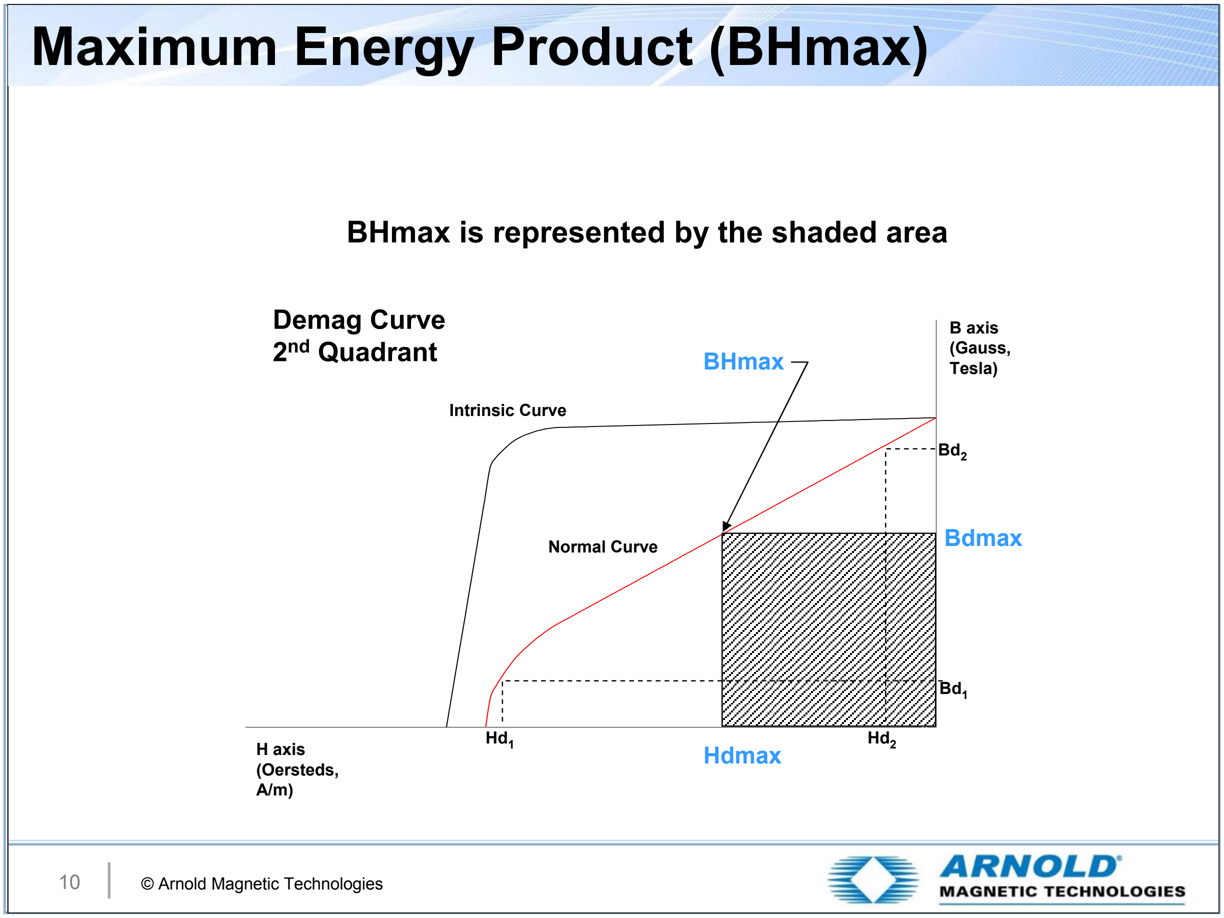
- At this point we can use the hysteresis curves (Fig 1) and the DC magnetizing curves (Fig 2) to demonstrate the difference between the soft magnetic materials and the hard magnetic materials.
- Intrinsic Coercivity (Hci) is most often used to delineate between “hard” and “soft” materials. Most “soft” magnetic materials exhibit Hci < 25 Oersted (See Fig 1), i.e., the ease with which they can be magnetized. If a small applied field suffices to produce saturation, the material is said to be magnetically soft. (See Fig 2). If a large field is required, as represented by curve “c,” the material is said to be magnetically hard. Materials having properties between “hard” and “soft” materials are occasionally referred to as “semi-hard” magnetic materials (curve “b”).
- For a hard magnetic material, the area inside the hysteresis curves (Fig 1) should be large because it represents the amount of useful magnetic energy that can be made available to do work. For soft magnetic material, it represents undesirable “core loss” and the area should be minimized.



Maximum Energy Product (BHmax)

BHmax is represented by the shaded area

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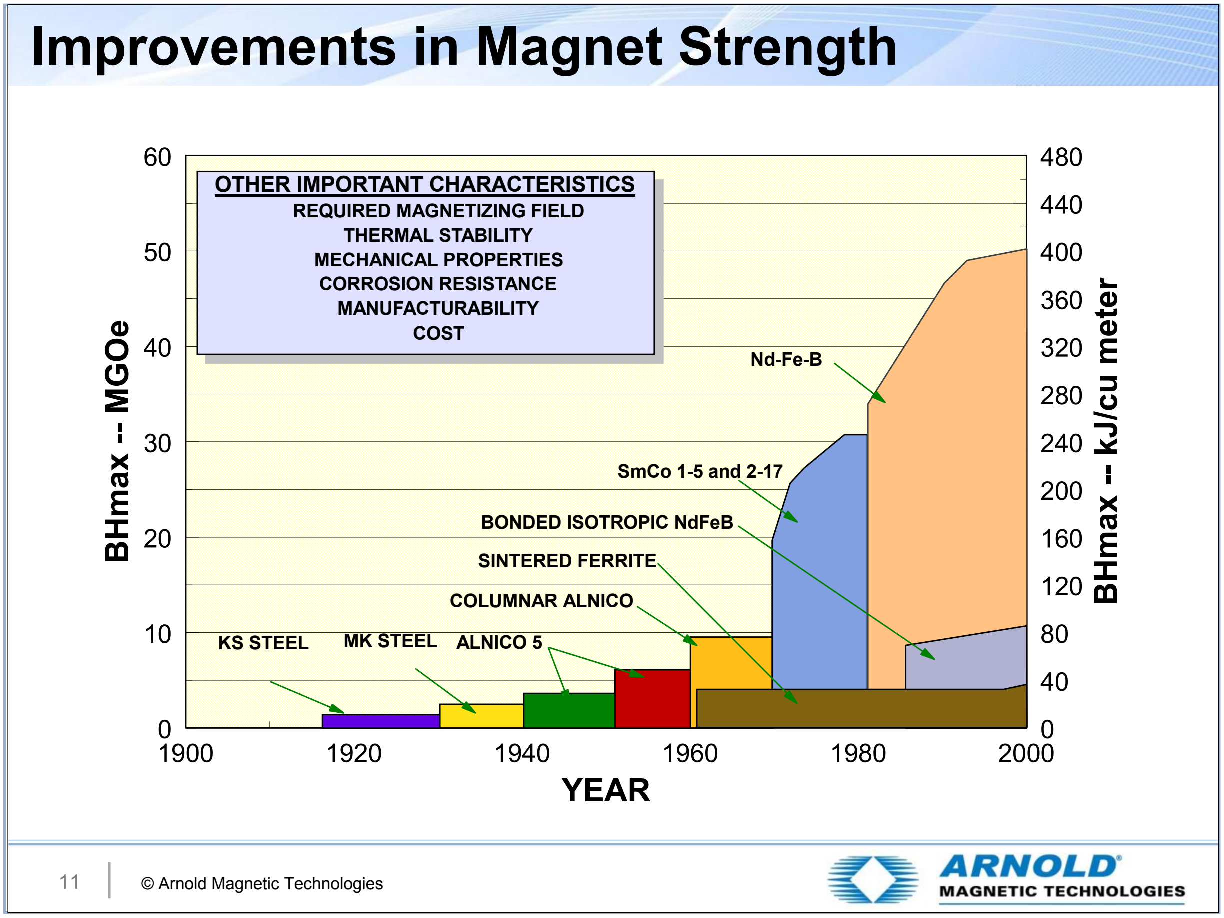
- When the operating point on the normal curve is known, the energy product of the magnet may be calculated. This is calculated by multiplying the Bd value by the Hd value. Energy = Bd x Hd , e.g., the energy products for points 1 and 2 are Hd1 x Bd1 or Hd2 x Bd2
- This calculates the rectangular area under the normal curve between the origin and the operating point. Common units obtained are Gauss-Oersteds and are typically referred to in Mega Gauss Oersteds (MGOe in cgs, and Joules/cubic meter in SI).
- Maximum Energy is found by locating a single point on the Normal curve where the product of Bd x Hd is greater than at any other point. For “Straight Line” materials this point is at approximately Bd = 1.1 Hd
- BHmax is commonly used to rate materials for maximum energy output per unit volume. However, this does not mean that material with greater BHmax will always perform better.

