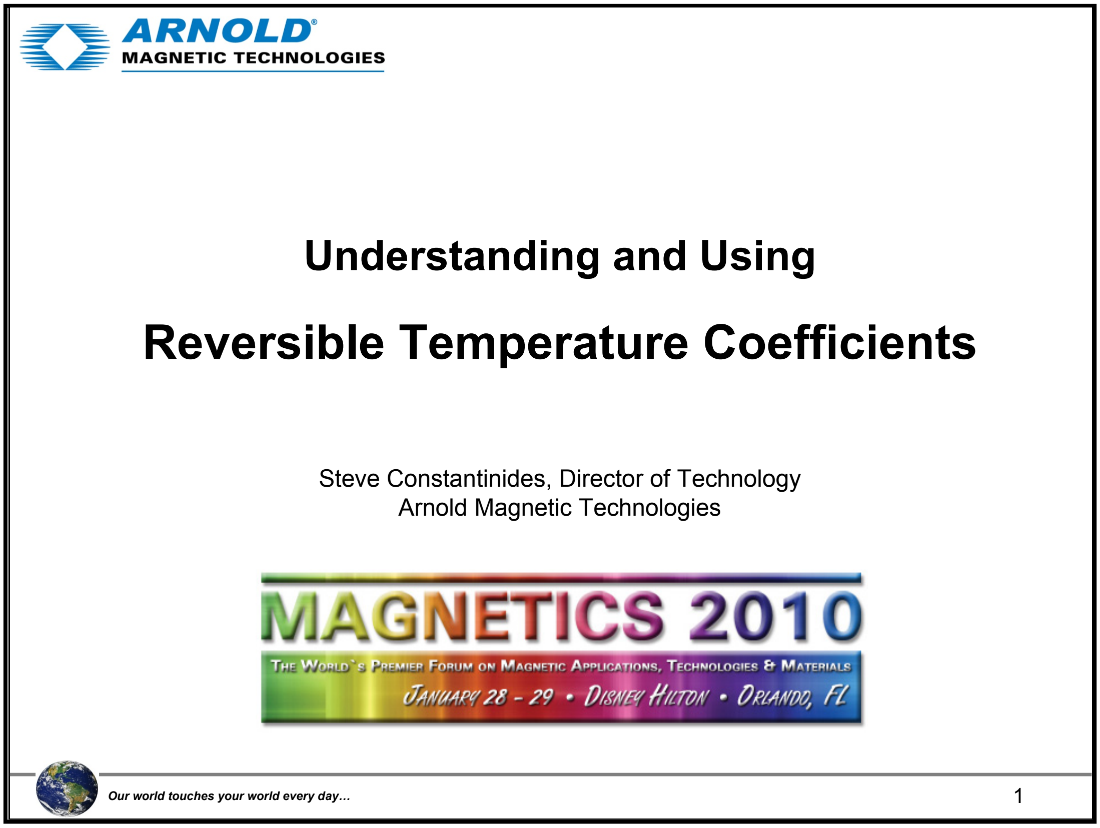

- Users of permanent magnets are often challenged to design systems for use at high (or low) temperatures or over a wide temperature range.

- Magnetic properties change with temperature posing a design challenge.

- Understanding how the properties change is requisite for sound design.

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Agenda

- Magnet terminology
- What are Reversible Temperature Coefficients?
- How are they measured / calculated?
- Do they tell the whole story?
- Irreversible Loss (Design Issues)
- Summary

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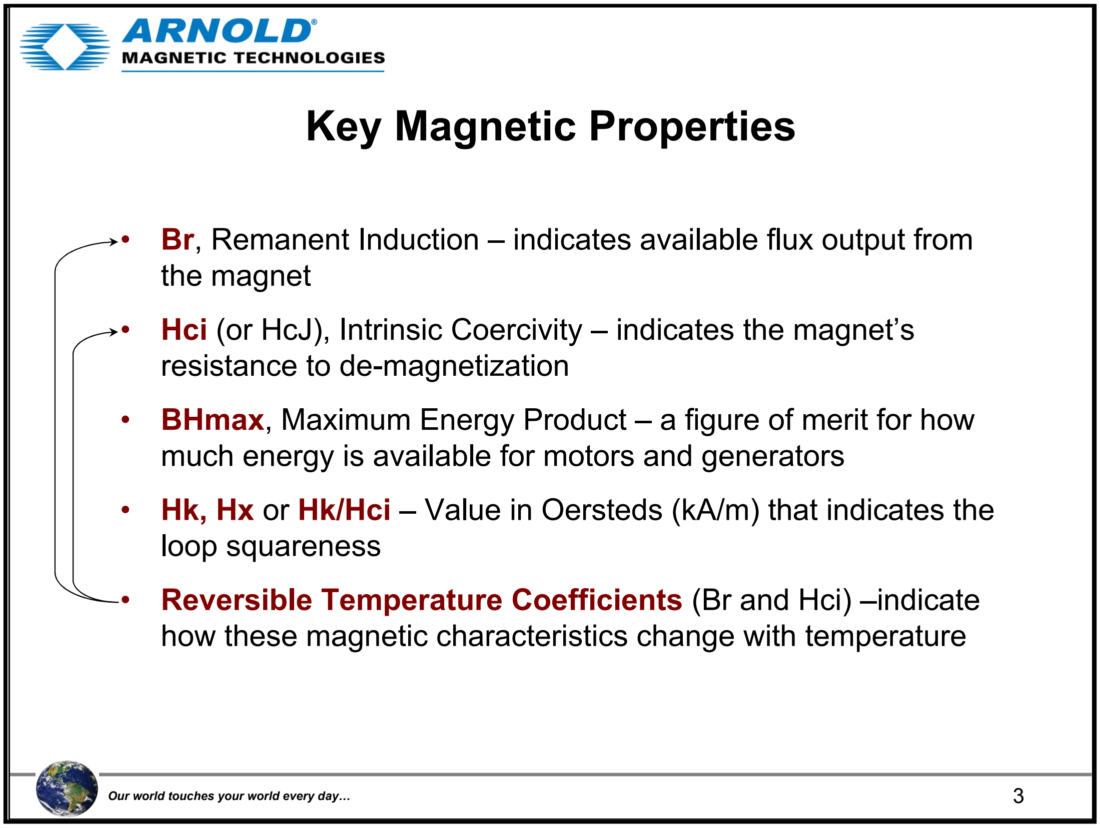
- These subjects will be covered



- The first characteristic specified for motor applications is usually the energy product as that directly affects device size and performance.
- Secondly, the intrinsic coercivity is specified to be high enough to survive both elevated temperature and demagnetizing stress.
- These key properties are used most often to gauge magnetic "quality".
- The Reversible Temperature Coefficients manifest themselves in the modified hysteresis loop away from room temperature.

