# Permanent Magnets for Energy Applications Part 1

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Spontaneous Materials


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# Permanent Magnets for Energy Applications Part 1

- Perspective
- Things we already knew
  - Poles
  - Living on a magnet
  - Viewing magnetic fields
- Magnetic Theory
  - Hysteresis
  - Three vectors
  - Units and Conversions
- Materials
- Processing
- Dysprosium
- Magnequench process
- Self-demagnetization
- Magnetizing

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# Perspective

**The Blind Men and The Elephant**
John Godfrey Saxe's (1816-1887)

It was six men of Indostan,
To learning much inclined,
Who went to see the Elephant
(Though all of them were blind),
That each by observation
Might satisfy his mind.

The *First* approach'd the Elephant,
And happening to fall
Against his broad and sturdy side,
At once began to bawl:
"God bless me! but the Elephant
Is very like a wall!"

The *Second*, feeling of the tusk,
Cried, -"Ho! what have we here
So very round and smooth and sharp?
To me 'tis mighty clear,
This wonder of an Elephant
Is very like a spear!"

The *Third* approach'd the animal,
And happening to take
The squirming trunk within his hands,
Thus boldly up and spake:
"I see," -quoth he- "the Elephant
Is very like a snake!"

The *Fourth* reached out an eager hand,
And felt about the knee:
"What most this wondrous beast is like
Is mighty plain," -quoth he,-
"'Tis clear enough the Elephant
Is very like a tree!"

The *Fifth*, who chanced to touch the ear,
Said- "E'en the blindest man
Can tell what this resembles most;
Deny the fact who can,
This marvel of an Elephant
Is very like a fan!"

The *Sixth* no sooner had begun
About the beast to grope,
Then, seizing on the swinging tail
That fell within his scope,
"I see," -quoth he,- "the Elephant
Is very like a rope!"

And so these men of Indostan
Disputed loud and long,
Each in his own opinion
Exceeding stiff and strong,
Though each was partly in the right,
And all were in the wrong!

MORAL,

So, oft in theologic wars
The disputants, I ween,
Rail on in utter ignorance
Of what each other mean;
*And prate about an Elephant*
*Not one of them has seen!*

This version of the famous Indian legend, published in 1878 in Linton's "Poetry of America" and can be found via Google Book Search. Linton, William James, (1878) "Poetry of America: Selections from one hundred American poets from 1776 to 1876." pages 150-152.

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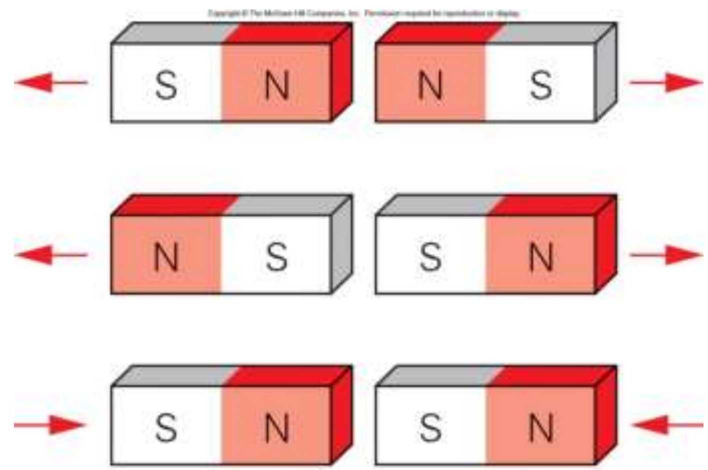
# Magnets Have Poles




Source: Griffith

- We call them North pole and South Pole
- Like poles repel; opposite poles attract
- A magnet has both a North and a South pole, regardless of size! No single poles.

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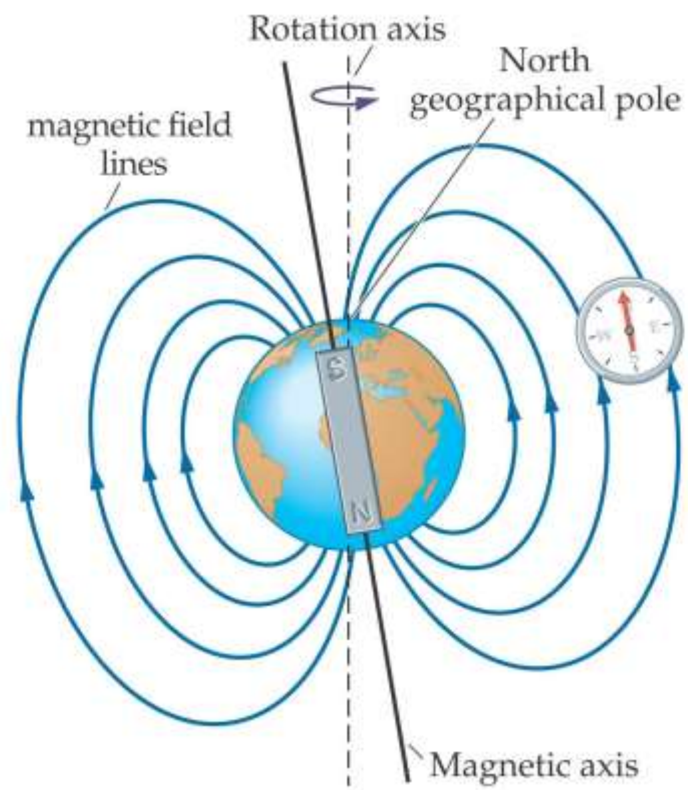
# The Earth is a Magnet

- Our tiny magnetic field
  - 100,000 times smaller than an MRI magnet
- Magnetic poles and geographic poles
  - Nearly the same location
  - The magnetic poles move
- A compass points North
  - A North seeking pole
- Notice the polarity of the Earth!




Source: Walker

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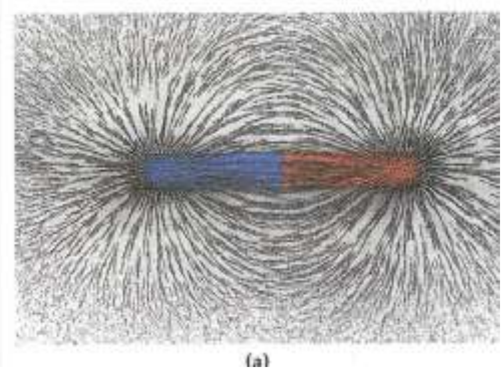
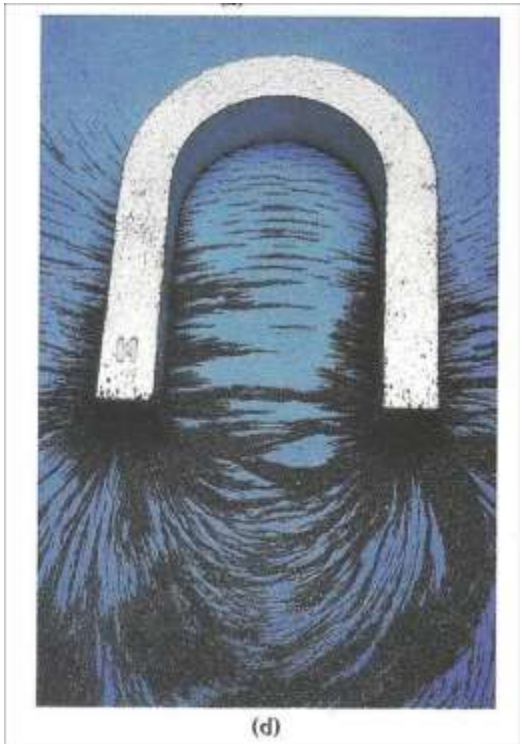
# We Can See Magnetic Fields

- Iron powder follows the magnetic field lines



(a)

Source: Walker



(d)

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# The Three Vectors

- B, Magnetic flux density or Induction.
- H, Magnetic field. (from current)
- M, Magnetization. (a material property)
- Vectors are not independent, but related.

# Flux Density or Induction, B

- Concentration of total magnetic flux in a region
- Lines of magnetic flux passing through a given area, lines per *area*
- Units: lines/cm² or Gauss (G)
  Webers/m² or Tesla (T)
- Magnetic Flux

$$\Phi = B\ A \cos\theta$$

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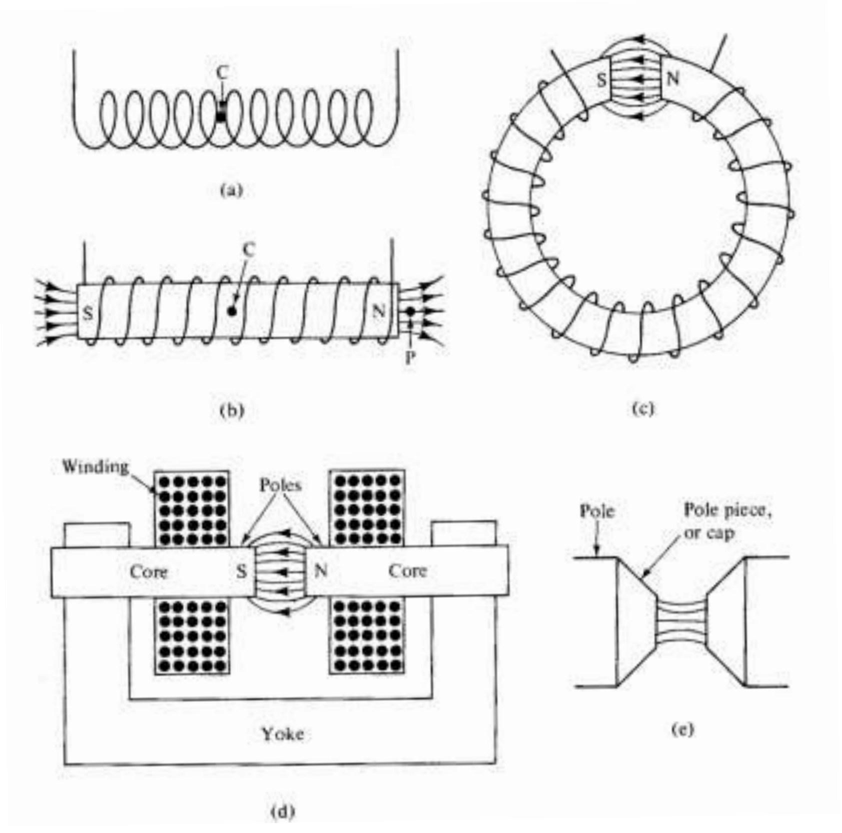
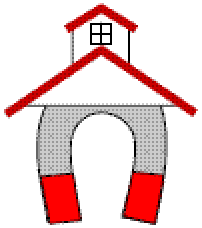
# Magnetic Field, H

- A magnetic field created by current flowing in a wire.
- Units: Oersted (Oe), Ampere-turn/meter (A/m)




Source: Cullity



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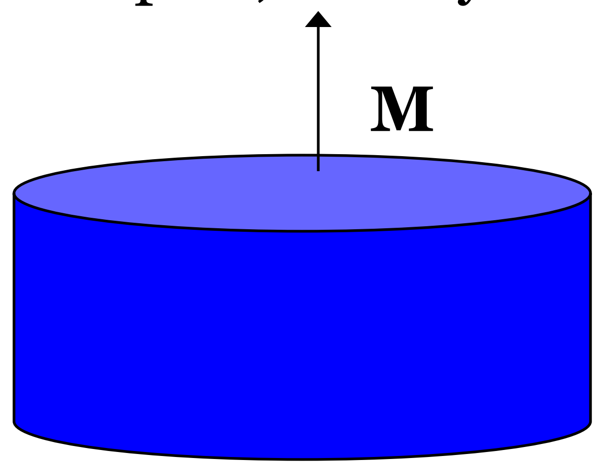
# Magnetization, M

- The magnetic state of a material
- The sum of all the individual magnetic moments per unit volume
- Moments arise from unpaired electron spins, usually in the 3d or 4f electron shells
- Units: Gauss (G) for $4\pi M$
  - emu/cm³ for M
  - emu/g for $\sigma$
  - Tesla (T) for $\mu_o M$ and J

Emu, source: Wikipedia

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# How are B, H and M related?