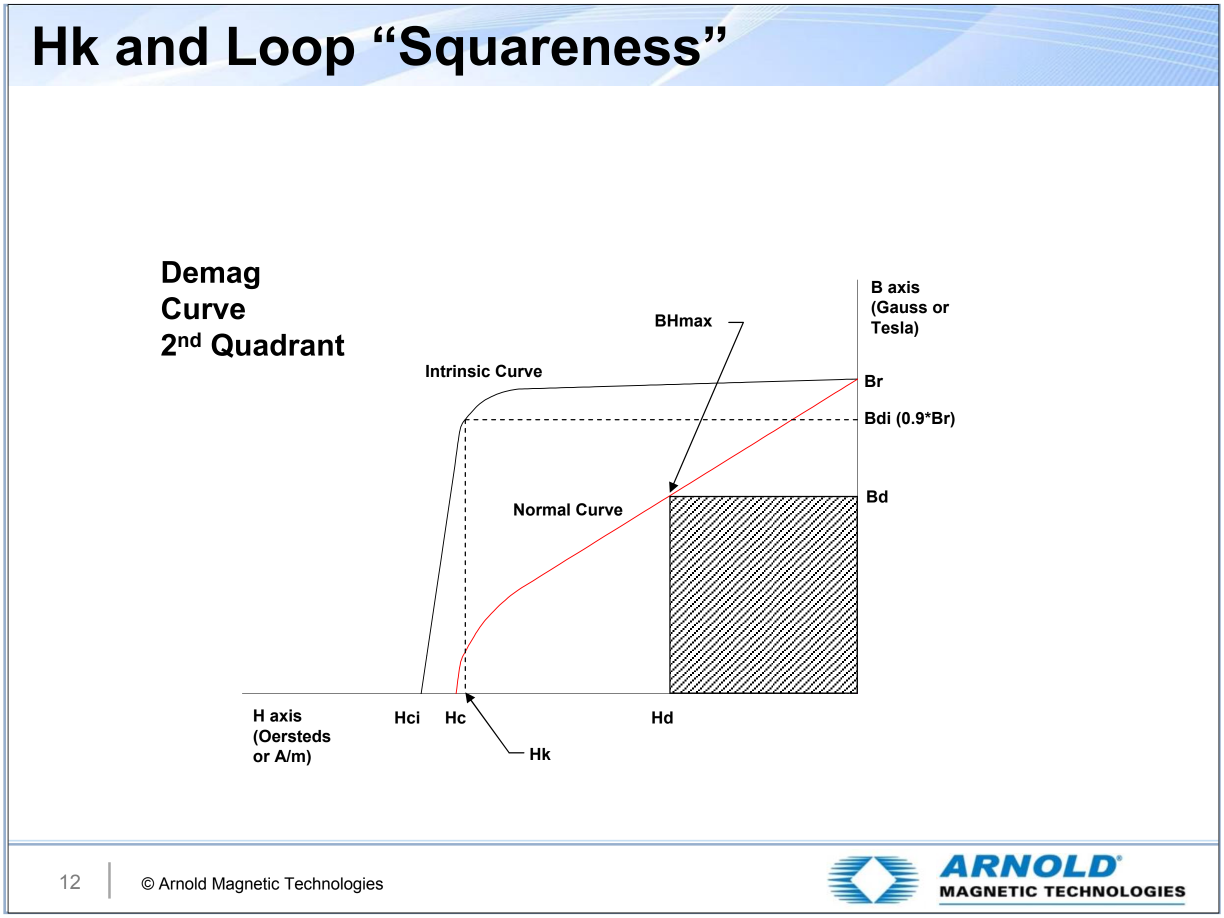


Improvements in Magnet Strength

OTHER IMPORTANT CHARACTERISTICS

REQUIRED MAGNETIZING FIELD
THERMAL STABILITY
MECHANICAL PROPERTIES
CORROSION RESISTANCE
MANUFACTURABILITY
COST

- At the start of the 20th century, the best magnets were made from iron alloys (carbon steel or cobalt steel) and had very low magnetic strength compared with today’s materials.
- In the late 1930’s, alnico was invented and this permitted the development of devices with which we are familiar today such as efficient and small motors, high quality loudspeakers, hard disk drives, etc.
- But it was the invention of ferrite (ceramic) magnets in the 1950s that revolutionized the industry. Ferrite remains predominant today representing about 85% of permanent magnets made on a weight basis.
- The reason: ferrite material cost is very low, especially compared with the rare earth magnets: NdFeB and SmCo.
- However, rare earth compositions provide very high magnetic energy allowing design of miniature equipment and small, light weight consumer electronics.
- The theoretical maximum strength for “Neo” magnets is 64 MGOe. Laboratories have reported achieving BHmax of 57 MGOe and >50 MGOe is available commercially.



Hk and Loop “Squareness”

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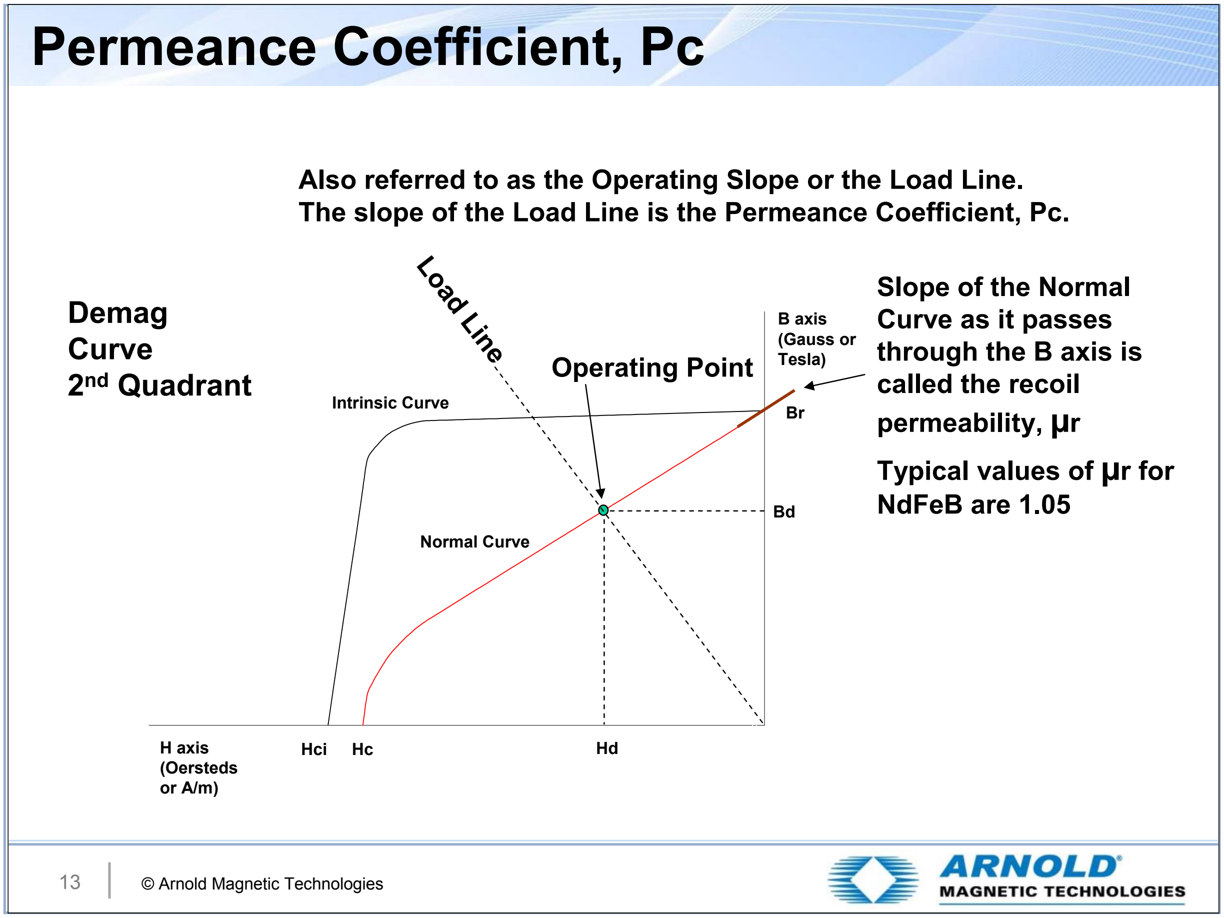
- Most magnet circuits are designed to operate in the 2nd quadrant on the demag curve. With the exception of hysteresis devices (hysteresis coupled drive, clutch, brakes, etc.), where the material sees the most of or the whole cycle of magnetization within in the application, the typical permanent magnet works mostly within the region known as the 2nd quadrant of the hysteresis curve.
- As a result, understanding of the demagnetization curves is very important. The demagnetization curves provide specific information about how a given material performs under a variety of magnetic loading and temperature conditions.
- One should remember that the curve is representative of the specific material used to make the magnet, and is independent of the geometry the magnet is made into.



Permeance Coefficient, Pc

Also referred to as the Operating Slope or the Load Line.
The slope of the Load Line is the Permeance Coefficient, Pc.

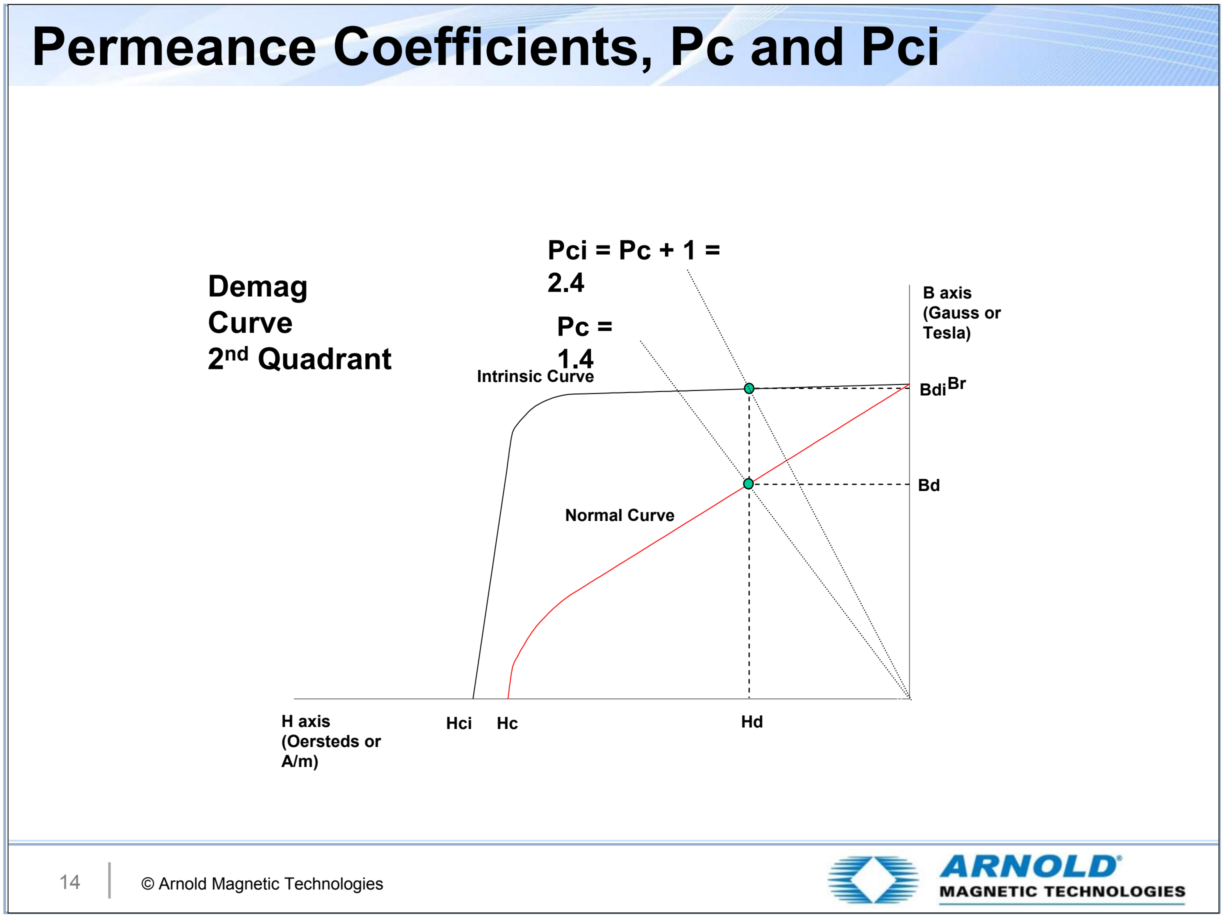
Demag Curve 2nd Quadrant

Slope of the Normal Curve as it passes through the B axis is called the recoil permeability, μr

Typical values of μr for NdFeB are 1.05

- This illustration shows a plot of a Load Line and its intersection with the Normal Curve. That intersection is known as the Operating Point.
- The slope of the line is referred to as the Permeance Coefficient (Pc). While the slope of the line is negative, by convention the Pc is a positive number.