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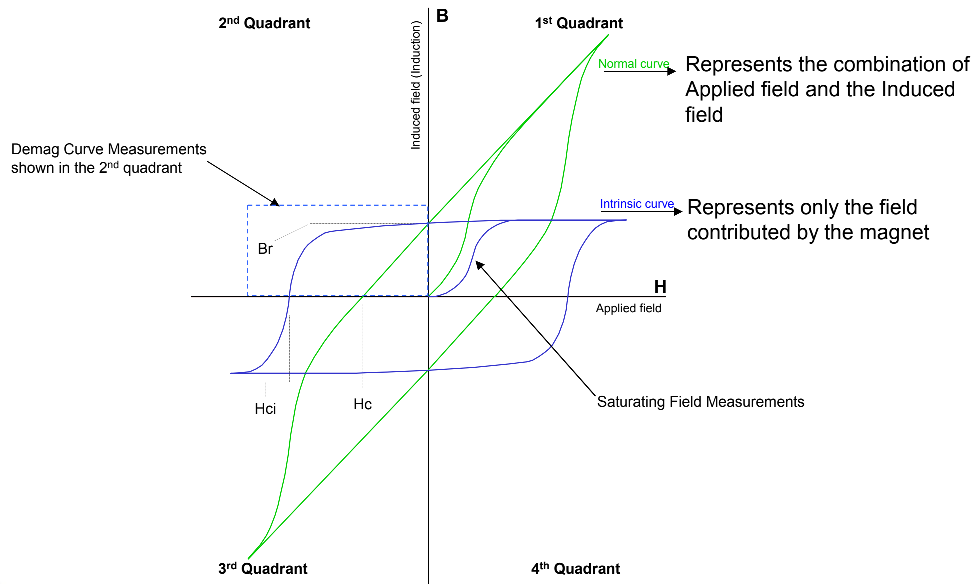
Magnet Terminology –The Hysteresis Loop



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- What each of these key properties represents can be seen by examining a typical permanent magnet hysteresis loop.
- The loop shape is made by comparing an applied field (electromagnetic) to the induced field (in the magnet). The horizontal axis (“H” axis) represents the magnitude of the applied field. The vertical (“B”) axis represents the measured induced field in the magnet.
- The Normal (green) curve is the plot of H versus B, where B is the sum of the applied field and the field contributed by the magnet.
- The blue Intrinsic curve is obtained by subtracting the magnitude of the applied field (H) from the B curve, thus leaving only the field contributed by the magnet. This curve is called the “B-H” or Intrinsic curve.

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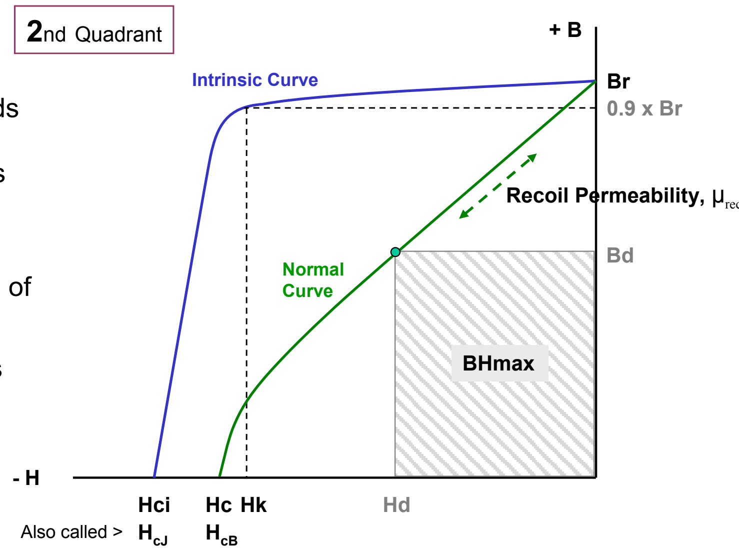
Review of the Hysteresis Loop

- Resistance to de-magnetization depends upon good loop squareness as well as high Hci
- Squareness is measured as the ratio of Hk to Hci (Hk/Hci)
- Product specifications will often include a minimum Hk value