Induction, B is a combination of H and M.

$B = H + 4\pi M$ CGS units

$B = \mu_o (H + M)$ SI units

$\mu_o = 4\pi \times 10^{-7}$ Tesla-m/A

$\mu_o M = J$, Polarization

# CGS and SI Units

| Parameter | Units | | Conversion |
|---|---|---|---|
| | CGS | SI | |
| Basic equation | $B=H+4\pi M$ | $B=\mu_o(H+M)$ | |
| $\phi$ | Maxwell | Weber (volt-second) | 1 Wb=$10^8$ Maxwell |
| B | Gauss | Tesla | 1 Tesla=$10^4$ Gauss |
| H | Oersted | A (turn)/m | 1 Oe=79.58 A (turn)/m |
| $\mu_o$ | Not used | $4\pi \times 10^{-7}$ Wb/A-m | None |
| $(BH)_{max}$ | GOe | J/$m^3$ | 1 J/$m^3$=125.7 GOe |
| J | Not used | Tesla | None |
| $4\pi M=(B-H)$ | Gauss | Not used | None |
| M | emu/$cm^3$ | A (turn)/m | 1 A (turn)/m= $10^3$ emu |

Source: IEEE Magnetics Society

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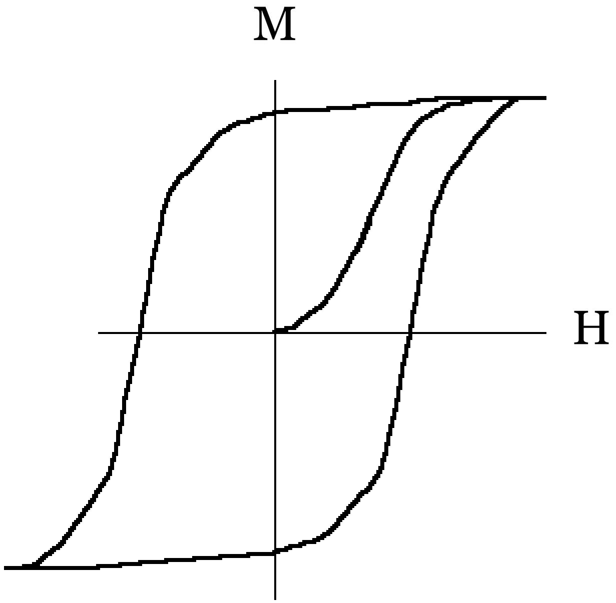
# Hard Magnetic Materials

- High $H_{ci}$
  - A wide hysteresis loop
- High $B_r$
  - A tall hysteresis loop
- Our battle with nature
  - Things that improve one parameter generally hurt the other

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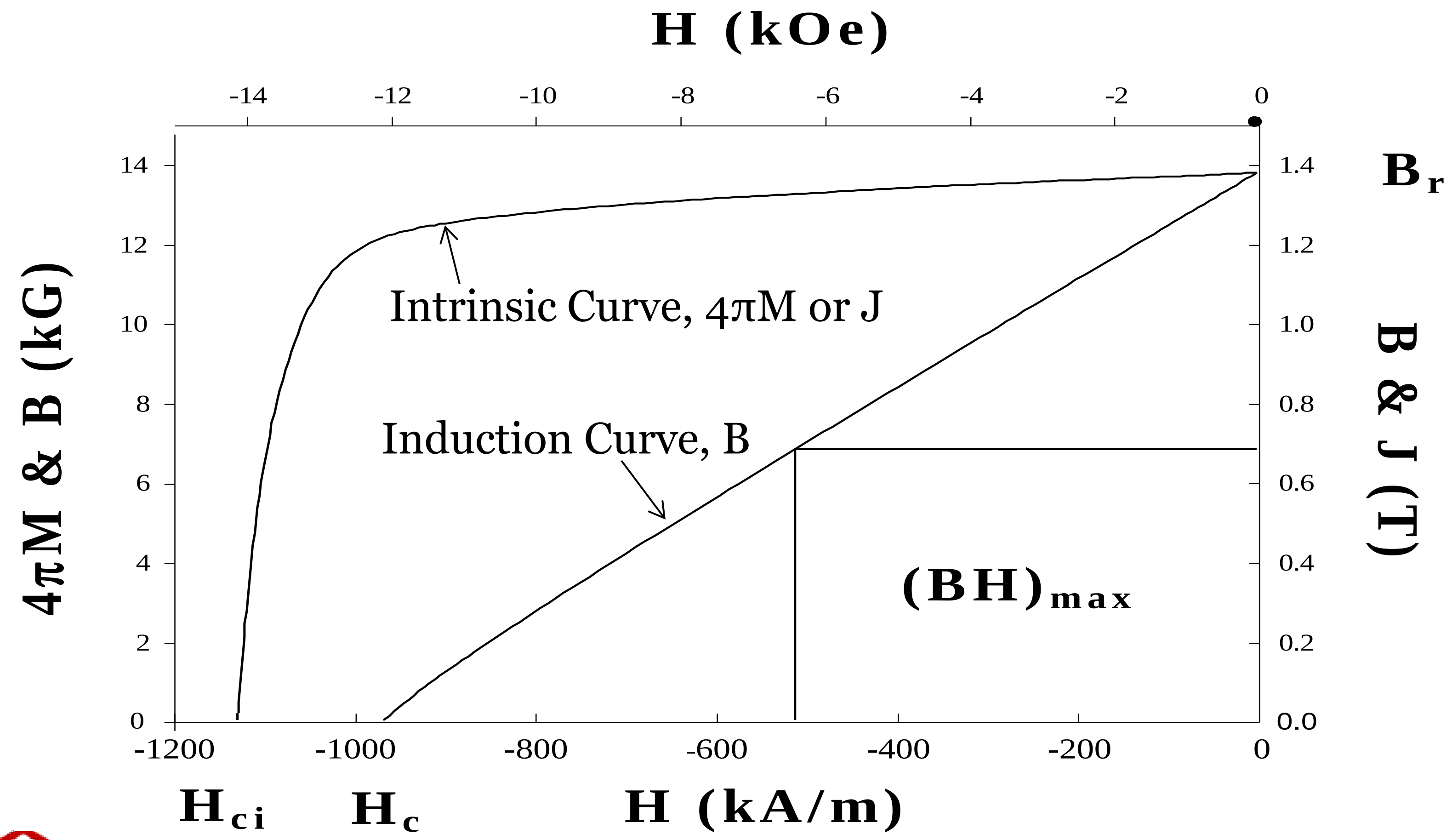
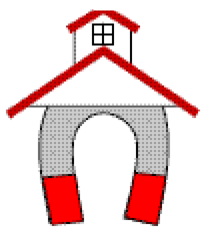
# Demagnetization Curves



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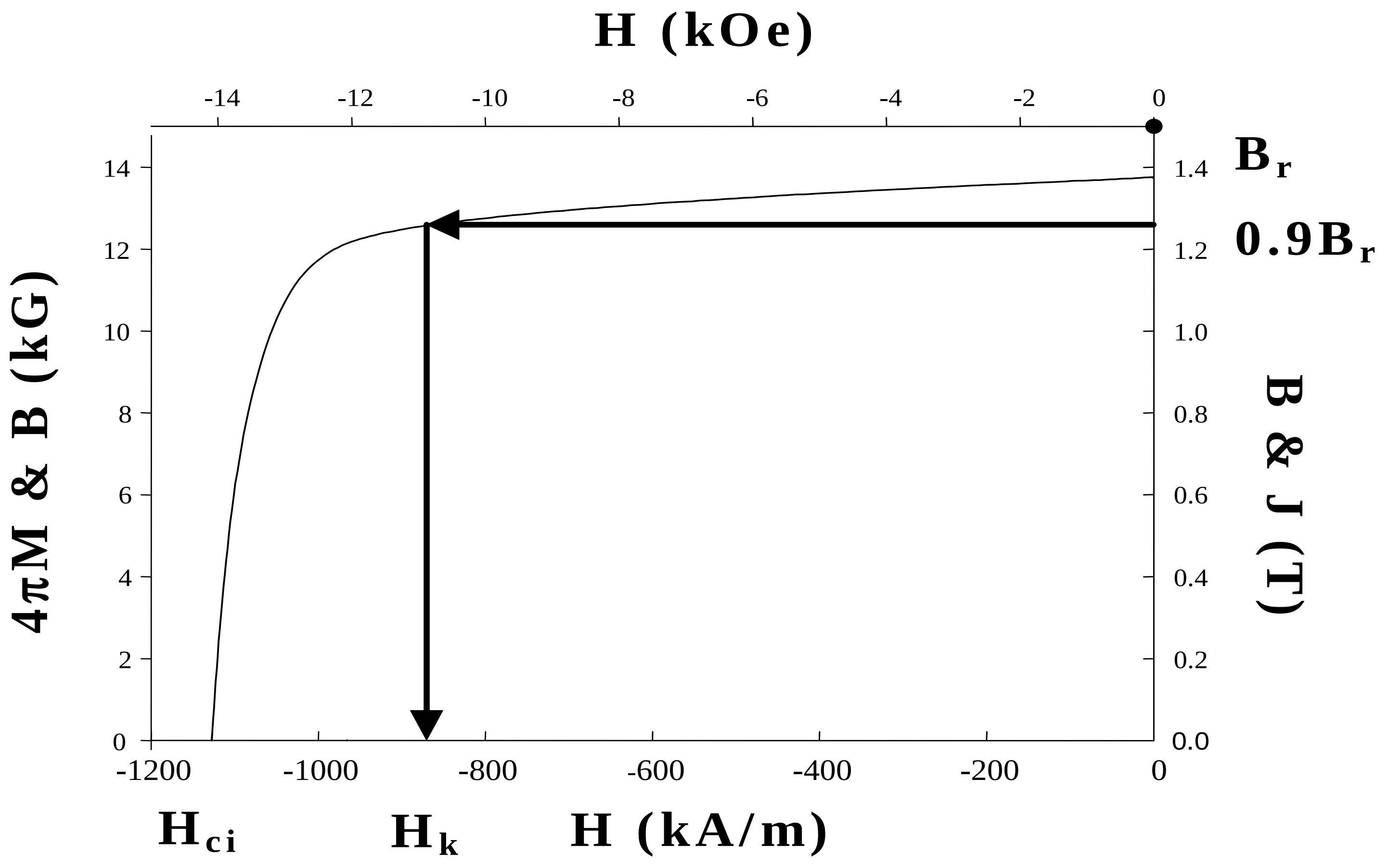
# Definition of $H_k$

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# Four Families of Permanent Magnets

| | Ferrite | Alnico | SmCo | | NdFeB | |
|---|---|---|---|---|---|---|
| Property | Ceramic 8 | Alnico 5 | 1-5 | 2-17 | Bonded | Sintered |
| $B_r$ (kG) | 4.0 | 12.5 | 9.0 | 10.4 | 6.9 | 13.4 |
| $\alpha$ (%/°C) | -0.18 | -0.02 | -0.045 | -0.035 | -0.105 | -0.12 |
| $(BH)_{max}$ MGOe | 3.8 | 5.5 | 20 | 26 | 10 | 43 |
| $H_{ci}$ (kOe) | 3.3 | 0.64 | 30 | 25 | 9 | 15 |
| $\beta$ (%/°C) | +0.4 | -0.015 | -0.3 | -0.3 | -0.4 | -0.6 |
| $H_s$ (kOe) | 10 | 3 | 20 | 30 | 35 | 35 |
| $T_c$ (°C) | 460 | 890 | 727 | 825 | 360 | 310 |

Notes:

The quantity $\alpha$ is the reversible temperature coefficient of $B_r$. (20 °C to 100 °C minimum)

The quantity $\beta$ is the reversible temperature coefficient of $H_{ci}$. (20 °C to 100 °C minimum)

The field required to saturate the magnet is $H_s$.