- The second item of note is the Recoil Permeability or μ_r. Typical values of Recoil Permeability are about 1.05 for sintered Ferrite, SmCo and NdFeB. Bonded ferrite is also about 1.05. Bonded Neo magnets range from about 1.1 to 1.7, depending upon grade.



Permeance Coefficients, Pc and Pci

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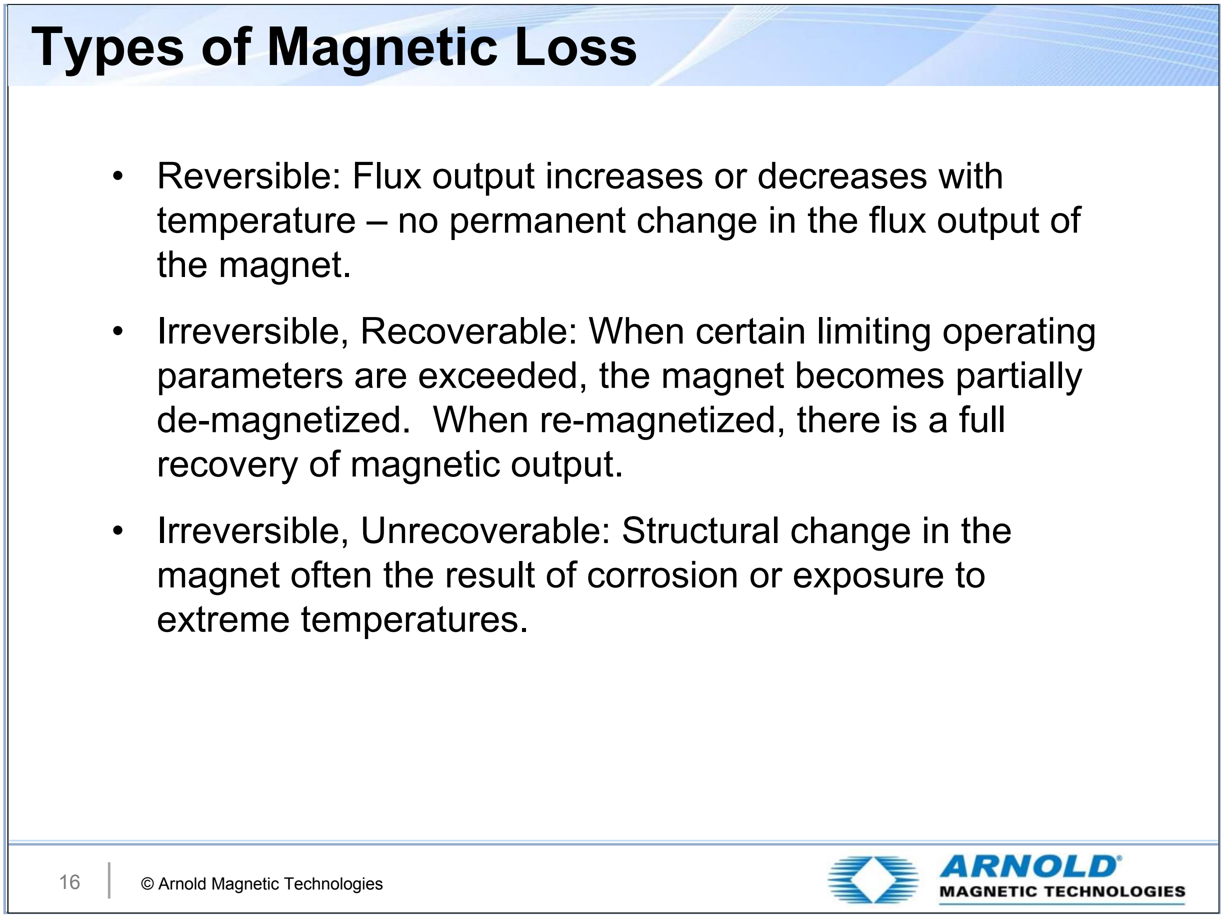
- If a vertical line is drawn from the Operating Point up to the Intrinsic curve and down to the H axis, a point is obtained on the Intrinsic curve which is at a level of B referred to as Bdi. The B value for the Operating Point on the Normal Curve is Bd.

- If a straight line is drawn from the origin to the Bdi point, the resulting line is called the Intrinsic Permeance Coefficient, Pci. Because of the special relationship between the Normal and the Intrinsic curves in the cgs units system, Pci is equal to Pc plus 1.

Topics

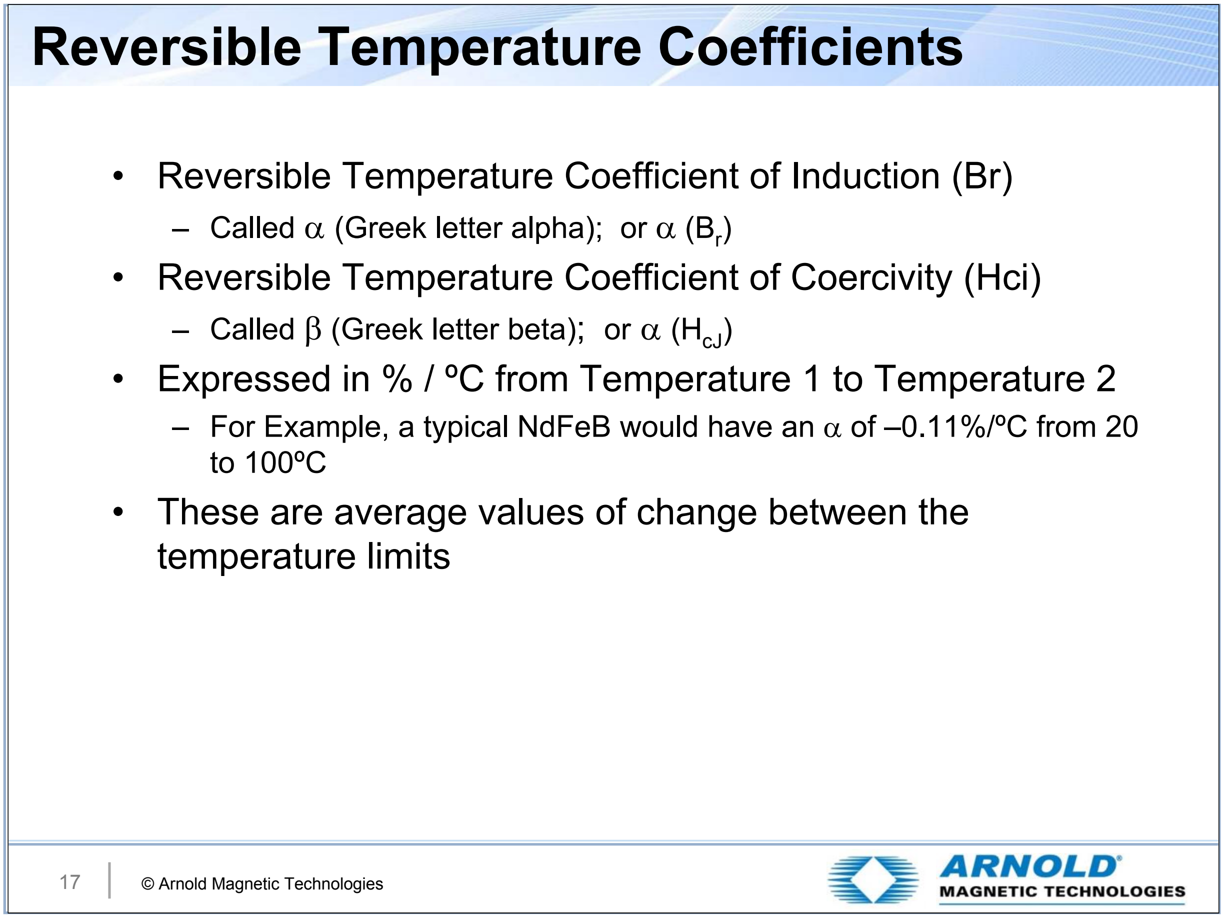
- Magnet Basics
- Temperature Effects
- Demagnetization Stress
- Combined Effects



Types of Magnetic Loss

- Reversible: Flux output increases or decreases with temperature – no permanent change in the flux output of the magnet.
- Irreversible, Recoverable: When certain limiting operating parameters are exceeded, the magnet becomes partially de-magnetized. When re-magnetized, there is a full recovery of magnetic output.
- Irreversible, Unrecoverable: Structural change in the magnet often the result of corrosion or exposure to extreme temperatures.

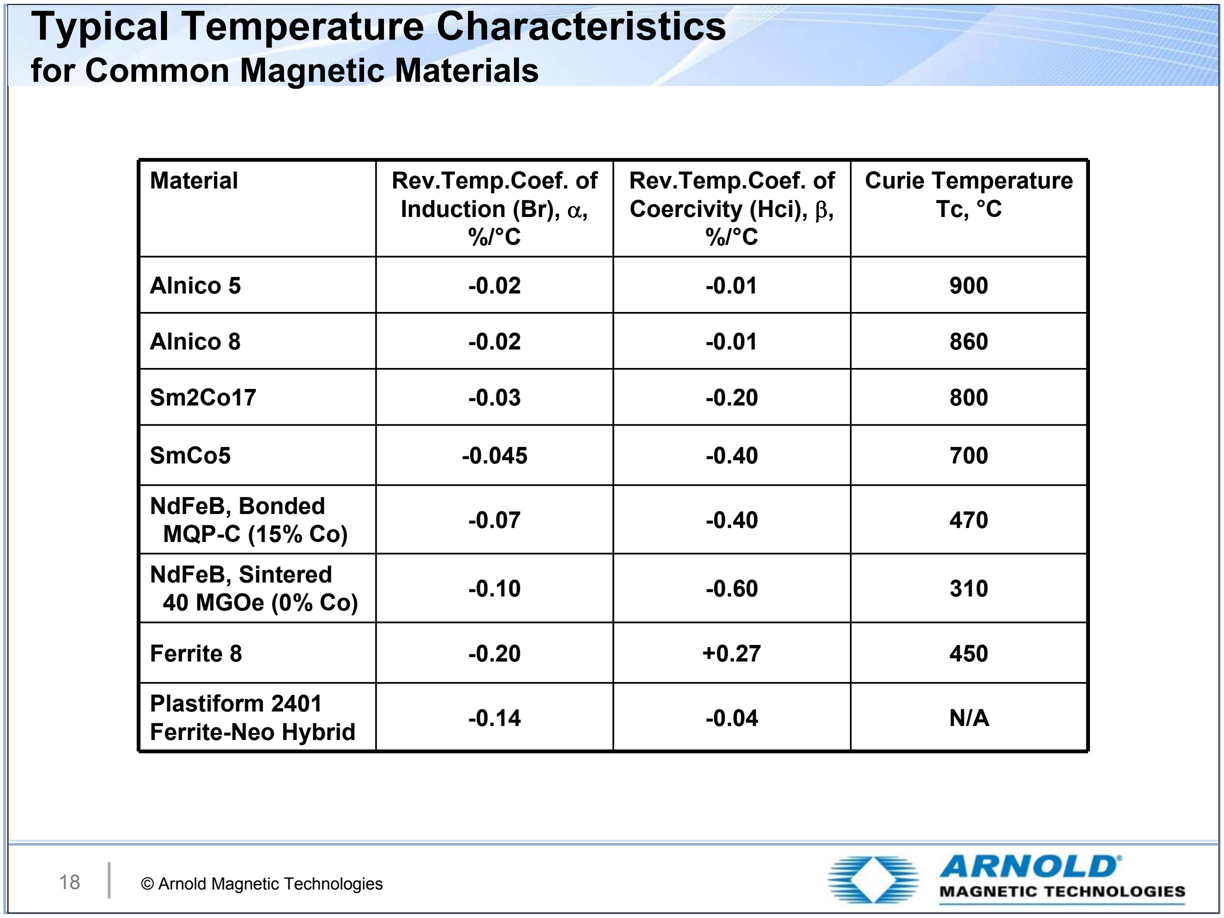
- Permanent magnets lose their magnetism exceedingly slowly unless certain critical parameters are exceeded or structural damage occurs.
- From a practical standpoint, since the user is unlikely to re-saturate the product, any loss of flux output is detrimental.