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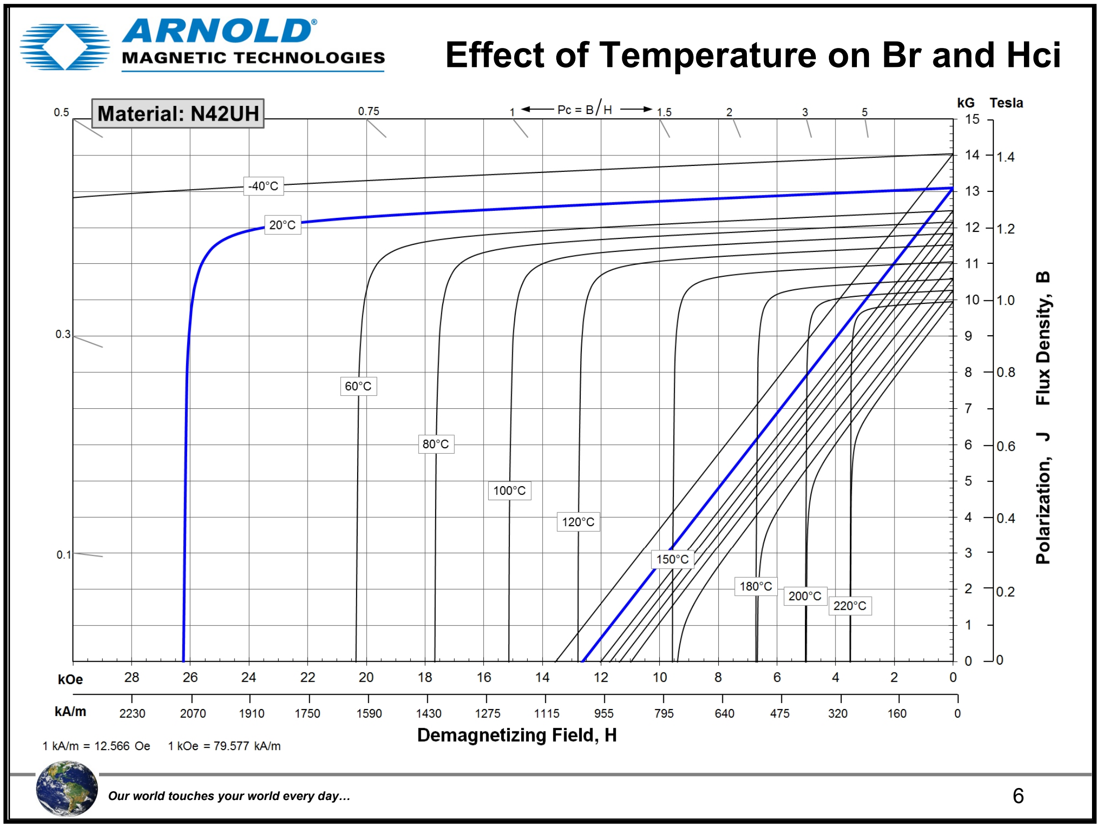
- The value of Br (remanence or remanant induction) is proportional to how strong a magnet will “stick” to a block of steel - - what we think of as the magnetic strength of the magnet.

- The value of Hci (or Hcj) represents the magnet’s resistance to demagnetization.

- Hk is an artificial construct to indicate the shape of the intrinsic curve. It is generated by making a horizontal line at the level of 0.9 x Br. Where this line intersects the intrinsic curve, a vertical is dropped to the H axis creating the Hk point.

- Hk/Hci is a measure of loop squareness. Poor loop squareness represents a potential for partial knockdown in the presence of moderate demagnetizing stress, with elevated temperature, or with both.

- Some users specify Hk in addition to Hci to ensure satisfactory magnet performance at elevated temperature.



- This is an example of a product sheet showing the affect of temperature on magnetic properties for a 35 MGOe grade of neo magnet.

- The room temperature plot uses nominal Br and specified minimum Hci.

- N35EH is specified to have a minimum Hci of 30,000 oersteds (2390 kA/m).

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- What are Reversible Temperature Coefficients?

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Reversible Temperature Coefficients

- Reversible Temperature Coefficient of Induction
  - Is a measure for the average of the change in Br as a function of temperature
  - Is often referred to as α (Greek letter alpha)
  - The IEC proposes naming it "α (B_r)"
- Reversible Temperature Coefficient of Coercivity
  - Is a measure for the average of the change in Hci as a function of temperature
  - Is often referred to as β (Greek letter beta)
  - The IEC proposes naming it "α (H_{cJ})"
- Expressed as % change per ºC (or K or ºF)
- These are average values over a specified temperature range

- There are two coefficients in common use: one for changes in Induction and one for changes in (intrinsic) coercivity.
- For our purposes today, let's agree to refer to the reversible temperature coefficients as "RTC" of Br and "RTC" of Hci.
- These are average rates of change over a specified temperature range.

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- How are these measured and calculated?

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Measuring the Coefficients

- Alternative 1:
  - Measure demag curve at both the lower and the higher temperatures for the temperature range of interest
  - Calculate the average change in property per ºC
- Alternative 2 (for improved accuracy):
  - Make numerous measurements at several temperatures between the lower and upper desired limits
  - Perform regression analysis on the data
  - Calculate the Br and the Hci values for the lower and upper limits of the range over which the values will be reported
  - Calculate the average change in property per ºC for that range

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- The simpler method is to measure magnet samples at the lower and higher temperatures and then calculate the average rate of change in Induction and Coercivity.

- With many measurements and use of regression analysis, values of Br and Hci can be calculated for any temperature within the measured range.

- Calculating Br and Hci outside the measured range can be done, but becomes risky the farther one goes outside the measured range - - a second (or third) order polynomial is likely to fit the data over a limited range only.

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The (Simple) Calculation of
Reversible Temperature Coefficients

RTC = Reversible Temperature Coefficient

“20” is the low or room temperature

“T” is the elevated temperature

Values are multiplied by 100 to create percents

$$RTC_{Br}\ \% = \frac{Br(20) - Br(T)}{Br(20 \cdot (T-20)} \cdot 100$$

$$RTC_{Hci}\ \% = \frac{Hci(20) - Hci(T)}{Hci(20 \cdot (T-20)} \cdot 100$$

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- Per alternative 1 of the previous slide, we use the results from just two temperatures to calculate the RTC’s using these equations.

- Multiplying by 100 provides results in percent.

- If T is measured in ºC, the then results are in %/ºC.

- Other temperature units that are used are ºF and K.

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Applying
Reversible Temperature Coefficients

Formulas to calculate Br or Hci at other than room temperature.

T = Specified temperature ºC

Br_{20} = Br specification for room temperature (~20°C)

Br(T) = Br adjusted for temperature T

Hci_{20} = Hci specification for room temperature (23°C)

Hci(T) = Hci adjusted for temperature T

RTC_{xx} = reversible temperature coefficient with respect to Br or Hci expressed in %/°C

$$Br\,(T) = Br_{20}\left[1 + \frac{RTC_{Br} \bullet (T\text{-}20)}{100}\right]$$

$$Hci\,(T) = Hci_{20}\left[1 + \frac{RTC_{Hci} \bullet (T\text{-}20)}{100}\right]$$

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- When the RTC’s and the room temperature magnetic properties are known, the properties at other temperatures can be estimated by these calculations.
- The results will be only approximate except at the elevated temperature for which the RTC was calculated.