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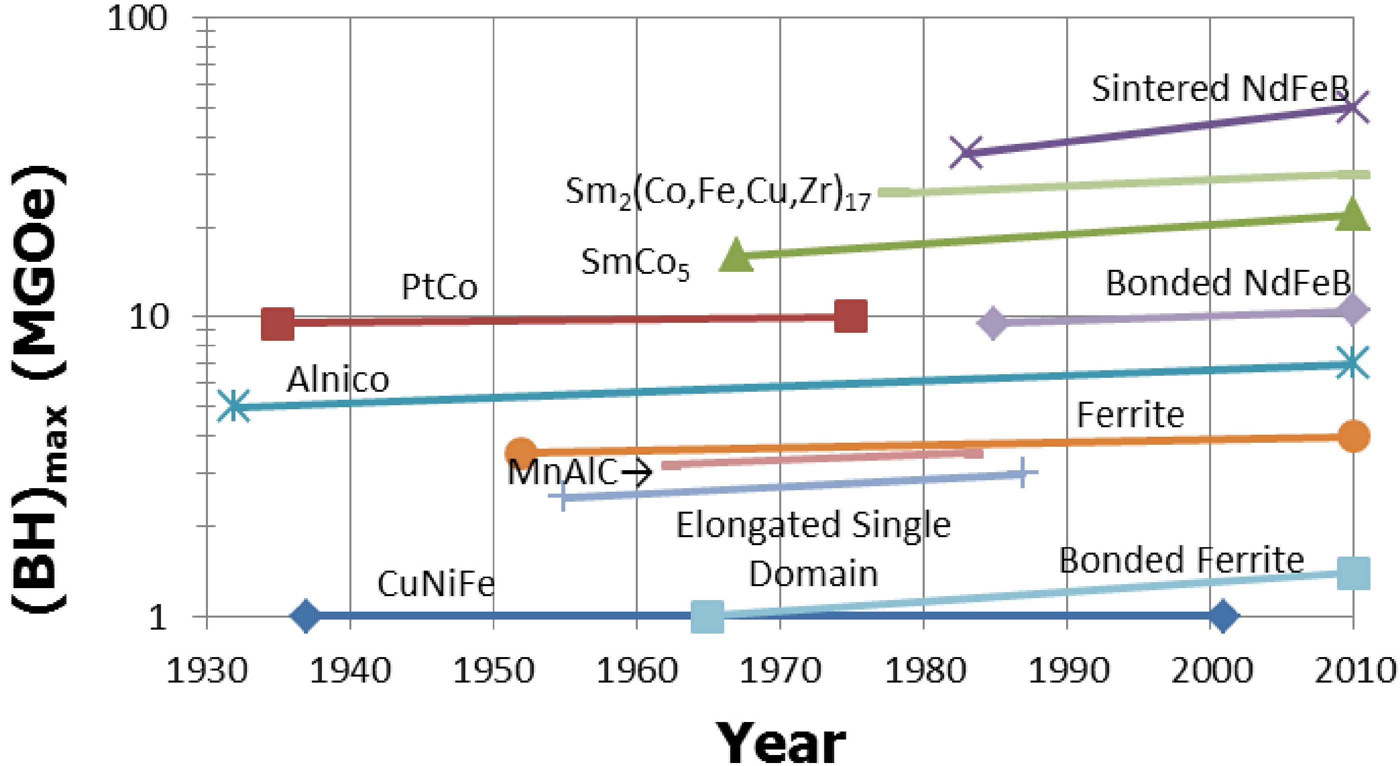
# Permanent Magnets 1930 to 2010

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# Requirements for a Permanent Magnet Material

1. High Curie Temperature
2. Large Saturation Magnetization
3. Highly Anisotropic
4. Physically and Magnetically Stable
5. Sufficiently Abundant Raw Materials
6. Simple, Profitable and Environmentally Safe to Manufacture
7. Easily magnetized to saturation

Conditions 1 through 3 are from W. E. Wallace, Rare Earth Intermetallics, Academic Press, New York (1973) p.159.

Condition 7 is from Reinhold Strnat, private communication

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# The Rare Earths

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
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| | | La | | | | | | | | | | | | | | | |
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| Ce | Pr | Nd | Pm | Sm | Eu | Gd | Tb | Dy | Ho | Er | Tm | Yb | Lu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | |

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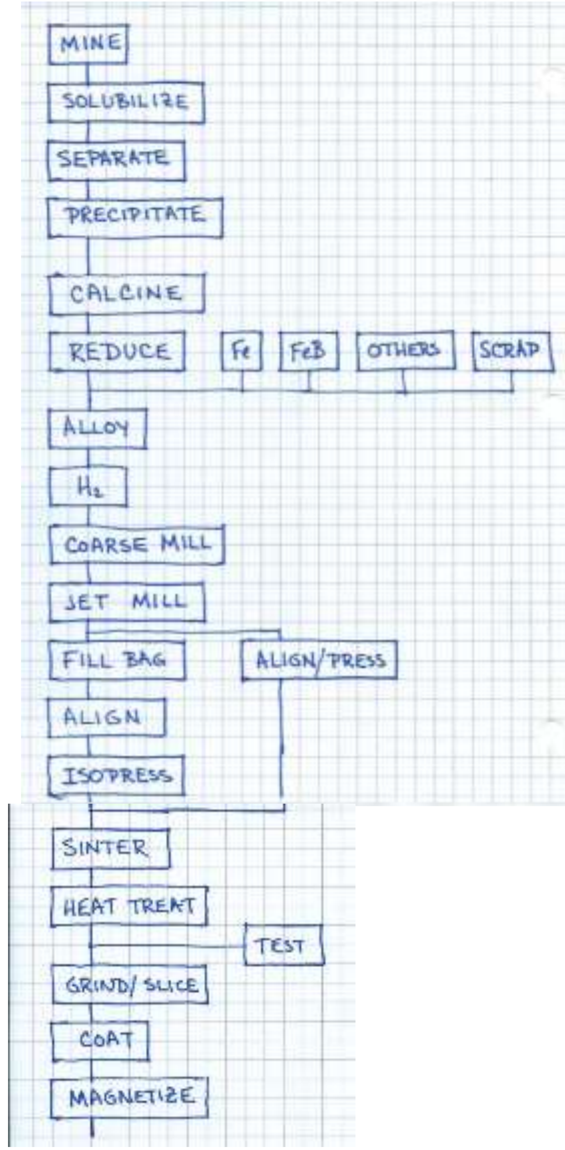


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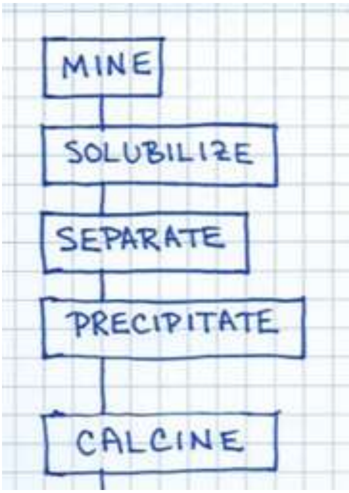
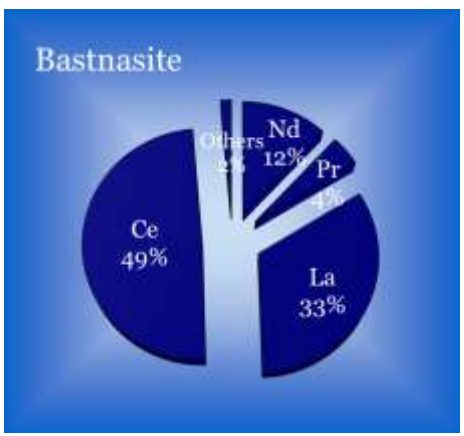
# Rare Earth Processing




- Mine
  - Bastnasite or Monazite or other ore
- Solubilize, digest
  - Put RE ions in $H_2O$
- Separate
  - Solvent extraction
  - Disadvantage of chemical similarity
  - Re ion's weak attraction to one liquid over another
  - Inefficient, many steps to high purity
  - Pregnant solution
- Precipitate
  - Oxalate or carbonate
- Calcine
  - Heat in air, 1000 °C
  - Convert into oxide

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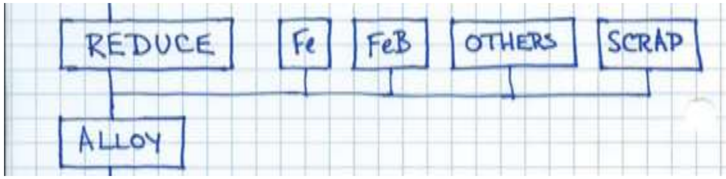
# Metal Making




- Reduction to Metal
  - Electrolysis with carbon electrode and flux
  - $2Nd_2O_3+3C \rightarrow 4Nd+3CO_2$
  - Energy intensive
  - Small batch process
  - Overvoltage causes CFC's

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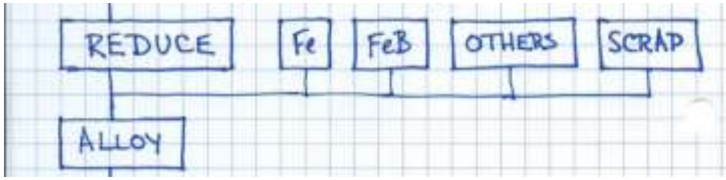
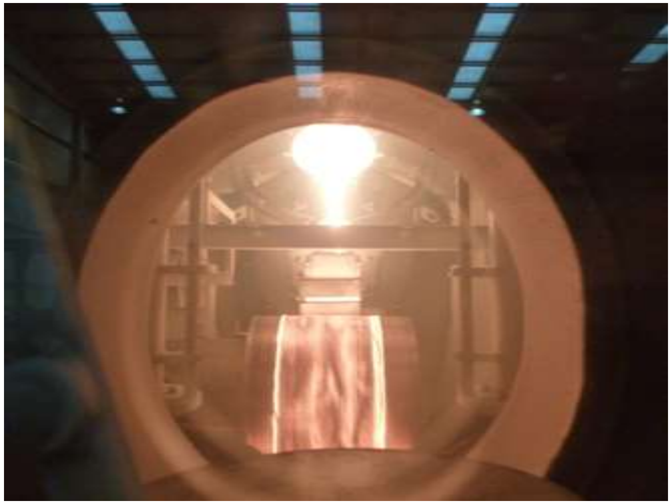
# Metals and Alloys