Reversible Temperature Coefficients

- Reversible Temperature Coefficient of Induction (Br)
  - Called α (Greek letter alpha); or α (B_r)
- Reversible Temperature Coefficient of Coercivity (Hci)
  - Called β (Greek letter beta); or α (H_{cJ})
- Expressed in % / ºC from Temperature 1 to Temperature 2
  - For Example, a typical NdFeB would have an α of –0.11%/ºC from 20 to 100ºC
- These are average values of change between the temperature limits

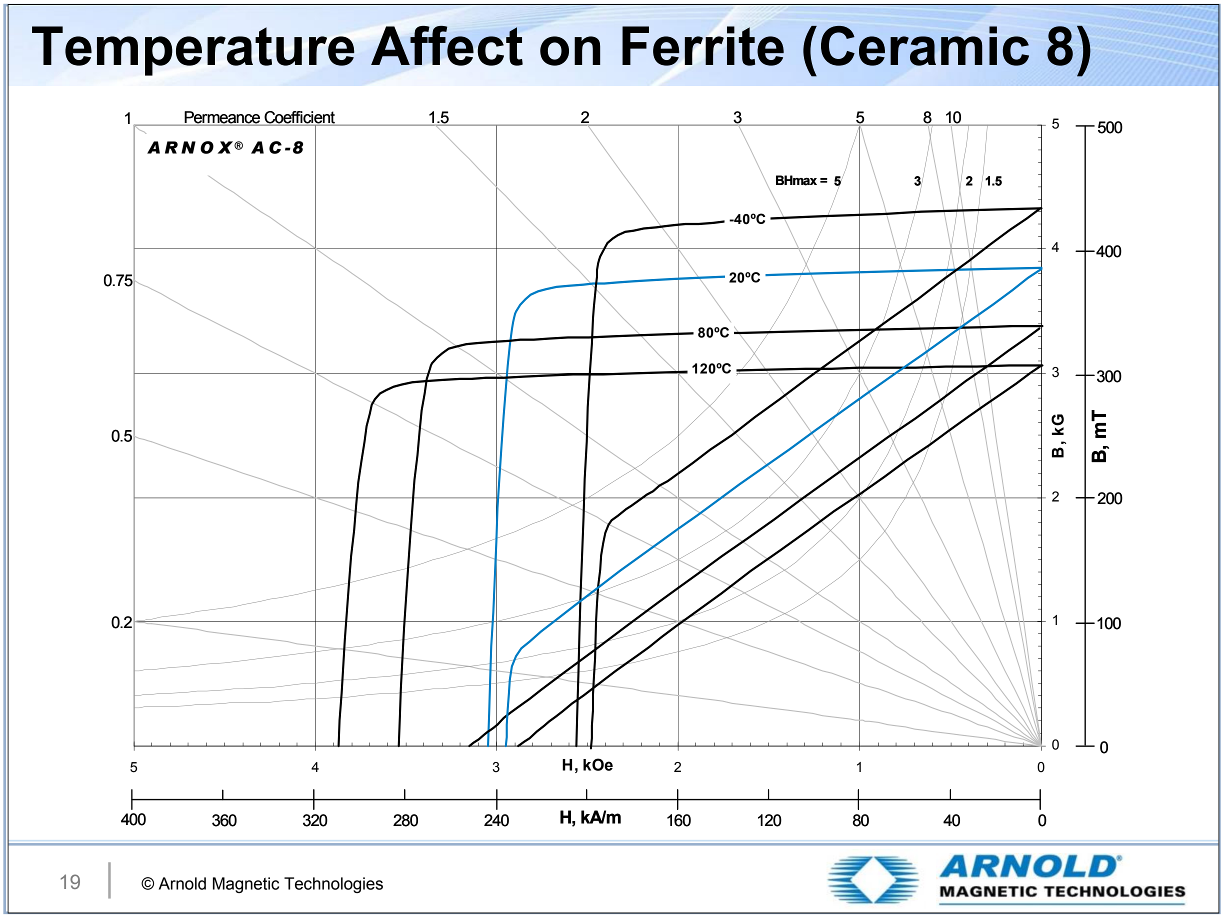
- The first cause of loss which we'll discuss is that due to the change in magnetic output as a function of temperature.
- Both Residual Induction (Br) and Intrinsic Coercivity (Hci) change as temperature changes. The relationships are referred to as the Reversible Temperature Coefficients.
- They can be expressed in % change per degree C or %/K.
- Br and Hci change non-linearly with temperature. The Alpha and Beta values are averages and should always be accompanied by the temperature range over which they are calculated.
- Chinese NdFeB material specifications generally refer to the temperature range from room temperature to the maximum recommended use temperature.



Typical Temperature Characteristics
for Common Magnetic Materials

Material	Rev.Temp.Coef. of Induction (Br), α, %/°C	Rev.Temp.Coef. of Coercivity (Hci), β, %/°C	Curie Temperature Tc, °C
Alnico 5	**-0.02**	**-0.01**	**900**
Alnico 8	**-0.02**	**-0.01**	**860**
Sm2Co17	**-0.03**	**-0.20**	**800**
SmCo5	**-0.045**	**-0.40**	**700**
NdFeB, Bonded MQP-C (15% Co)	**-0.07**	**-0.40**	**470**
NdFeB, Sintered 40 MGOe (0% Co)	**-0.10**	**-0.60**	**310**
Ferrite 8	**-0.20**	**+0.27**	**450**
Plastiform 2401 Ferrite-Neo Hybrid	**-0.14**	**-0.04**	**N/A**

- These are some typical values for different permanent magnet materials.
- Note that Ferrite has:
    - o Large negative Alpha
    - o Positive Beta



Temperature Affect on Ferrite (Ceramic 8)

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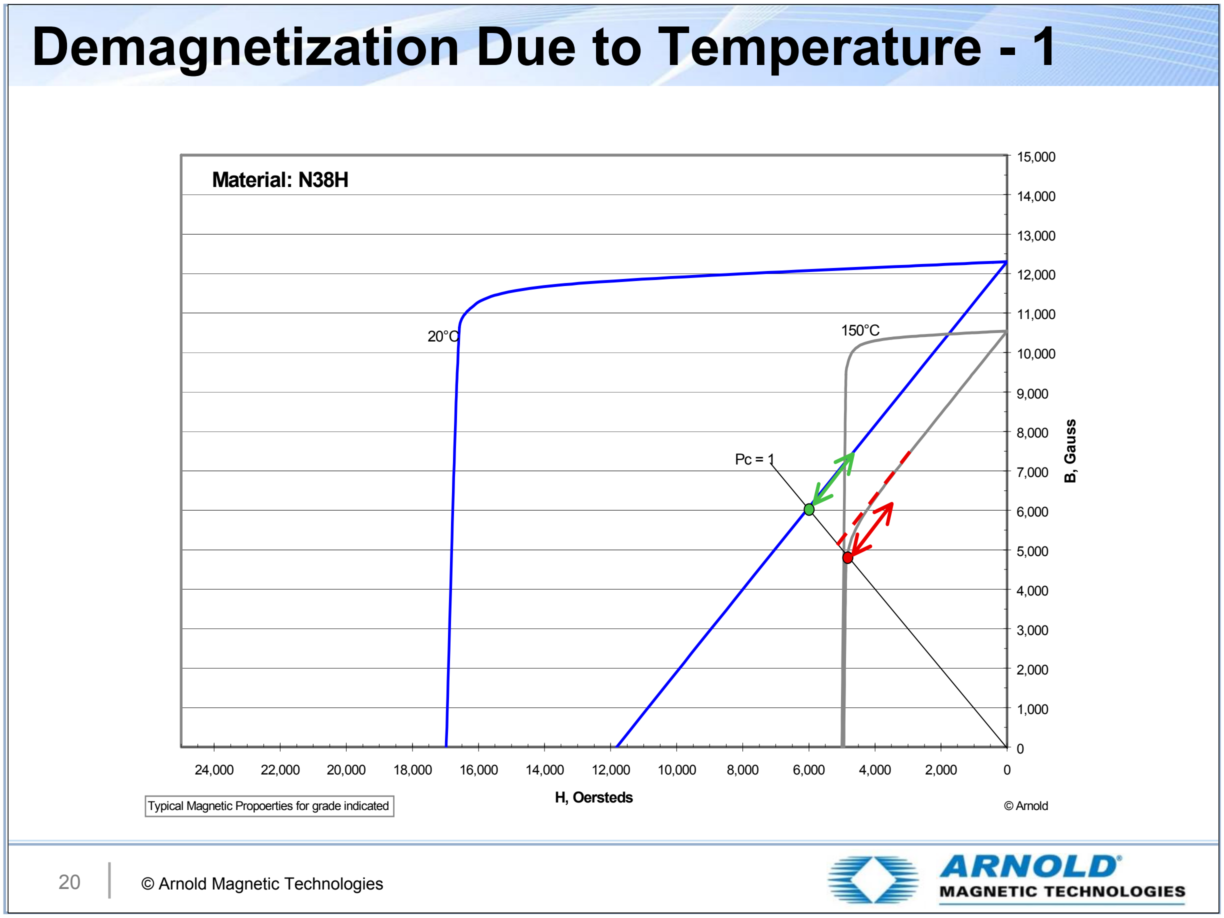
- Ferrite, unlike SmCo and NdFeB, exhibits a positive temperature coefficient of coercivity. While we have concern about the performance of the rare earth magnets at high temperature, with ferrite, we must be concerned about de-magnetization at low temperatures.
- Ferrites are generally limited in practical usage to above –40 degrees C.
- Since the Induction changes so much with temperature, a practical upper use limit is 150 degrees C.