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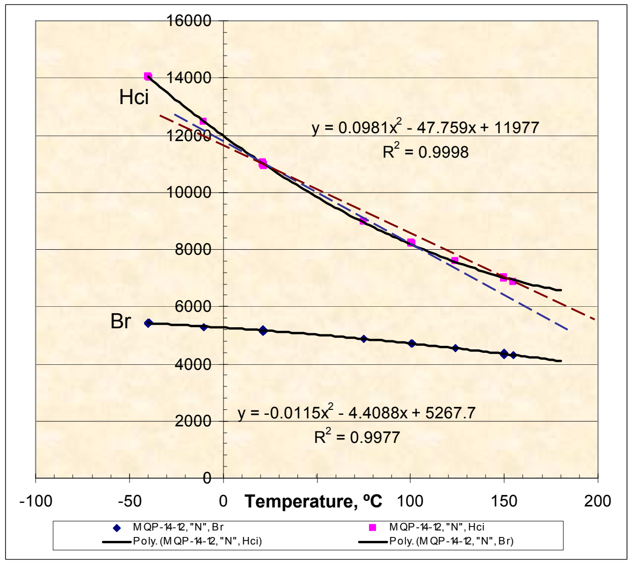
Alternative 2: Measurement & Calculation

- Setting the temperature range over which Beta is calculated is important as can be demonstrated by this illustration.
- The Reversible Temperature Coefficient decreases as the range is expanded from 20 - 100 ºC to 20 - 150 ºC as indicated by the slope of the red dashed line versus the indigo line.
- The actual Beta's are:
  - 20 to 100: -0.325% per ºC
  - 20 to 150: -0.281% per ºC



Material is injection molded MQP-14-12 in PPS

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- An example of the alternative, regression method for more accurate values is shown here.

- Data is charted and regression formula calculated. For ferrite, neodymium and standard grades of SmCo, a second order polynomial has been shown to fit data very well.

- For high temperature grades of SmCo which have a more complex microstructure, a third order polynomial is used and the RTC's must be interpreted with care.

- From this illustration one can see how the same magnet can have two (or more) reversible temperature coefficients of coercivity by merely adjusting the temperature range over which they are calculated.

- Note also that Br changes almost linearly up to about 150 ºC. This is true for Neo, SmCo and Ferrite.

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Reversible Temperature Coefficients: Comparisons

Material	Grade	Temp. Range Min ºC	Temp. Range Max ºC	Max Use ºC	Alpha(α) % / ºC	Beta (β) % / ºC	Tc ºC
Alnico, cast	5	20	100+	520	-0.02	-0.01	900
Alnico, cast	8	20	100+	520	-0.02	-0.01	860
Sm_2Co_{17}	27 MGOe	20	120	350	-0.035	-0.20	810
$SmCo_5$	20 MGOe	20	120	250	-0.04	-0.40	700
NdFeB, bonded	MQP-A, -O	20	100	110, 140	-0.13	-0.40	310
NdFeB, bonded	MQP-B	20	100	110	-0.11	-0.40	360
NdFeB, bonded	MQP-C, D	20	100	125, 110	-0.07	-0.40	470
NdFeB, sintered	L-38UHT	20	180	180	-0.10	-0.50	350
NdFeB, sintered	N38UJ	20	180	180	-0.12	-0.55	310
NdFeB, sintered	N48M	20	100	100	-0.12	-0.65	310
Ferrite, sintered	C-5, -8	20	120	250	-0.20	0.27	450

Typical values. Temperature range of the coefficients is 20 to "Max ºC".
Listed in order of increasingly negative Beta, except for Ferrite; values in %/ºC.
Alnico suppliers almost never supply the temperature range for the Coefficient Measurements.
Increases in Curie Temperature are mostly due to the presence of cobalt.

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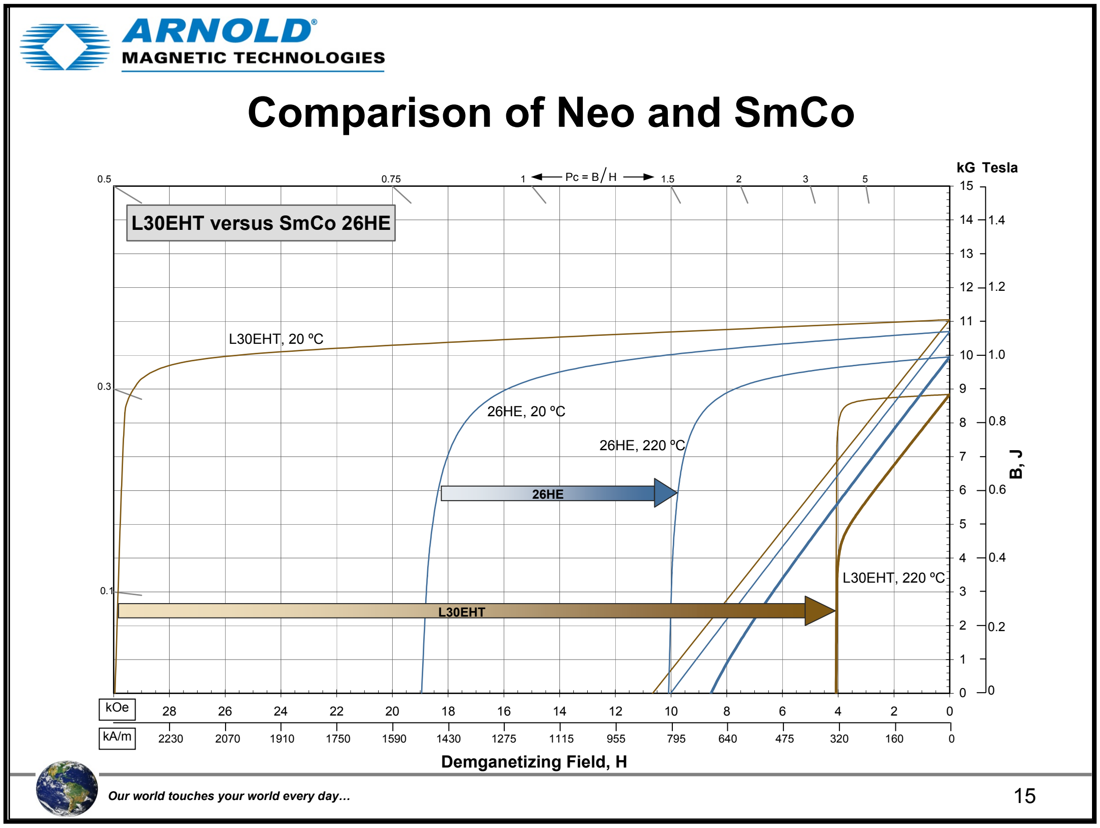
- Alpha and beta (RTC) values for common magnet materials are listed here in order of increasing Beta – with the exception of Ferrite which has a positive value of beta.