Source: Less Common Metals

- Alloy
  - Vacuum furnace
  - Strip casting

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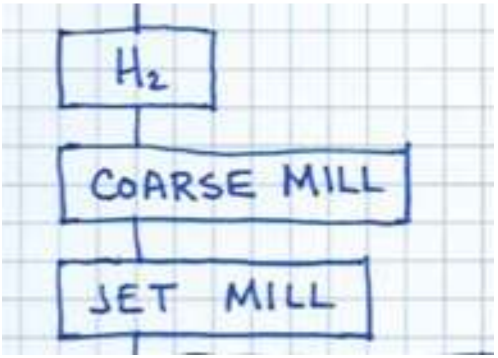
# Crushing




- Goal: single crystal particles
- $H_2$ rapidly diffuses into alloy and expands it
- Coarse mill
  - 40 mesh
- Jet mill
  - fine particles
  - uniform particles
  - 3 µm size
  - Non-contaminating


Source: The Jet Pulverizer Company

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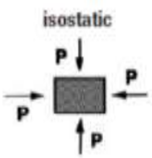
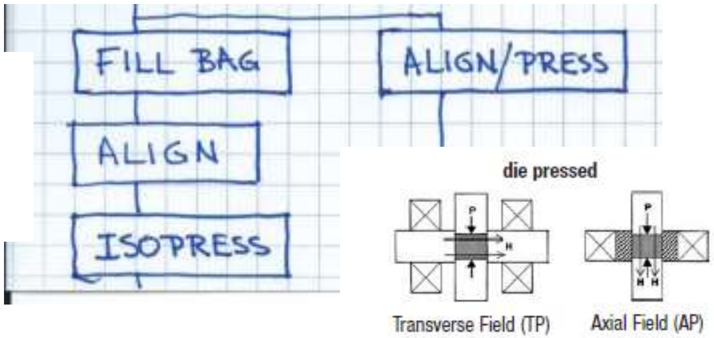
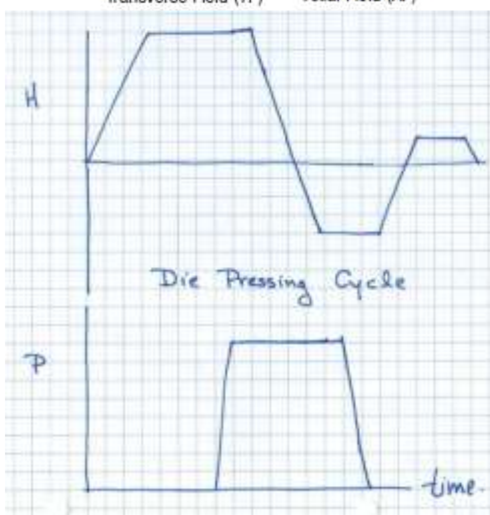
# Pressing




Sources:
Avure & VAC

- Shape powder
- Magnetically orient particles
- Apply pressure
  - Lock-in orientation
  - $1 \times 10^8$ Pa die press
  - $4 \times 10^8$ Pa isopress
  - Start densification

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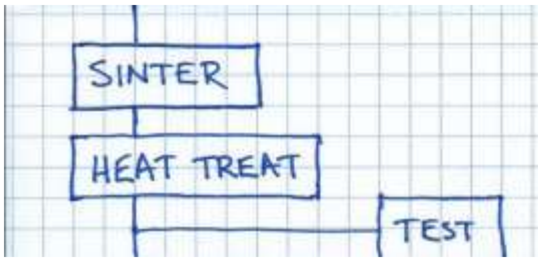
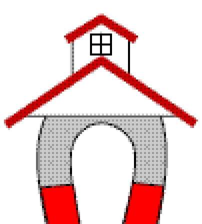
# Sinter & Heat Treat




Both steps are done in a Vacuum Furnace with gas quenching capabilities

Source: Solar Manufacturing

- Sinter
  - 1070°C, 1-2 hours, vac.
  - Quench
  - Density
  - Shrink and warp
- Heat Treat
  - 600°C, 1-5 hours
  - Quench
  - Not standardized
  - Develops $H_{ci}$ and $H_k$



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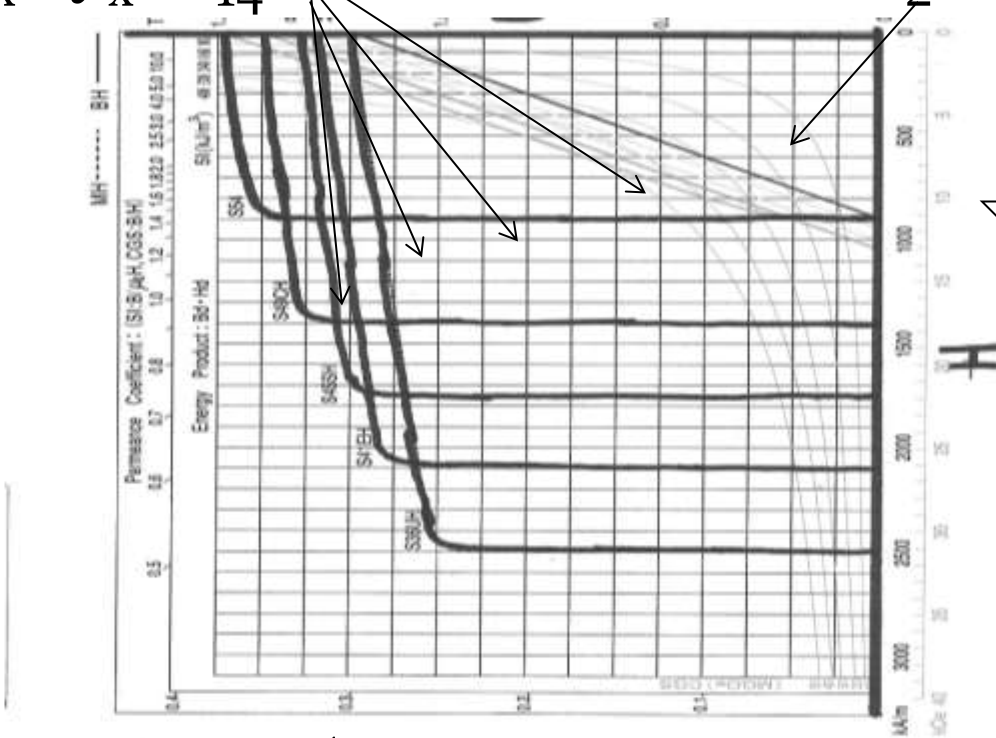
# The Role of Dy and Tb

$Nd_{2-x}Dy_xFe_{14}B$

$Nd_2Fe_{14}B$



Increasing x

Increasing x

Source: Hitachi Metals

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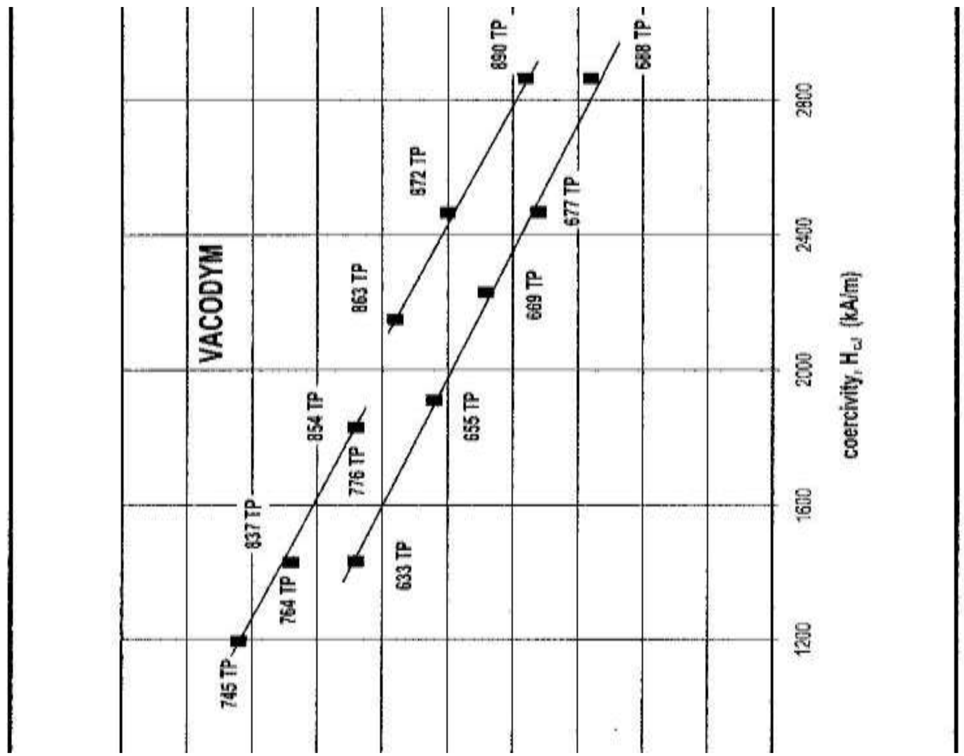
# The Role of Dy and Tb




Source: VAC

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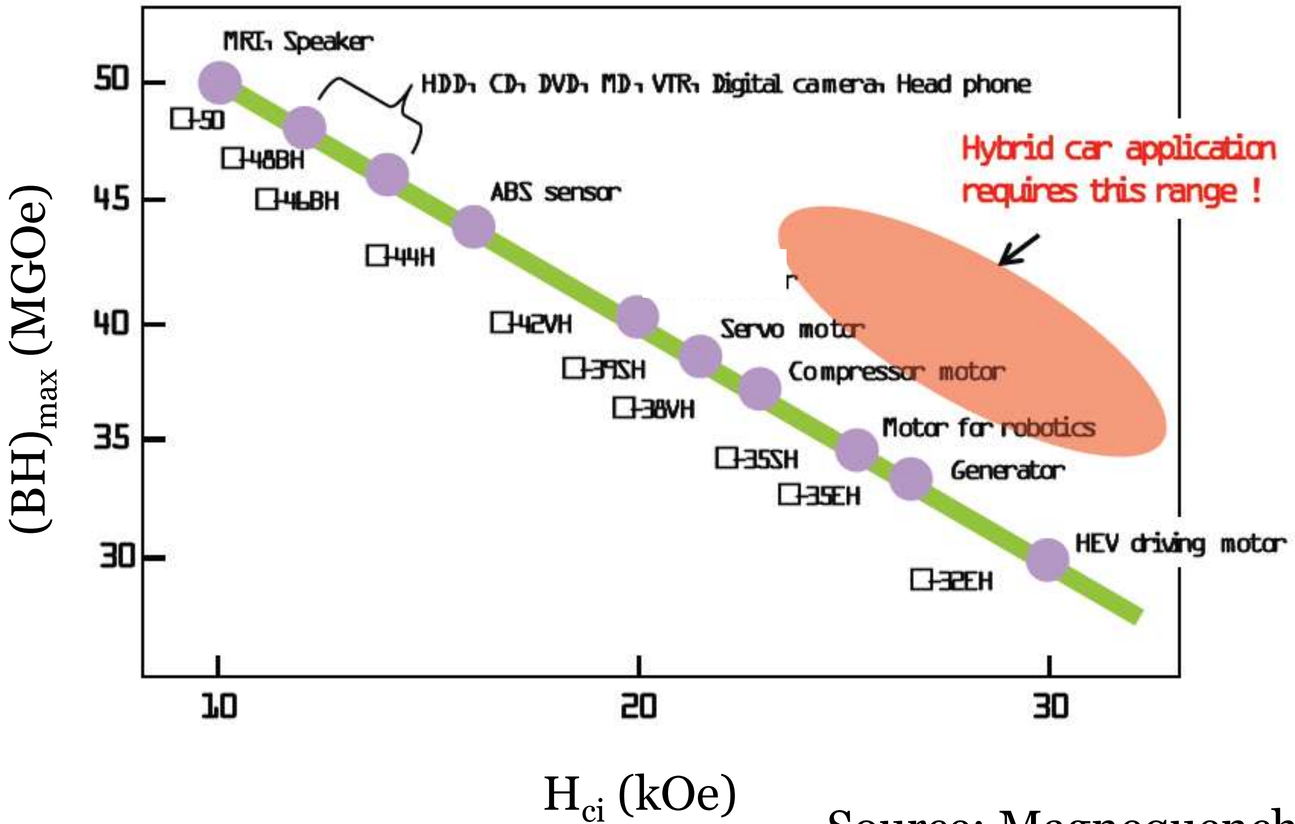
# The Role of Dy and Tb