Demagnetization Due to Temperature - 1

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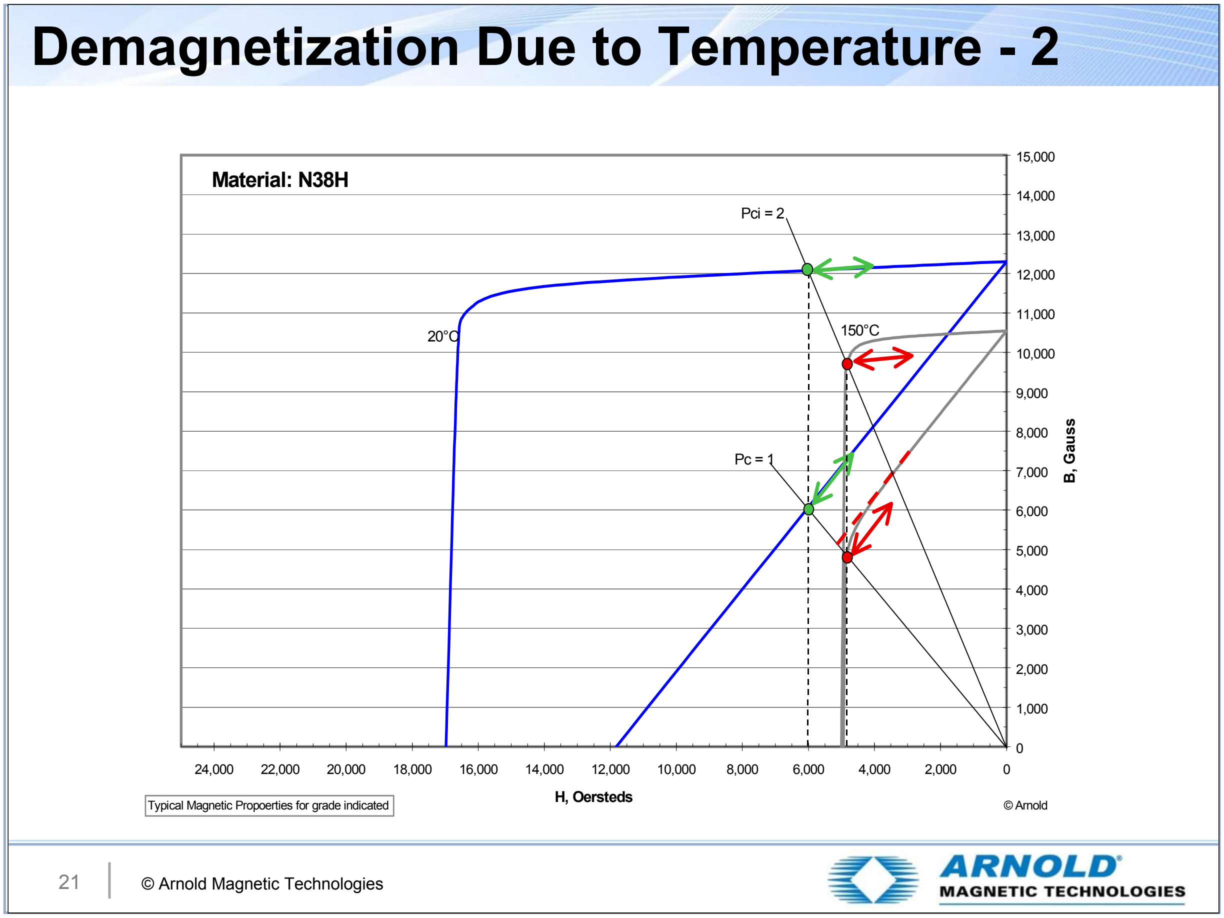
- If a Pc = 1 line is drawn on this plot of N38H NdFeB, the intersection with the Normal curves for 20 and 150 degrees would represent the Operating Points at each of those temperatures.
- In the application, when the Pc increases above 1, we see the Operating Point for 20 degrees move back and forth 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.



Demagnetization Due to Temperature - 2

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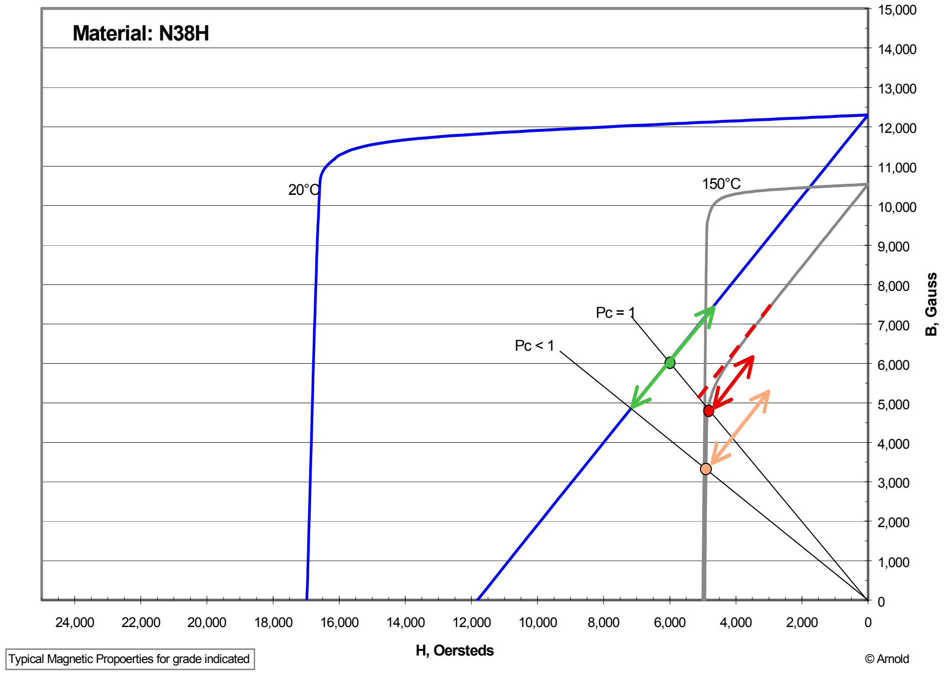
- It is also possible to view performance on the Intrinsic curve by drawing a vertical through the Normal Operating Point and up to intersect with the Intrinsic curve.
- A line drawn from this new point to the origin will have a slope of Pc + 1 (ignoring signs) and is referred to as Pci.
- Recoil along the Intrinsic curve is at a slope of the Recoil Permeability minus one ($\mu_r - 1$).

- Where only the effects of temperature are experienced, either the Normal or the Intrinsic curve may be used for observations.

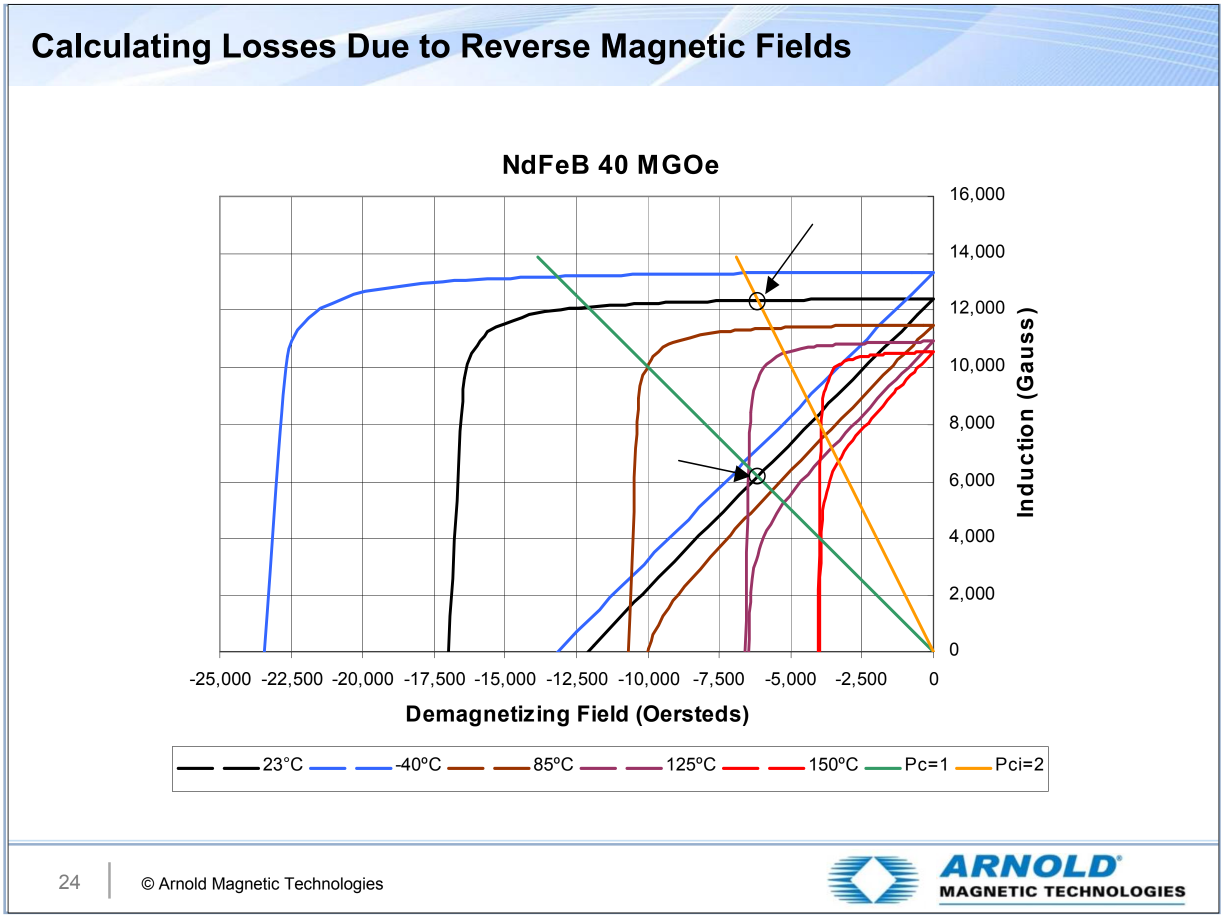
Demagnetization Due to Temperature - 3



- If, in the application, the Pc drops lower than 1:
- At room temperature the magnetic output will move back and forth approximately along the Normal curve.
- At 150 degrees, in this example, additional loss will occur as the Operating Point moves further around the Knee.