- Ferrite magnets are ferri-magnetic (instead of ferro-magnetic) and exhibit a positive change in beta with temperature. This makes them resistant to demagnetization at high temperatures, but limits their low temperature use to about -40 ºC (-40 ºF).

- Incidentally, the large RTC of Br for ferrite suggests a maximum practical use temperature of between 150 and 200 ºC even though they are physically capable of being used to temperatures over 250 ºC.



• This is an example of why RTC's are so important.

• Due to the differences in RTC's, even the best Neo is not up to the performance of SmCo at elevated temperatures.

• The transition range where SmCo begins to outperform Neo is about 150 °C.

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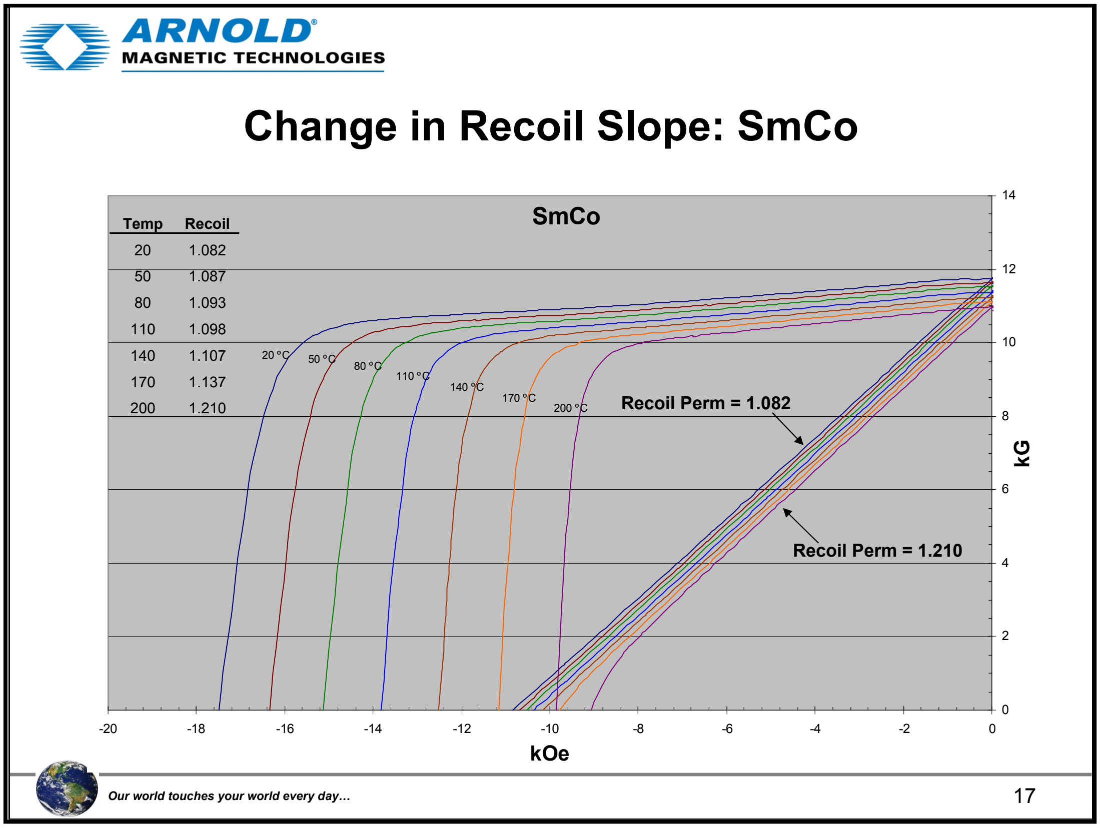
- We've learned what Reversible Temperature Coefficients are and how they are measured / calculated.
- And we can see that they are every bit as important as the more frequently specified magnetic characteristics, for example energy product.
- Are the characteristics defined so far adequate for engineering magnetic systems?
- Let's examine demagnetization curves in a bit more detail.