Source: Magnequench, Sagawa

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# The Role of Dy and Tb

Source: Livingston 1985

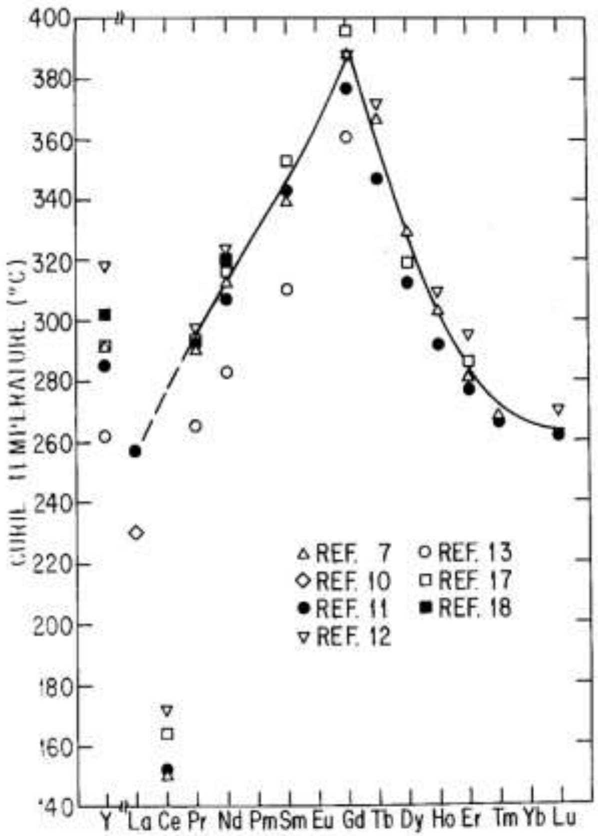


Fig. 2. Reported Curie temperatures of $Fe_{14}R_2B$ compounds.

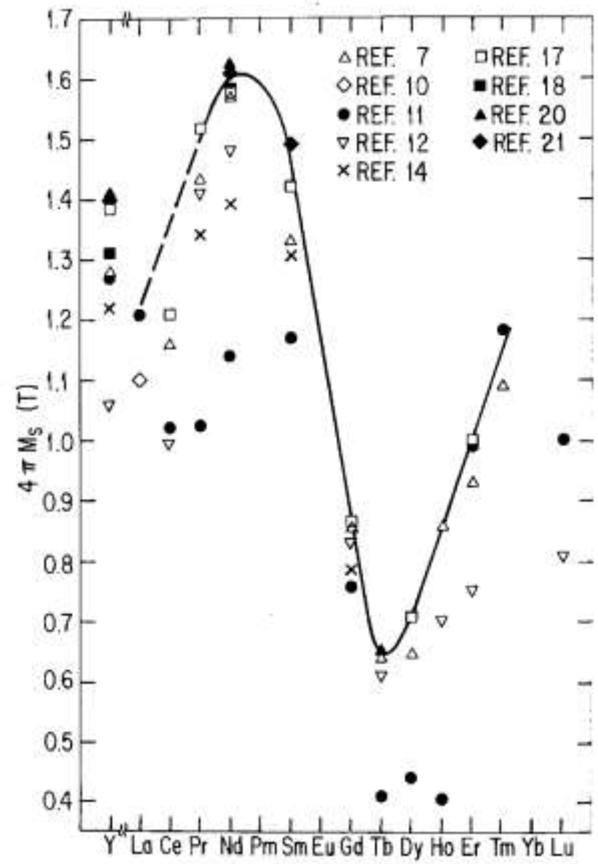


Fig. 3. Reported magnetizations of $Fe_{14}R_2B$ compounds.

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# The Role of Dy and Tb

Source: Livingston 1985

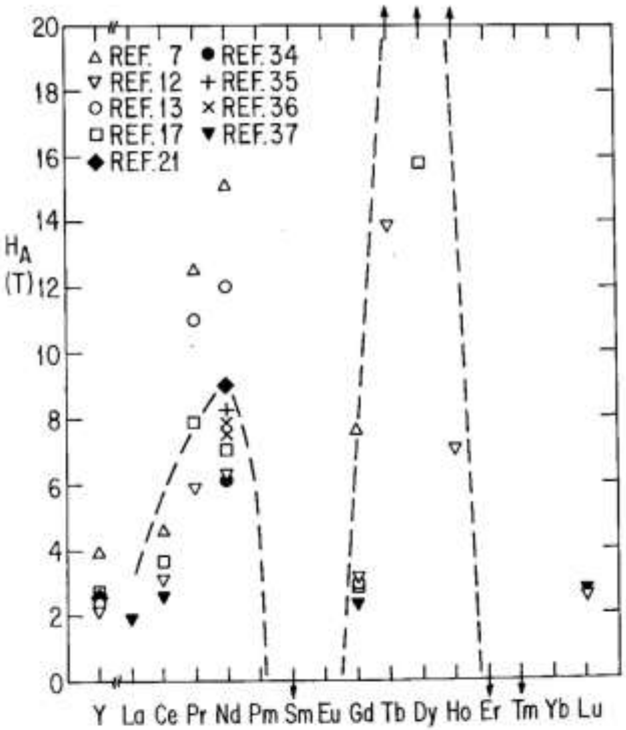


Fig. 4. Reported anisotropy fields of $Fe_{14}R_2B$ compounds. Arrows along top indicates values above 20 T reported for R = Tb, Dy, and Ho in Ref. 7. Arrows along bottom indicate negative (easy-plane) anisotropies reported for R = Sm, Er, and Tm by several investigators.

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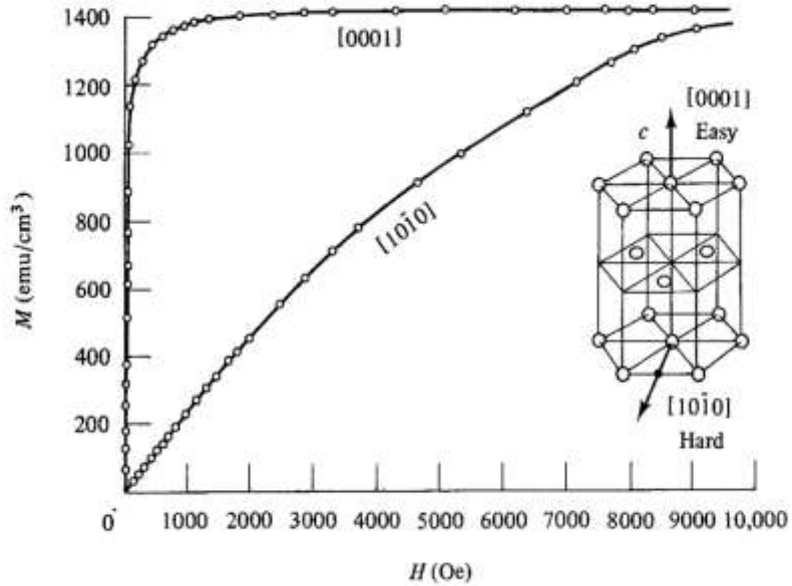
What is $H_A$, anisotropy field?




Source: Cullity

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# The Role of Dy and Tb

- Increase the anisotropy
- Increase $H_{ci}$
- Decrease $B_r$ and $(BH)_{max}$
- Increase the cost of the alloy
- The thermal influence is indirect
  - Increased $H_{ci}$ at elevated temperature
  - Slight influence on $\beta$, $\alpha$ and $T_C$
- Identified early, little progress, until recently

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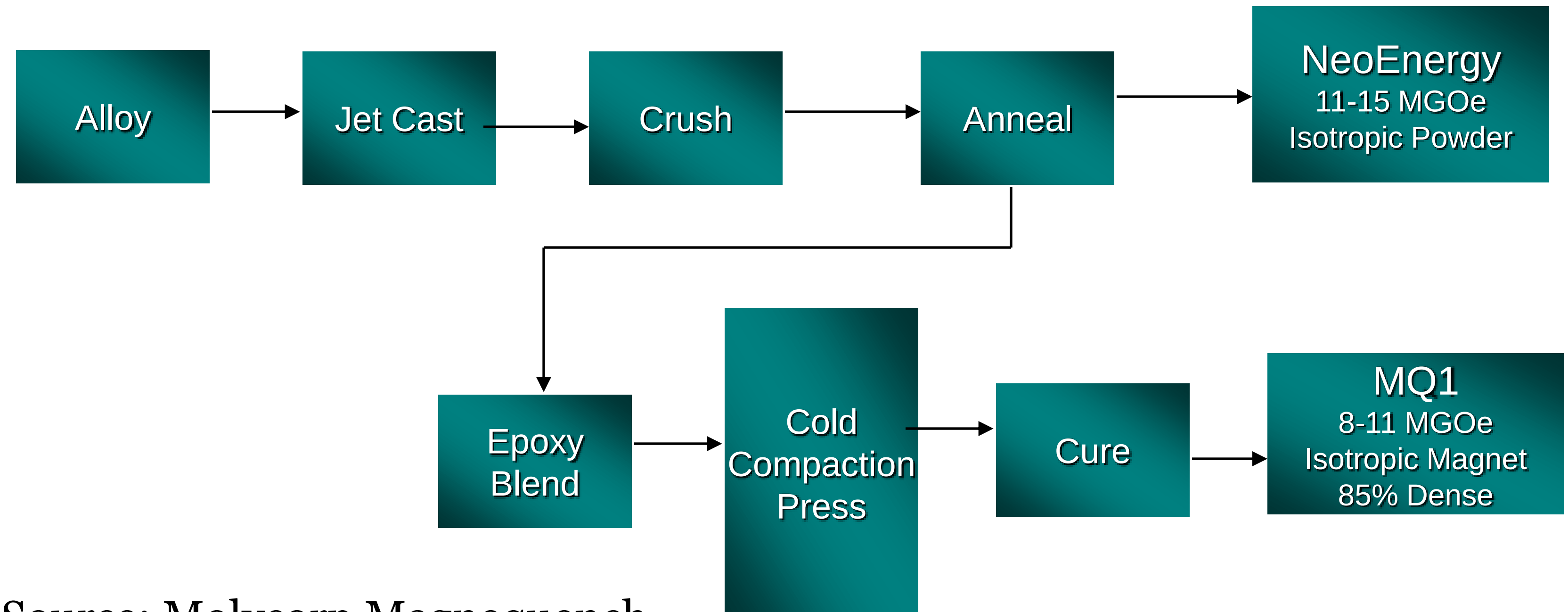
# Magnequench Process