Topics

- Magnet Basics
- Temperature Effects
- Demagnetization Stress
- Combined Effects



Calculating Losses Due to Reverse Magnetic Fields

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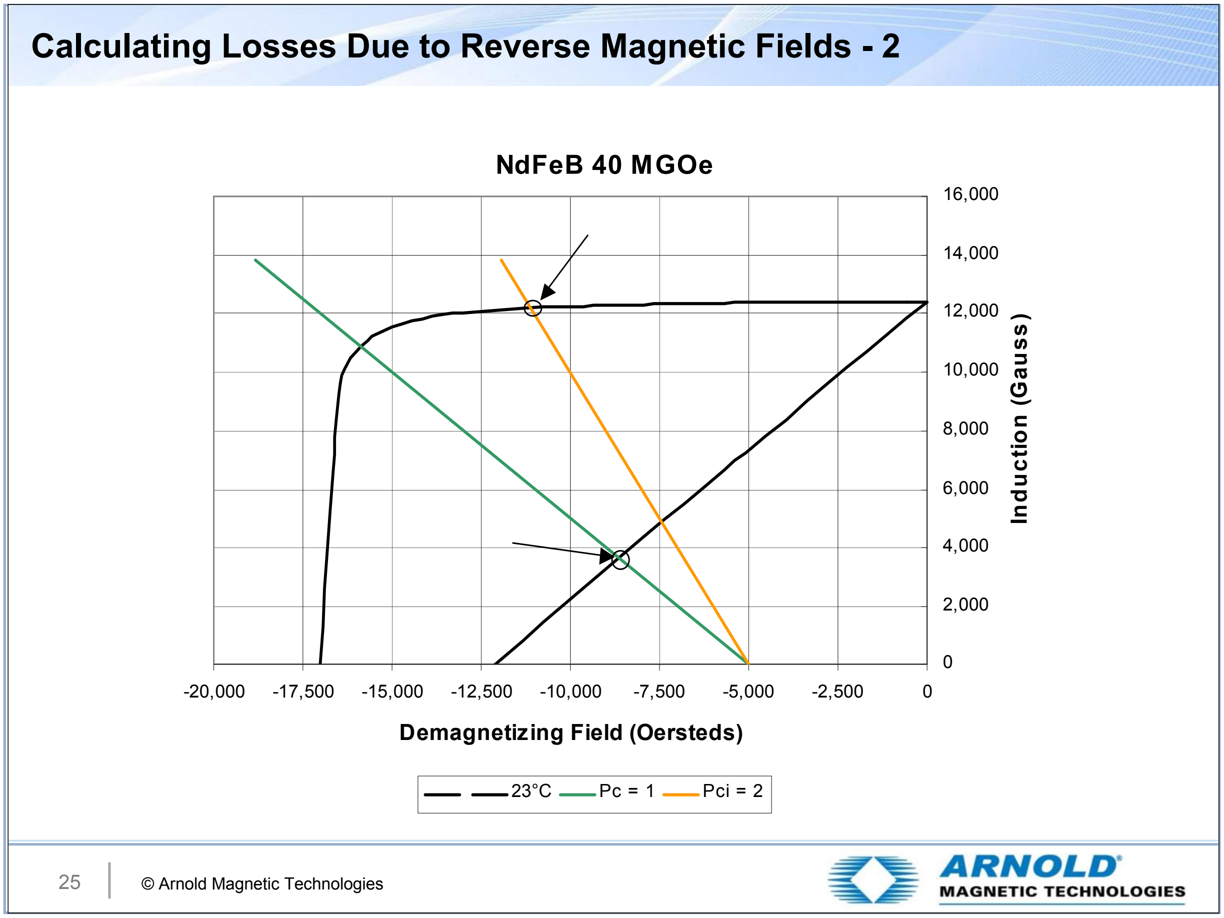
- As demonstrated before, both a Pc and a Pci line can be drawn to intersect with the Normal and the Intrinsic curves respectively.
- Note that when there is no reverse applied field, the Pc and Pci lines intersect the Normal and Intrinsic curves with the same Hd value. This condition is only true when there is no applied magnetic field.
- Applying a reverse field (demagnetizing influence) creates a shift in the origin of the slope equal to the applied field. At this time it is standard practice to drop the Pc slope as it no longer accurately describes the situation.



Calculating Losses Due to Reverse Magnetic Fields - 2

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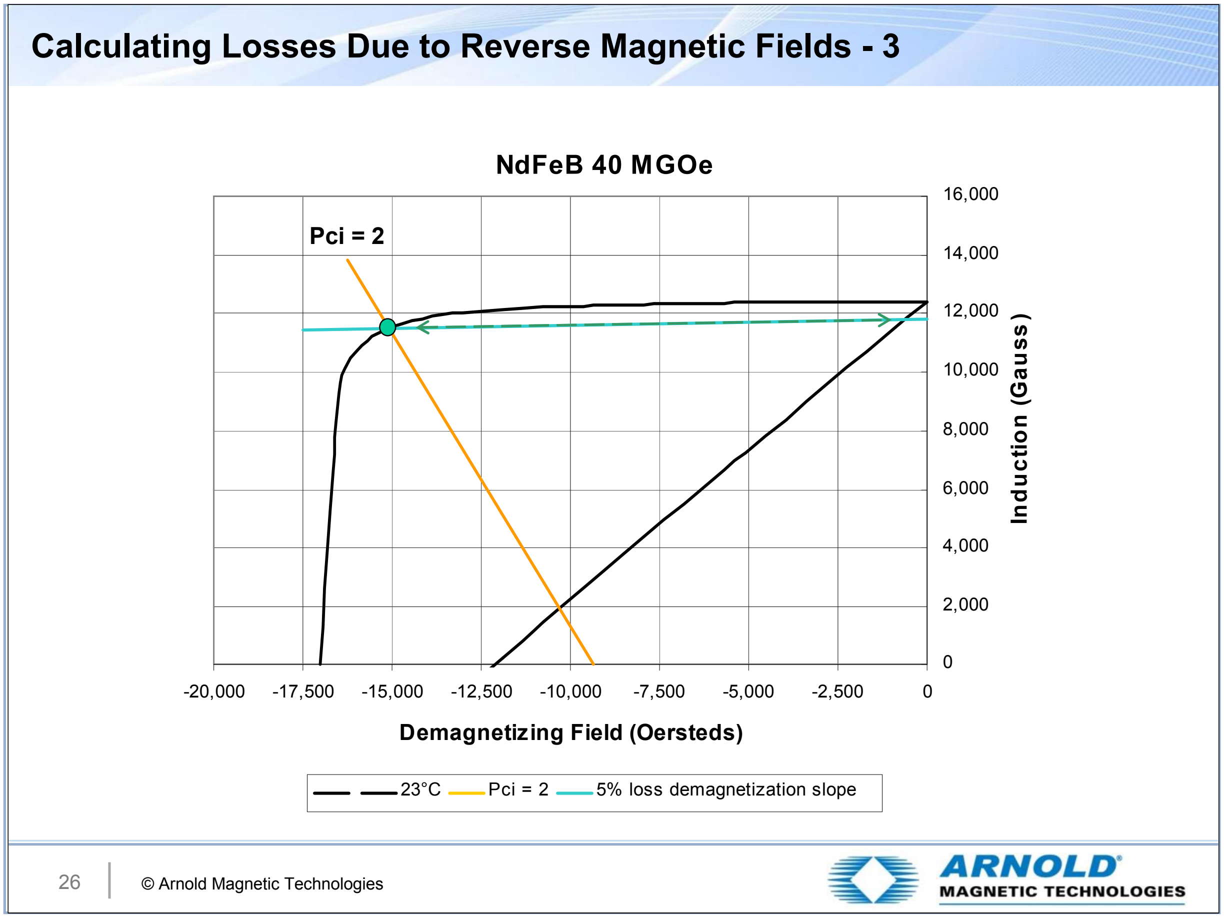
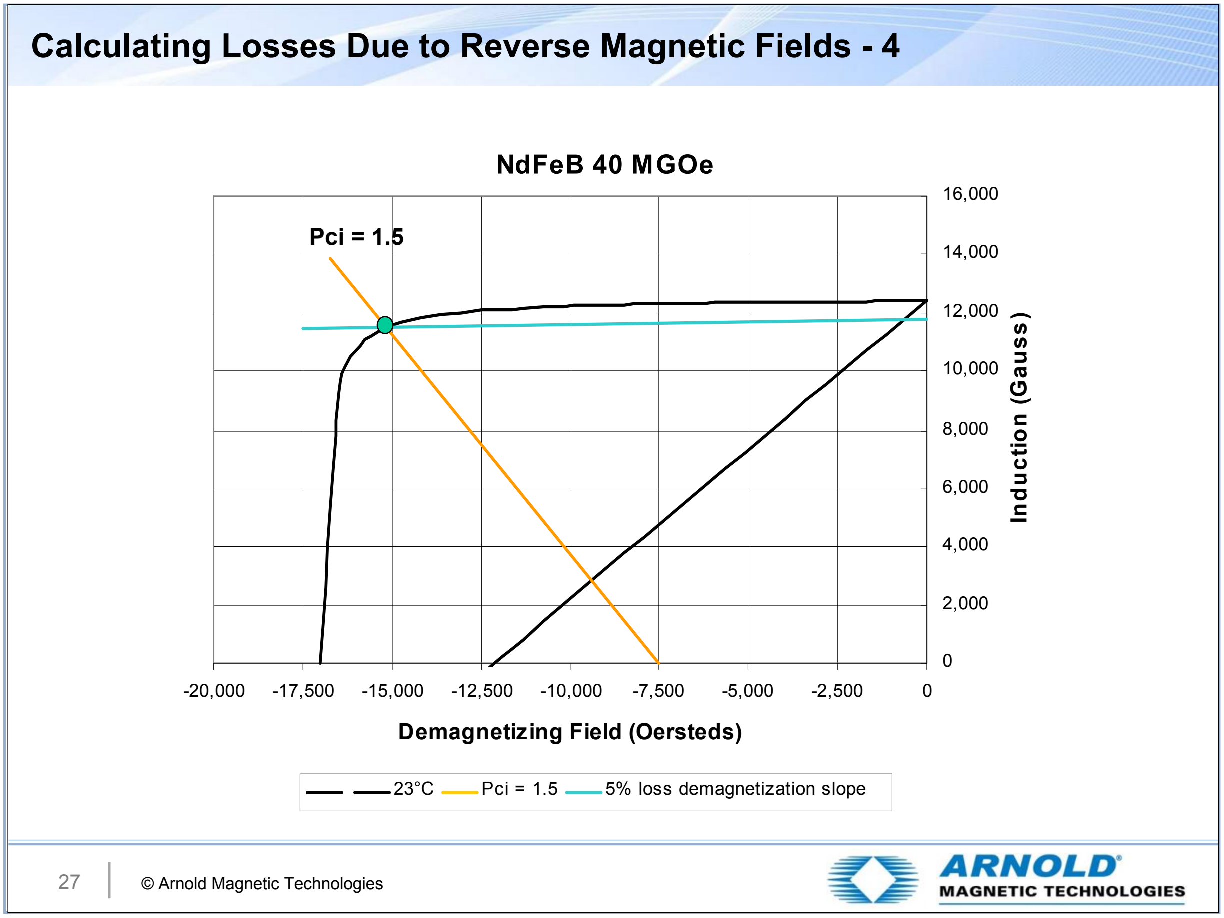
- To demonstrate this, the illustration shows both the Pc and Pci lines with the reverse field applied.
- Note how different the Hd values would be for the appropriate intersections if one looked at the Pc line instead of the Pci line.
- Using the intersection of the Intrinsic curve and the Pci slope, one obtains the magnetization of the magnet under the reverse applied field. Adding the Bdi and Hd values results in Bd under the influence of the reverse field (Bd=Bdi + Hd; remember that Hd is negative in the second quadrant).
- The Recoil Permeability of this material is 1.04. The Intrinsic Recoil Permeability is 0.04 (i.e., $\mu_r - 1$).
- The Bdi value at the intersection of the Pci=2 and the Intrinsic curve is 12050 and ocurs at Hd= 11,330 Oersteds. Applying the intrinsic recoil slope to the Bdi value will result in a reduced Br' of 12,503 Gauss (12,050 + 0.04 x 11,330 Oe). This is only a 0.18% loss compared to the original Br of 12,525.