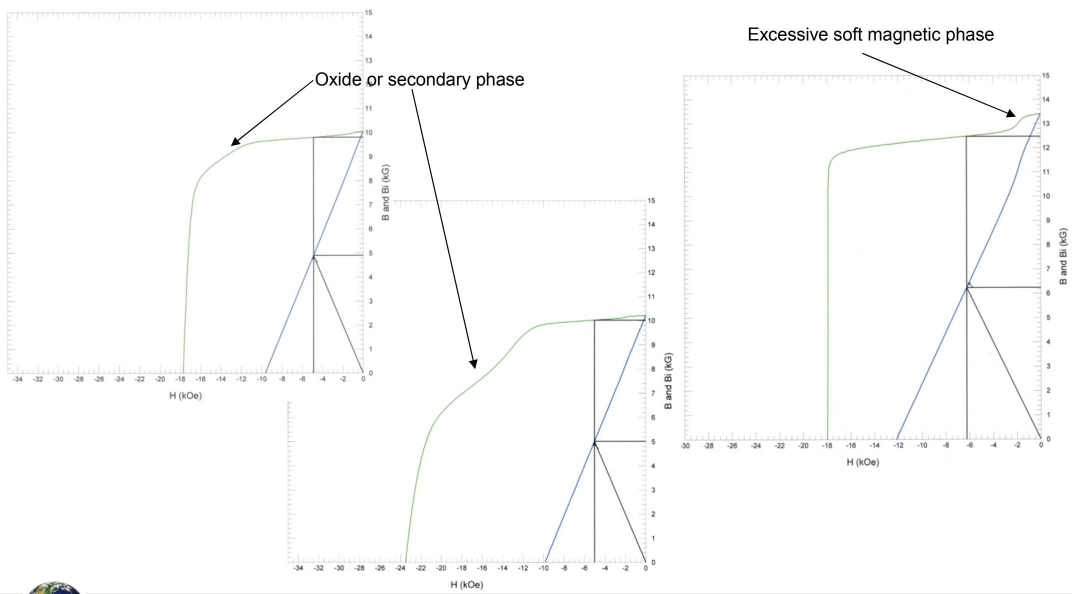
- In addition to the change in values of Br and Hci, the demag curve undergoes some subtle changes.

- One of these is a change to the recoil slope.

- The recoil slope for the SmCo sample shown here varies between 1.082 at room temperature up to 1.210 at 200 ºC.

- Each material's slope changes, but not all to the same extent.

Imperfect Neo Hysteresis Loop Shapes



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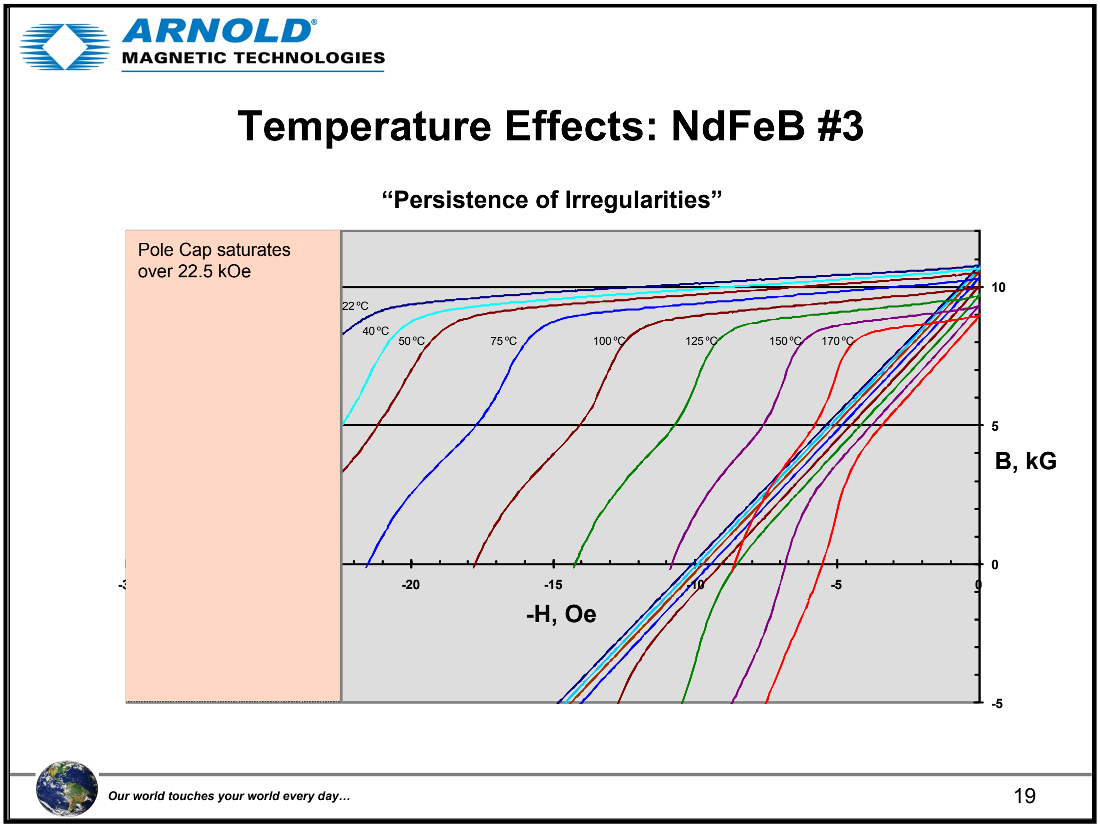
- Early imports of neo manufactured in China exhibited problems with uniformity of properties.
- Some of the problems were due to the presence of secondary phases such as neo-oxide or the presence of soft phases such as from excessive neo-rich or alpha-iron phases in the grain boundaries.
- Properties of Br and Hci at room temperature might well be in specification, but the displaced knee in the curve will cause premature magnetic knockdown.
- Whatever the cause for the discontinuity in the curve, a question exists: Even if the material has adequate properties (of Br and Hci) at room temperature, how will the curve change as a function of temperature?



- This chart shows a series of curves between 22 and 170 ºC. It's also been plotted to show part of the 3rd quadrant (to -5 kG).

- It's an extreme example for illustration with a marked step to the curve which persists over the entire temperature range.

- The pole caps of the hysteresigraph saturate at ~22,500 oersteds applied field, so curve shape in the tan shaded area (at the left of the chart) must be considered imprecise.

- However, Hci values will be approximately correct.

- Of interest is: Will the Hk value - location of the knee of the intrinsic curve where irreversible demagnetization starts - vary differently than the change in Hci? Can we predict the Hk value as a function of temperature?

- When measured at or near room temperature, can one predict the high temperature curve shape?