Source: Molycorp Magnequench

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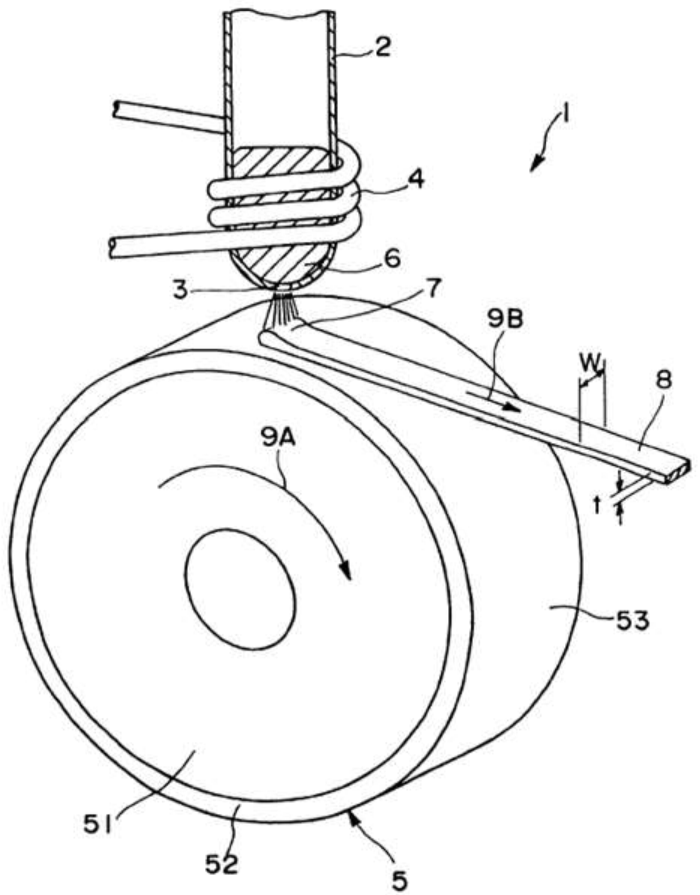
# Jet Casting




Source: US Patent 6,503,415

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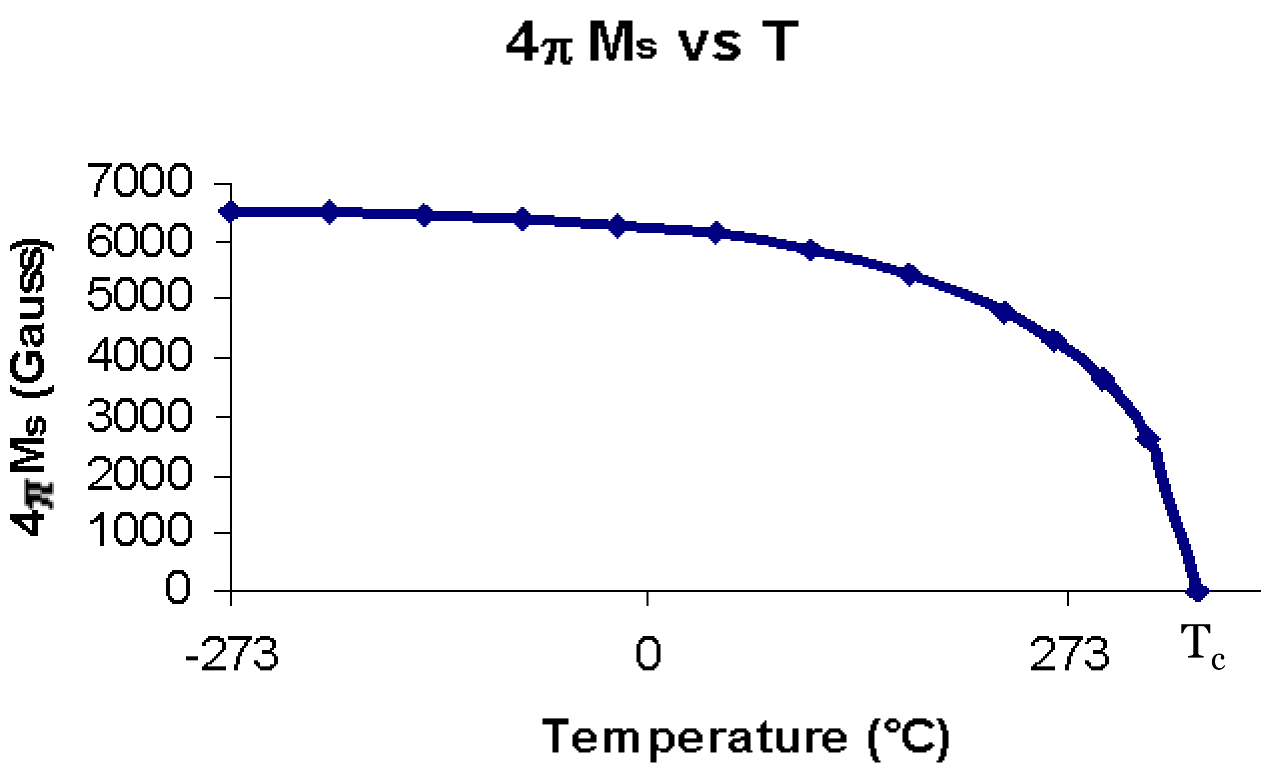
# Thermal Properties

- Curie Temperature
- Demagnetization Curves at Temperature
- Reversible Loss
- Irreversible Loss
- Maximum Operating Temperature

# Curie Temperature

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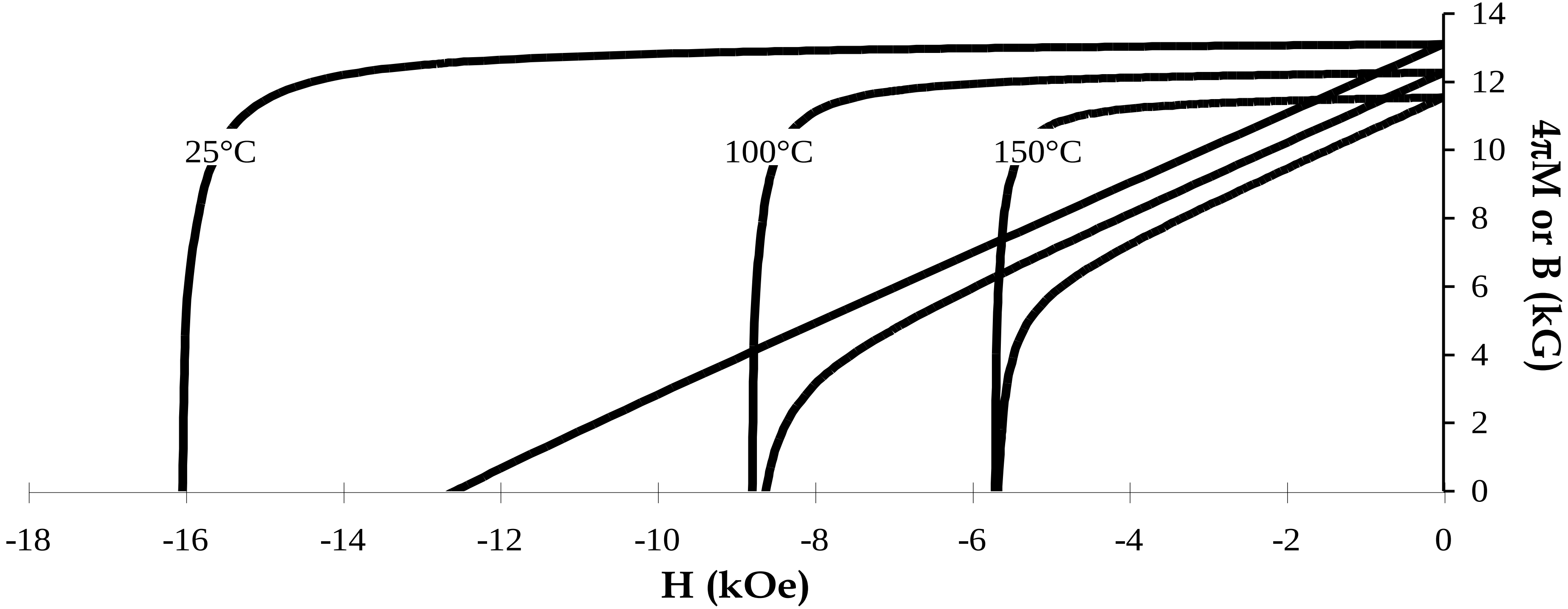
# Demagnetization Curves @ Temp.

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# Reversible Thermal Properties

- Temperature coefficient of $B_r$, $\alpha=(1/B_r)\Delta B_r/\Delta T$
  - Related to Curie Temperature
- Temperature coefficient of $H_{ci}$, $\beta=(1/H_{ci})\Delta H_{ci}/\Delta T$
  - Related to Curie temperature and coercivity mechanism

Typically, a temperature range is specified

Typical values (0 to 100°C)

| Material | α (%/°C) | β (%/°C) |
|---|---|---|
| Ferrite | -0.2 | +0.2 |
| Alnico | -0.02 | +0.01 ($H_c$) |
| $SmCo_5$ | -0.04 | -0.3 |
| NdFeB | -0.09 | -0.5 |

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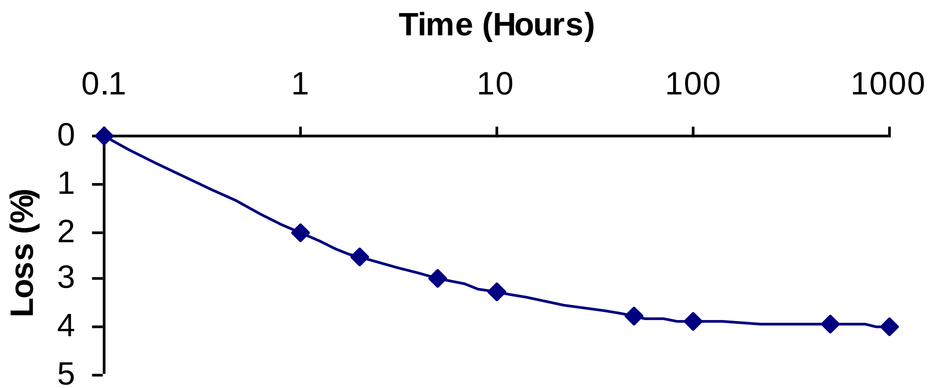
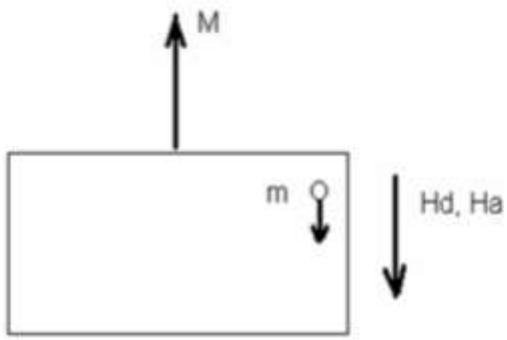
# Irreversible Loss



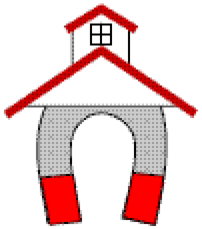




## Key parameters

- Temperature
- Time
- Loadline, self-demagnetization
- Adverse field, armature reaction

## Comments

- Logarithmic
- Recovered be remagnetization
- Properly saturated
- A one-time event