Calculating Losses Due to Reverse Magnetic Fields - 3

- In order to prevent this demagnetization, one may choose to pre-stabilize the magnet by inducing a loss of 5-10% prior to use. This is shown here.
- In this case, a pre-stabilization of approximately 5% is sought and may be graphically shown by starting a line at the B axis with a value of 95% of Br and drawing it left until it intersects the Intrinsic curve. The line should be drawn with a slope equal to the Intrinsic Recoil (0.04).
- The point of intersection with the Intrinsic curve is at a Bdi which will continue to be observed until or unless a stronger demagnetizing stress is applied.
- The magnet will operate along the recoil line, shown with arrows, until the intersection point at which time it will follow the Intrinsic curve.
- It can be noted that for a Pci = 2, the reverse applied field to stabilize at this level is 9,300 Oersteds.



Calculating Losses Due to Reverse Magnetic Fields - 4

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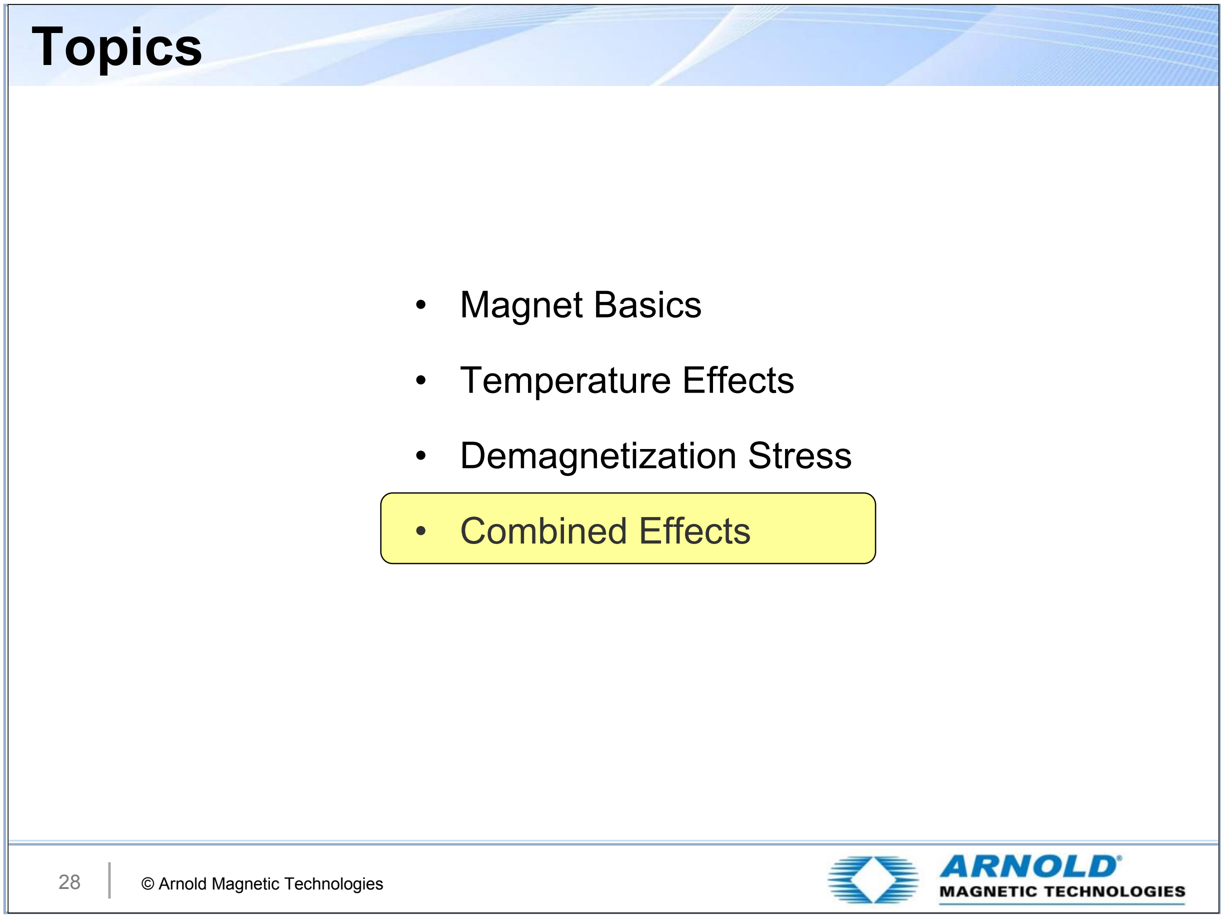
- If the Pci is reduced to 1.5, then the magnitude of the reverse field that may be applied without de-magnetization is less.
- This can be seen by plotting a new line from the intersection of the 5% stabilization curve with the original intrinsic curve but using a slope of 1.5 and noting the intersection with the H axis.
- The intersection is now shows a maximum allowable reverse magnetic field 7,500 Oersteds.



Topics

- Magnet Basics
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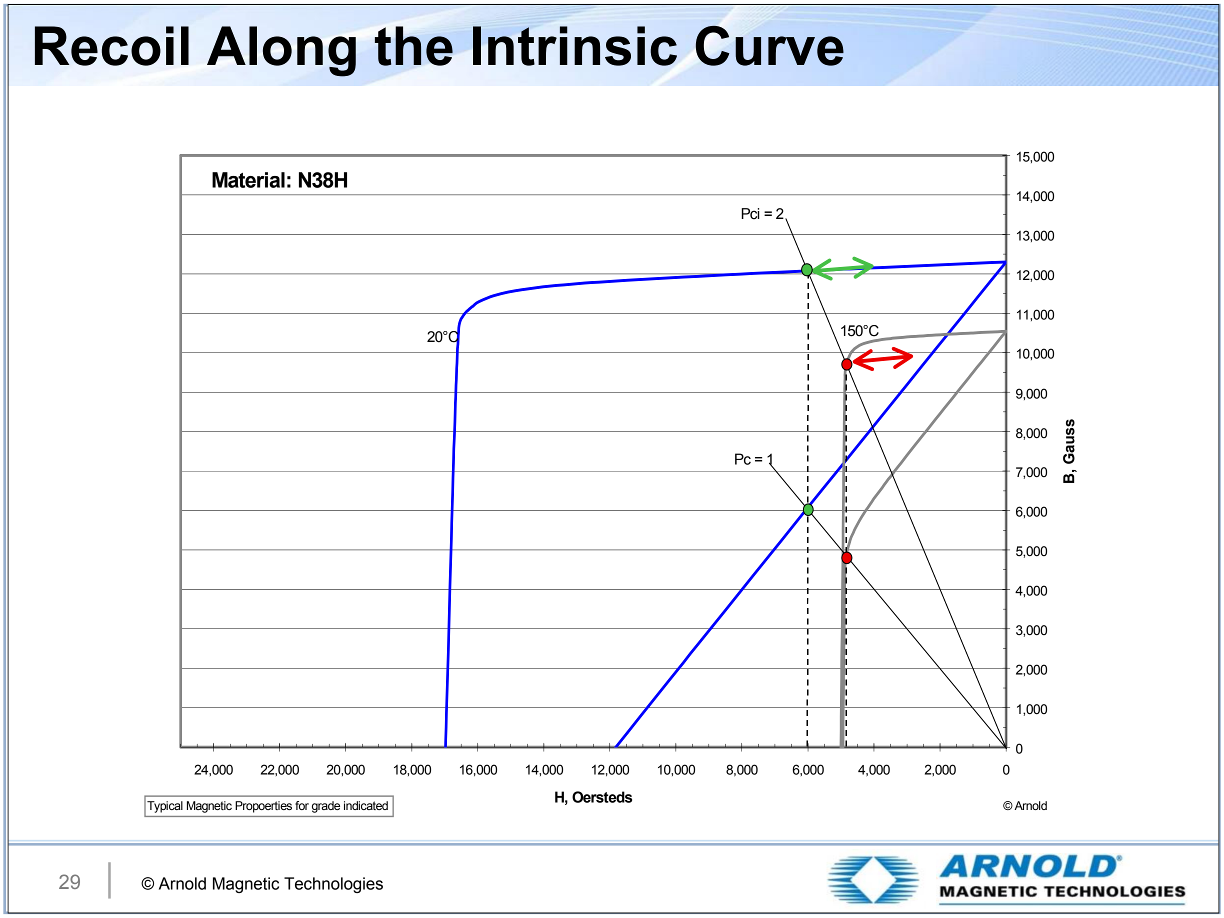
- Combined Effects