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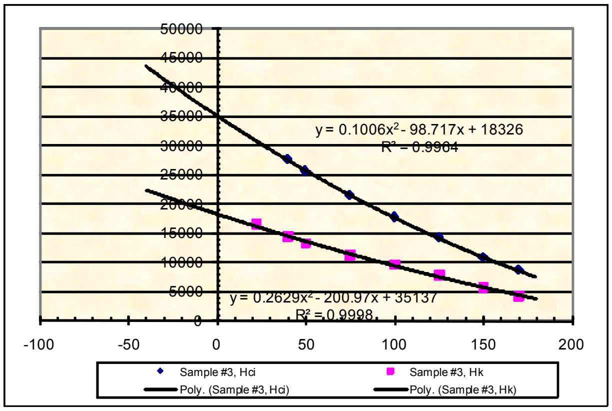
Comparison on Hci and Hk

N30EH



Average Temperature Coefficients				
Coefficients Calc		Sample #3		
From	To	Br	Hci	Hk
-40	100	-0.068%	-0.425%	-0.428%
20	100	-0.089%	-0.543%	-0.548%
20	150	-0.105%	-0.501%	-0.504%
20	180	-0.115%	-0.475%	-0.478%
20	200	-0.121%	-0.458%	-0.460%

Similar values

- In this case, the answer is yes.
- We see that the RTC's of Hk are very close to those of Hci regardless of temperature range specified.
- Of course, one would not wish to have material with such a curve shape.

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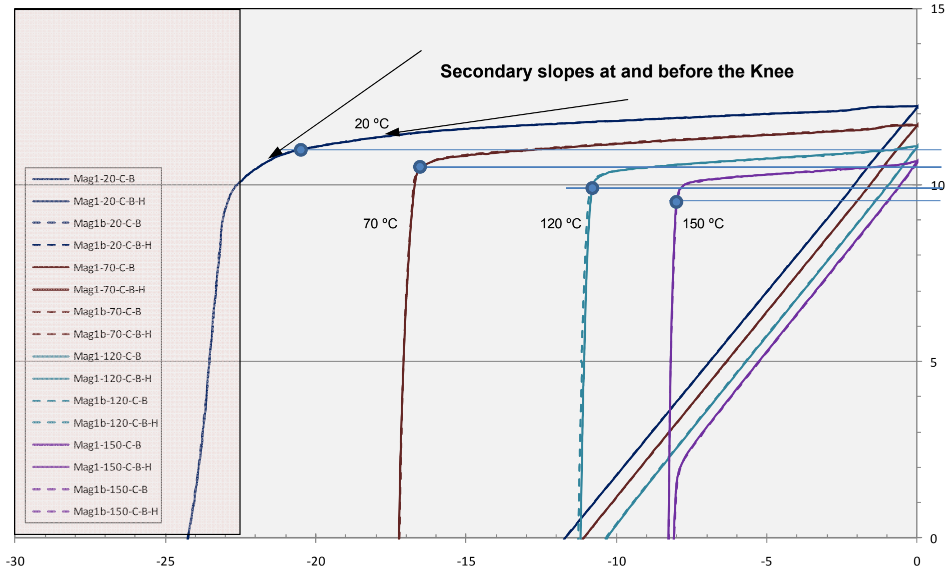
Temperature Effects: NdFeB #3



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- In a second example, this neo has a nearly "perfect" curve shape.
- There is just a slight irregularity around the knee: two "secondary" slopes are seen in the chart identified by the added straight lines.
- Hk intersection points have been created to show that these points intersect the intrinsic curve at varying locations along the curves: At room temperature it is above the knee and at the highest temperature, the intersection point is below the knee of the curve.
- This magnet was measured twice. One set of data is plotted as a solid line; the second is plotted as a dashed line.
- With this repeatability, there can be little question of the uniqueness of the curves.
- As before, can we estimate the Hk and elevated temperature performance from the curve data? Are the RTC's of Hk similar to those of Hci?

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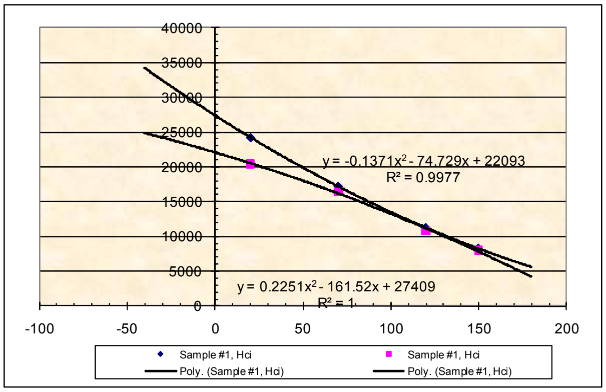
Comparison on Hci and Hk

N35SH



Average Temperature Coefficients				
Coefficients Calc		**Mag-1**		
From	**To**	Br	Hci	Hk
-40	100	-0.032%	-0.204%	-0.207%
20	100	-0.034%	-0.237%	-0.234%
20	150	-0.036%	-0.241%	-0.232%
20	180	-0.036%	-0.243%	-0.231%
20	200	-0.037%	-0.245%	-0.230%