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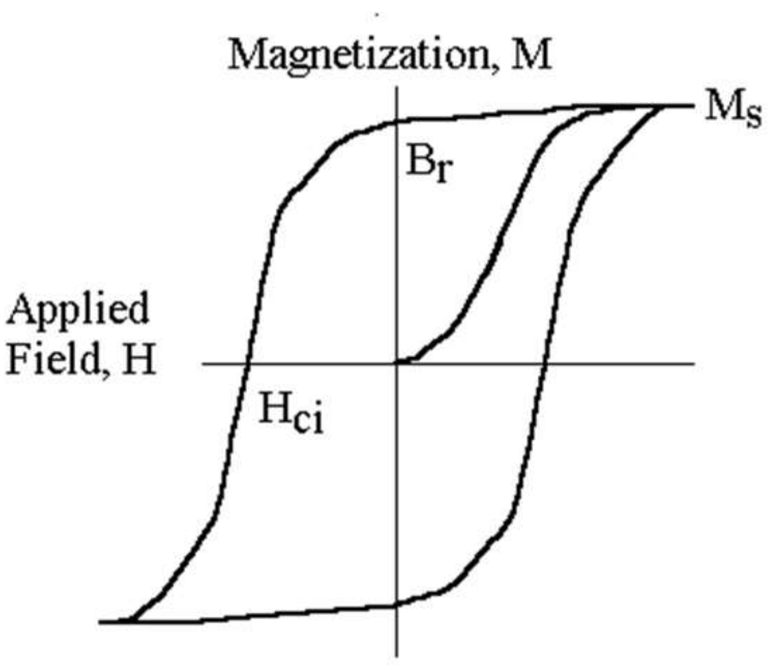
# 1000 Ping Pong Ball Model

- Imagine a magnet consisting of 1000 identical grains, all perfectly aligned
- The magnetization of each grain can either be ↑ or ↓
- At $B_r$, all 1000 grains are magnetized and pointing in the same direction, ↑ .

# 1000 Ping Pong Ball Model

- What percentage of grains have flipped at the following points?
  - $H_{ci}$, i.e. M=0
  - $H_k$, i.e. M=0.9$B_r$
  - @ 1% flux loss

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# Maximum Operating Temperature

- What is it?
- No standard definition
- Loss or linearity?
- More confusing than helpful

A proposed definition

The highest temperature where the B vs. H curve remains linear from $B_r$ to B/H=1, *and* where the irreversible losses at B/H=1 flatten out over time, i.e. show essentially no additional irreversible loss after 100 hours.

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# Thermal Summary

| Parameter | How used? | Comments |
|---|---|---|
| **Curie temperature, $T_c$** | **Absolute temperature limit** | **Helpful for material development, not helpful for designers** |
| **Reversible temperature coefficients: $\alpha$, $\beta$** | **Estimate curves at temperature when data not available** | **Good tools** |
| **Demagnetization curves at temperature** | **Model performance at temperature** | **Fundamental data, essential for modeling** |
| **Irreversible loss** | **To de-rate curves at temperature for accurate performance estimates** | **Very design specific** |
| **Maximum operating temperature** | **To compare materials** | **No standard definition, dangerous to use without considering definition** |

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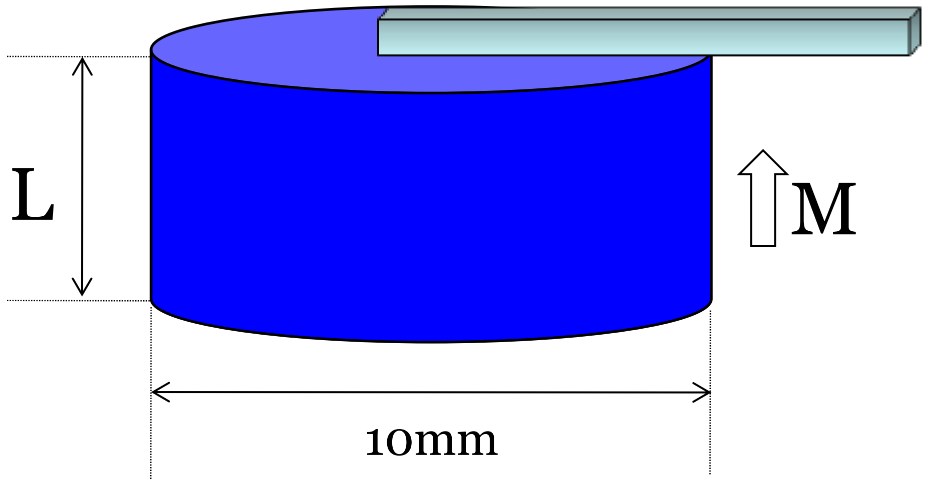
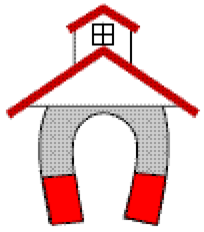
# Self-Demagnetization

- Thought Experiment
  - NdFeB Disc Magnet
  - $B_r$=12,500 G
  - Diameter=10 mm
  - Measure H at surface
  - Vary magnet length, L



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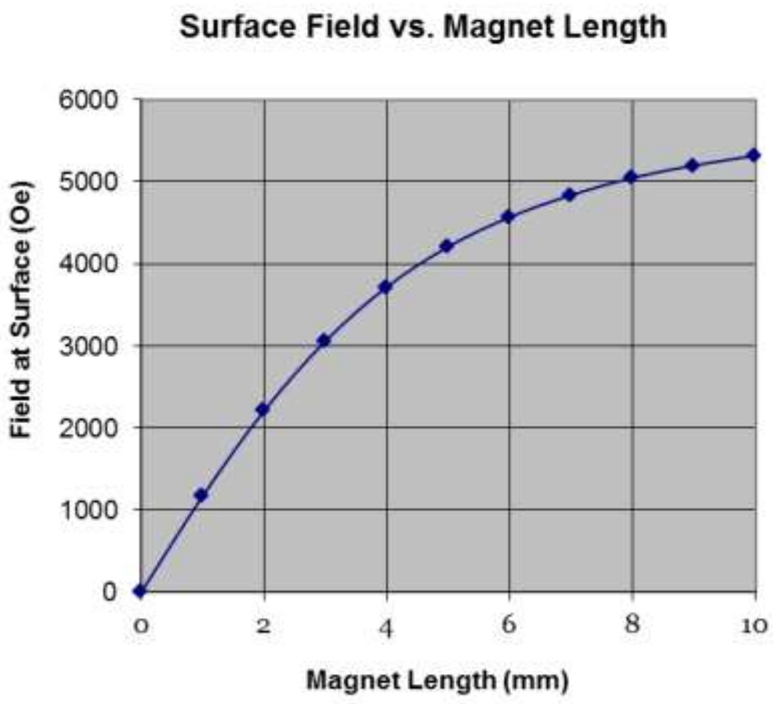
# Self-Demagnetization

- What happens?
  - Surface field decreases as magnet length decreases
  - Strictly geometric effect
  - Not due to the material
  - Maximum surface field?

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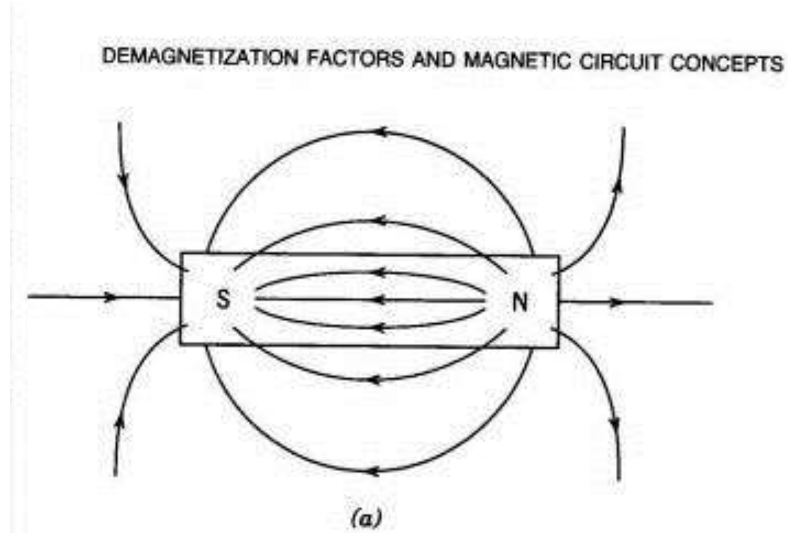
# Self-Demagnetization

- Lines of B are continuous
- H lines originate and terminate at the poles
- Two paths
  - Outside magnet
    - Parallel
  - Inside magnet
    - Antiparallel
- Free poles cause an internal demagnetizing field
- The closer the poles, the stronger the effect




Source: Parker

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# Influence of Self-Demagnetization

- Design
  - B/H, permeance coefficient, p.c.
  - L/D ratio
    - 2 times rule
  - $H_c \approx B_r$
    - Short L: disc, arc
  - $H_c < B_r$
    - Long L: horseshoe

- Measurement
  - Open-circuit
    - Adjustment
    - Shearing of curve
  - Closed circuit
    - No adjustment

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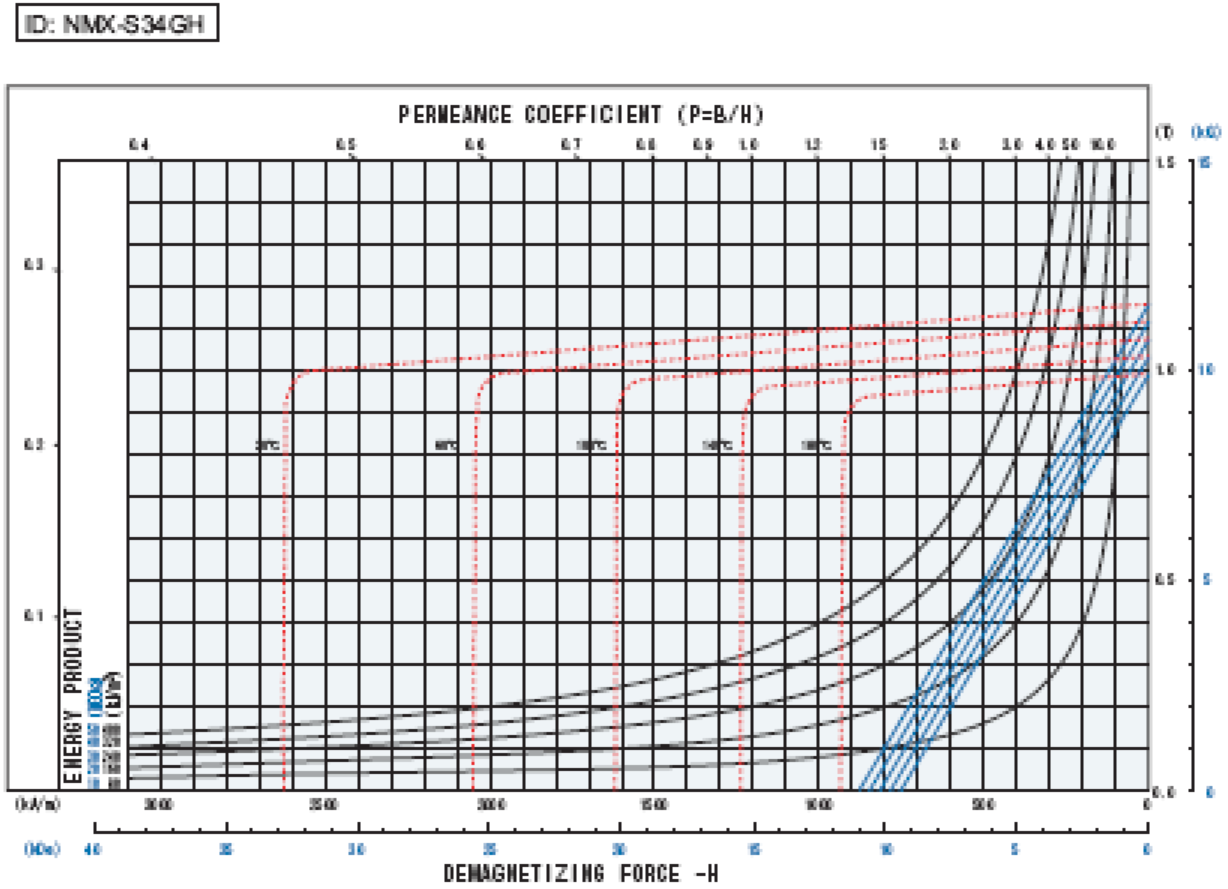
# Influence of Self-Demagnetization