Recoil Along the Intrinsic Curve

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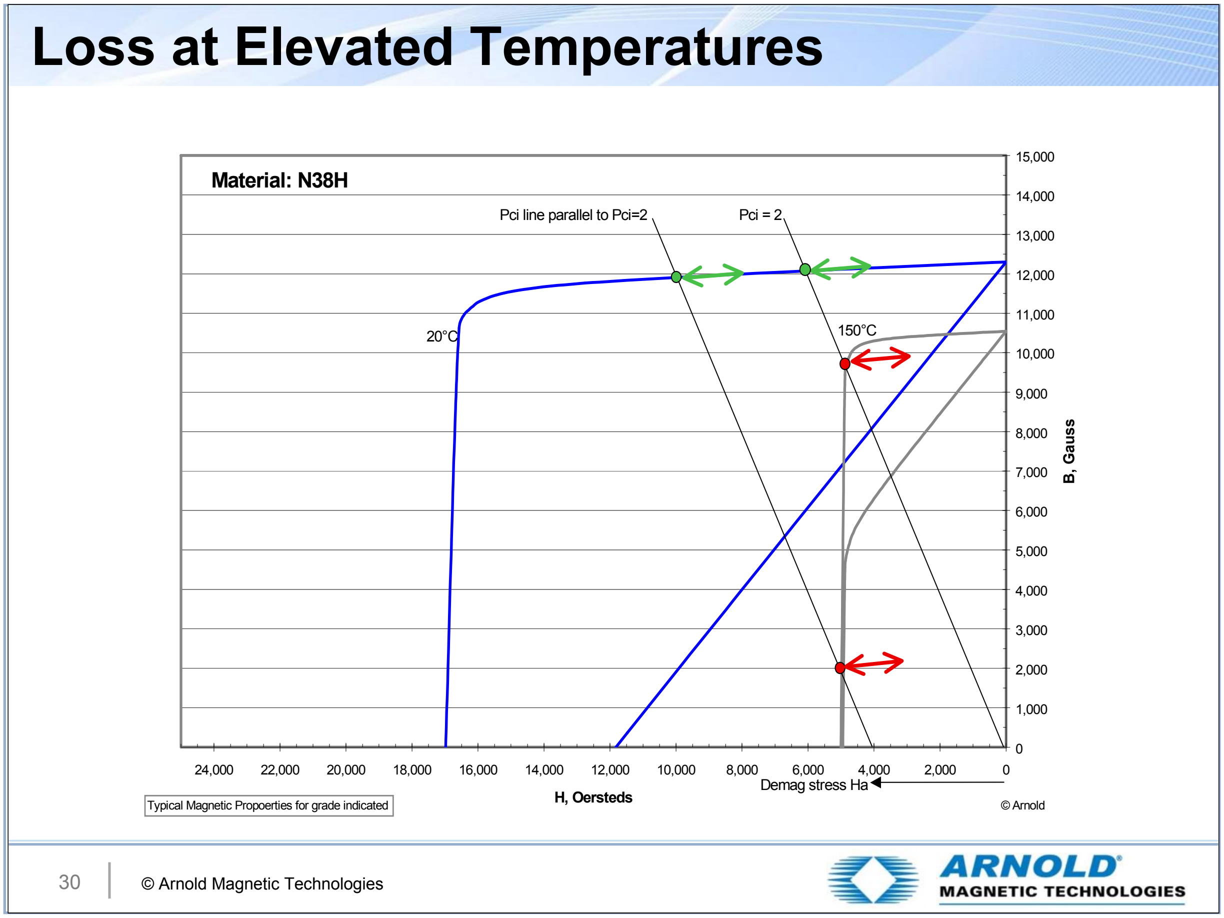
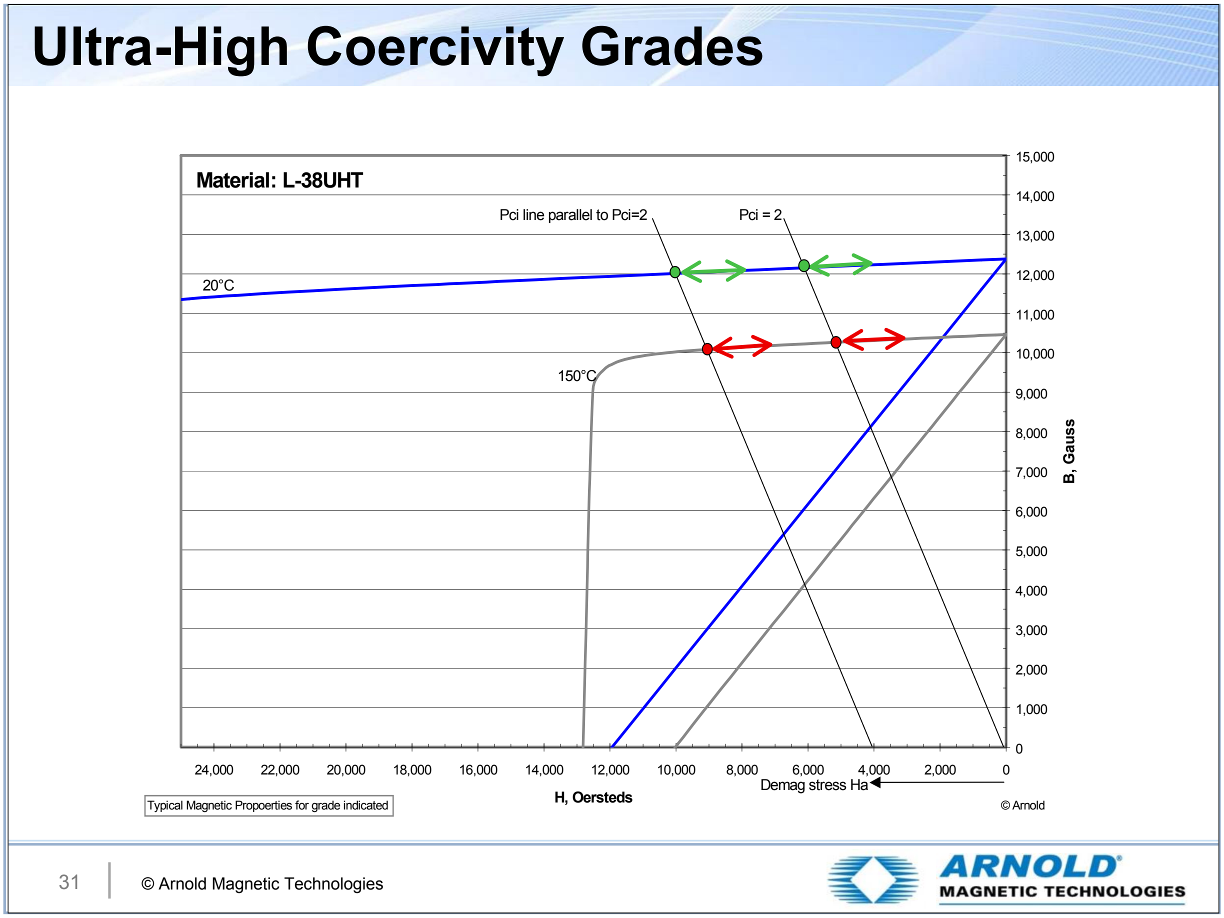
- Let us look again at NdFeB curves for 20 and 150 degrees and showing a Pc line = 1 and Pci line equal to 2.



Loss at Elevated Temperatures

- When a reverse magnetic field is applied, we can now only refer to the Pci line.
- A new Pci line of the same slope is drawn originating along the H axis at the magnitude of the applied field. The field shown here is 4,000 Oersteds.
- At 20 degrees, both the original Pci line and the line drawn showing the demag stress intersect the Intrinsic curve in a region where very low loss in magnetization would be expected (<1%).
- However, the 150 degree Intrinsic curve, with greatly reduced Hci, provides intersection points showing substantial loss with and without a reverse field applied - - though much greater with the reverse field.
- To overcome this shortcoming, either the design must be modified to operate at a higher Load Line or a material with higher Hci must be used.



Ultra-High Coercivity Grades

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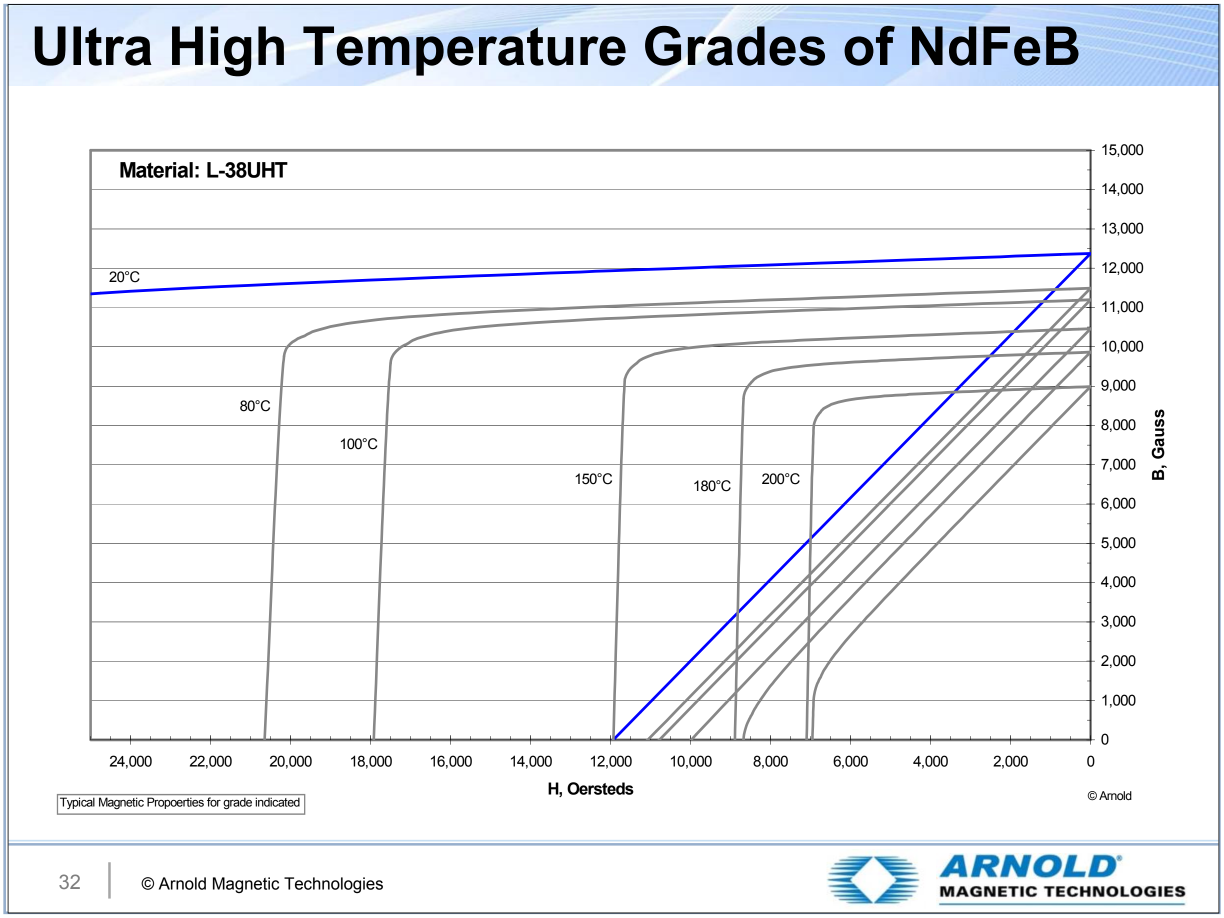
- This is an example of an Ultra-High (“UH”) coercivity NdFeB, L-38UHT from Ningbo Yunsheng.
- Even at temperatures above 150 degrees, the Operating point is along the flat region of the Intrinsic curve.



Ultra High Temperature Grades of NdFeB

- This shows test results on the L-38UHT material from 20 to 200 degrees. (This grade is rated to 180 degrees, but appears capable of performing at higher temperatures).

Summary

- Irreversible Loss of magnetization can result from either or both: elevated temperatures and reverse magnetic fields
- Other factors affecting resistance to this loss include the Operating Point (Pc and Pci) and the material Hci (at operating temperature)
- All 2nd Quadrant curves shown here are typical for “square loop” material. Irregularities in the curves can have a profound influence on performance
- Higher performance magnet grades are becoming available to allow successful application in motors at use temperatures over 150 degrees C