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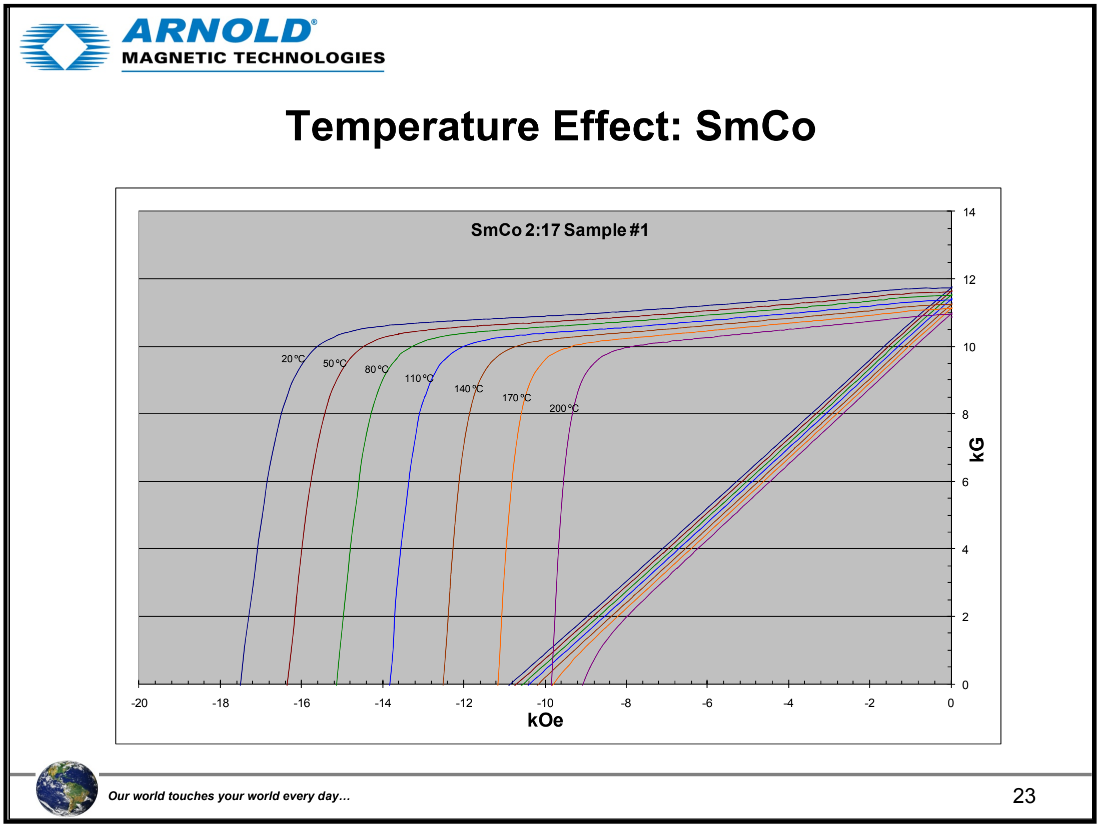
- Unlike the first example, the Hk intersection point moves around the knee of the intrinsic curve and in so doing, its calculated coefficients are measurably different from those of Hci.

- We must conclude that RTC's for the current defined Hk's are a more complex calculation than that of Hci.



- What about SmCo? Can one calculate the Hk values at various temperatures using the RTC of Hci?

- In this example we use a well-mannered sample…

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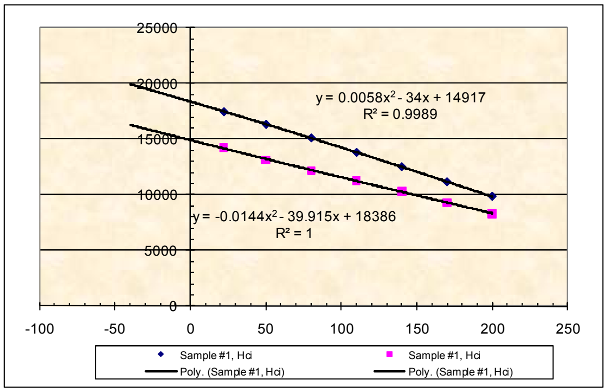
Comparison on Hci and Hk

SmCo 2:17



Average Temperature Coefficients				
Coefficients Calc		SmCo 2:17 #1		
From	**To**	Br	Hci	Hk
-40	100	-0.032%	-0.204%	-0.207%
20	100	-0.034%	-0.237%	-0.234%
20	150	-0.036%	-0.241%	-0.232%
20	180	-0.036%	-0.243%	-0.231%
20	200	-0.037%	-0.245%	-0.230%

Dissimilar values

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- As with one of the previous neo sample, the Hk changes differently than Hci as shown both in the shapes of the curves in the chart and in the tabulated values of RTC for Hci and Hk.

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What have we learned?

- While measurements and calculations can be made for establishing Br and Hci at a range of temperatures, these values and the resulting calculations are not always adequate for predicting behavior.
- Rollin Parker states it thus:

"The temperature coefficients of magnetization and coercive force in many instances do not give enough information about how a magnet will respond to temperature change. In many magnets the demagnetization curve is not well defined by Br and Hci. Changes in the curve shape and the intersection with load lines can only be seen from a complete set of demagnetization curves measured at several temperatures over the temperature range of interest."

Rollin J. Parker, *Advances in Permanent Magnetism*, John Wiley & Sons, 1990, p. 111

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- While RTC's are useful for estimating both elevated and lower temperature magnetic characteristics (Br and Hci), they must be used with care.

- Wherever necessary, request a set of actual curves.

- But please recognize that these curves take considerable time to generate and only represent the magnet that was tested.

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Summary

- RTC's can effectively and accurately be measured
- The resulting values are for a limited sample set and should only be considered (closely) approximate for batches of material
- RTC's do not predict curve shape
- Curve shape has a significant affect upon performance
- We should pay strict attention to magnetic loop shapes as to their affect on device performance

Summary - 2

- RTC's are not linear - - temperature range of the specified value must be provided
- Demagnetization curve shape undergoes only minor changes
  - Standard magnetic materials
  - Over limited temperature ranges
- Hk as currently defined is not adequate for producing an RTC of Hk characteristic

References

- Advances in Permanent Magnetism, Rollin J. Parker, John Wiley & Sons, 1990
- Applications of Magnetism, J.K. Watson, Storter Printing, 1985
- Ceramic Permanent Magnet Motors, James R. Ireland, McGraw-Hill, 1968
- Ferromagnetism, Richard M. Bozorth, IEEE Press, 1993
- Measurement and Characterization of Magnetic Materials, Fausto Fiorillo, Elsevier Academic Press, 2004
- Permanent Magnets and Their Application, Rollin J. Parket, Robert J. Studders, John Wiley & Sons, 1962, pps 343-350
- Physics of magnetism and magnetic materials, K. H. J. Buschow, Frank R. Boer, Springer, 2003

The subject of Reversible Temperature Coefficients is rarely covered in reference texts.