Source: Hitachi

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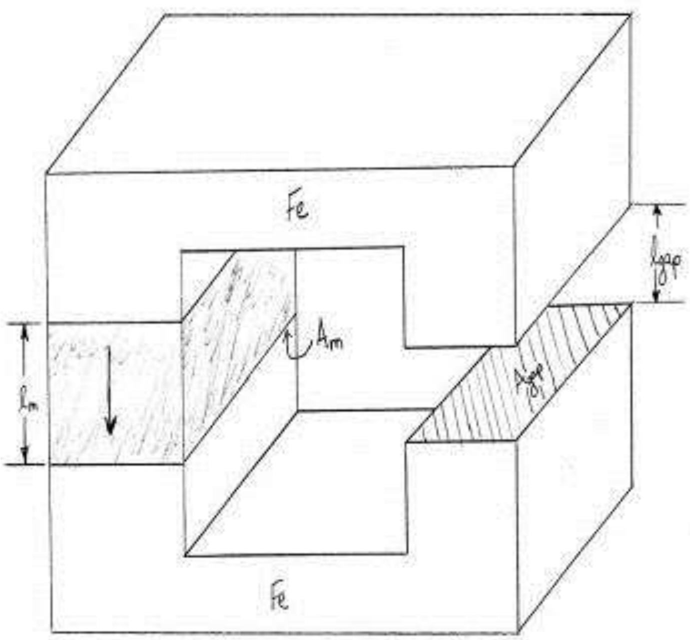
# Influence of Self-Demagnetization

- Apply Maxwell's equations in simple circuits

$$\Phi = B_m A_m = B_{gap} A_{gap}$$

$$H_m \ell_m = H_{gap} \ell_{gap}$$

$$B_{gap} = H_{gap}$$




C-frame

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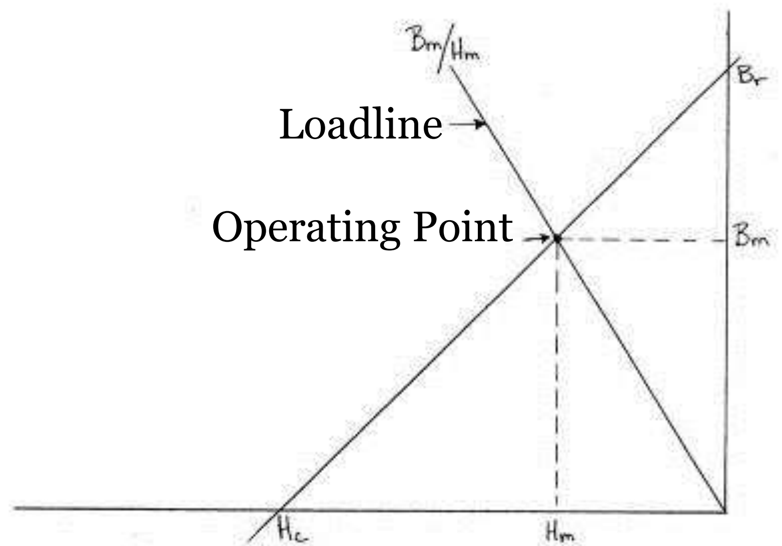
# Influence of Self-Demagnetization

$$\frac{B_m}{H_m} = \frac{\ell_m A_{gap}}{\ell_{gap} A_m}$$

$$B_{gap} \approx \frac{B_m A_m}{A_{gap}}$$

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# Magnetizing

Source: Magnetic Instrumentation, Inc.

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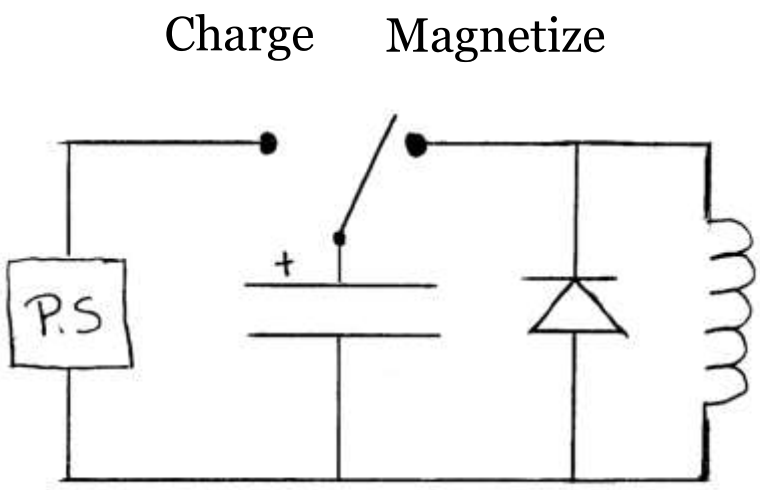
# Basic Circuit

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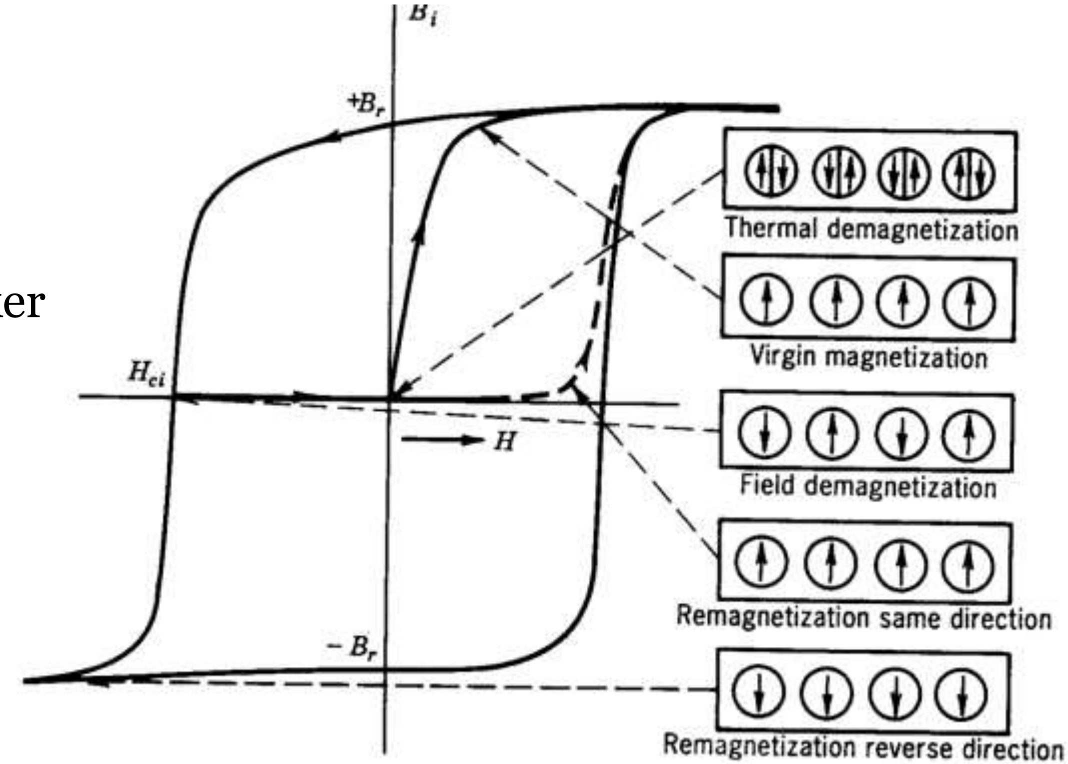
# Initial Magnetization

Source: Parker

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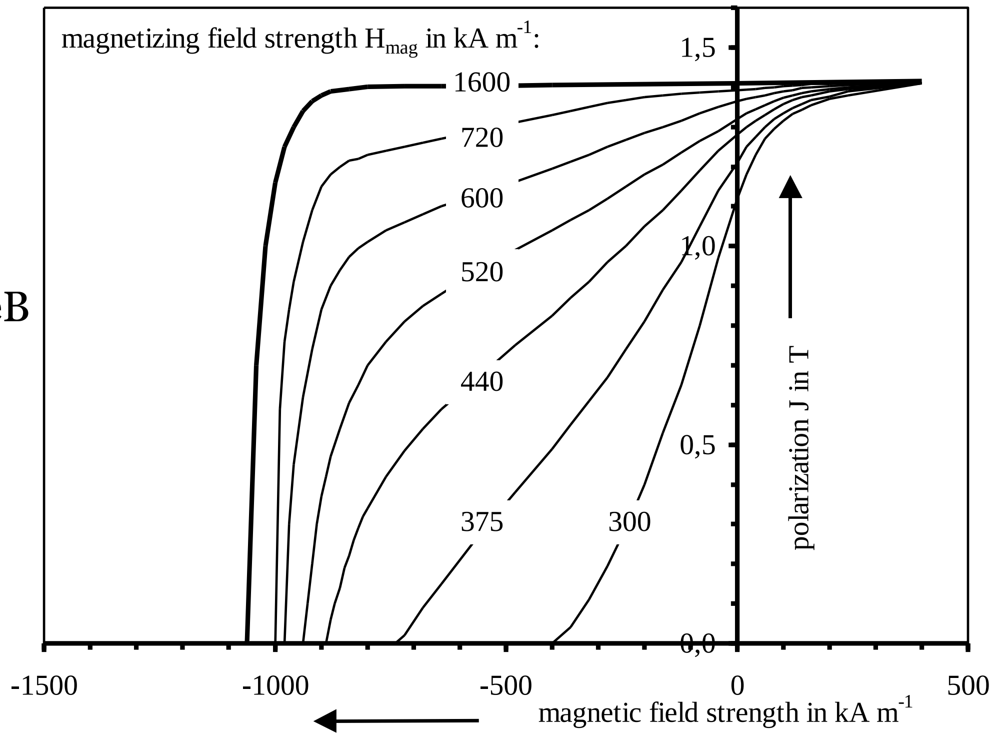
# Importance of Full Saturation

Material: NdDyFeB




Source: Magnetizing Behavior of Permanent Magnets, IEC

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# Common Issues with Magnetizing

- Assuring Saturation
- Dead zones
- Cycle time
- Heat

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# Permanent Magnets for Energy Applications Part 1

- Perspective
- Things we already knew
  - Poles
  - Living on a magnet
  - Viewing magnetic fields
- Magnetic Theory
  - Hysteresis
  - Three vectors
  - Units and Conversions
- Materials
- Processing
- Dysprosium
- Magnequench process
- Self-demagnetization
- Magnetizing

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