ZA-01

Hard magnets made easy.

Stanley R. Trout, Molycorp Minerals, LLC

Greenwood Village, CO 80111 USA

The first things we learned about magnets as children, and perhaps forgot in the intervening time, are still largely true today. This tutorial will review these basic concepts. In addition, it will define anisotropy, coercivity and energy product and will explain what makes a hard magnet hard and a soft magnet soft, using these concepts. The basic characteristics of popular hard materials and their relevance to technological application will be described.

Hard Magnets Made Easy

Stanley R. Trout

April 25, 2011

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Outline

- Things we learned as children
- Things we need to know as adults
  - Hysteresis
  - Coercivity
  - Basic parameters
  - Electron spin
  - Exchange interaction
  - Anisotropy
- A Brief History of Permanent Magnets
- Material Properties
- How are magnets made?

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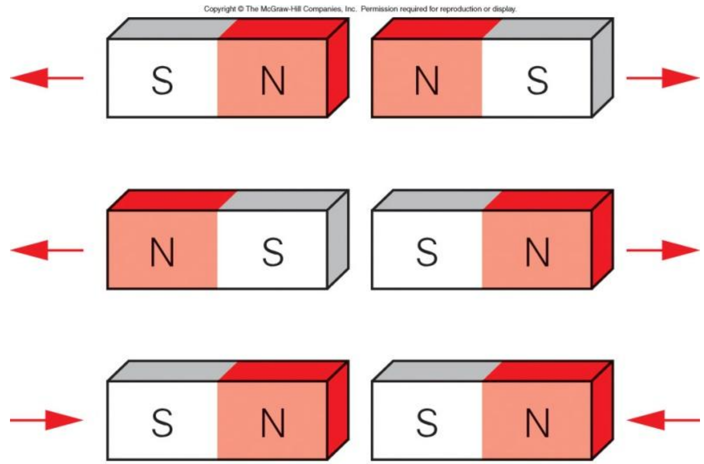
Magnets Have Poles



Source: Griffith

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

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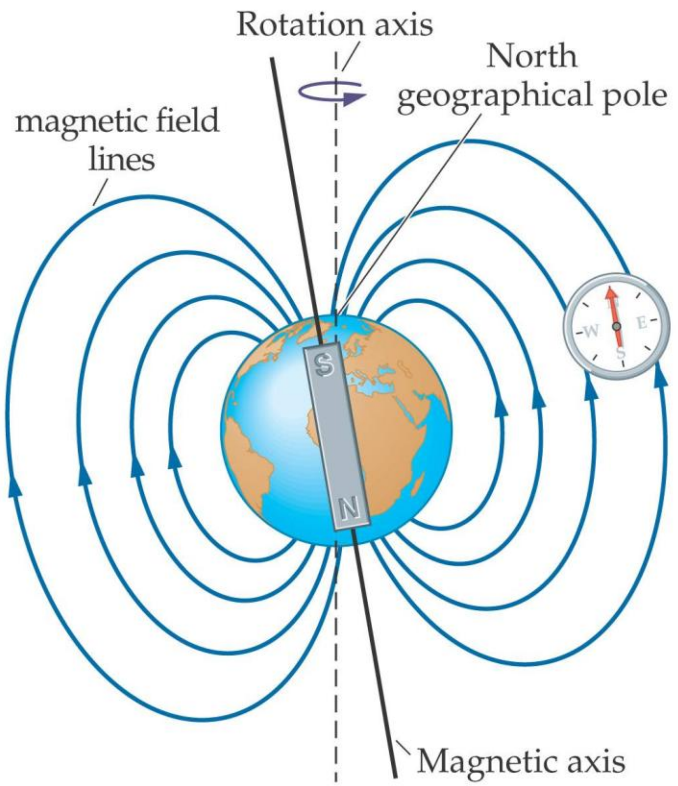
The Earth is a Magnet

- We live in a magnetic field
  - 100,000 times smaller than an MRI magnet
- There are magnetic poles and geographic poles
  - Nearly the same location
  - The magnetic poles move and occasionally flip
- A compass points North
  - A North seeking pole
- Notice the polarity of the Earth!



Source: Walker

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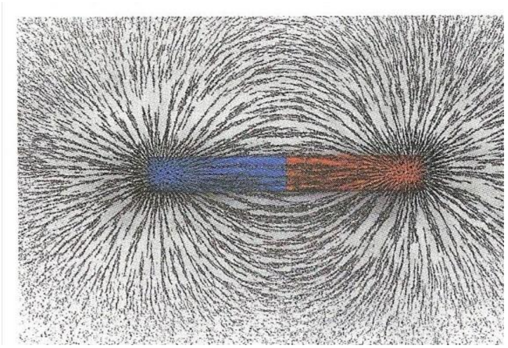
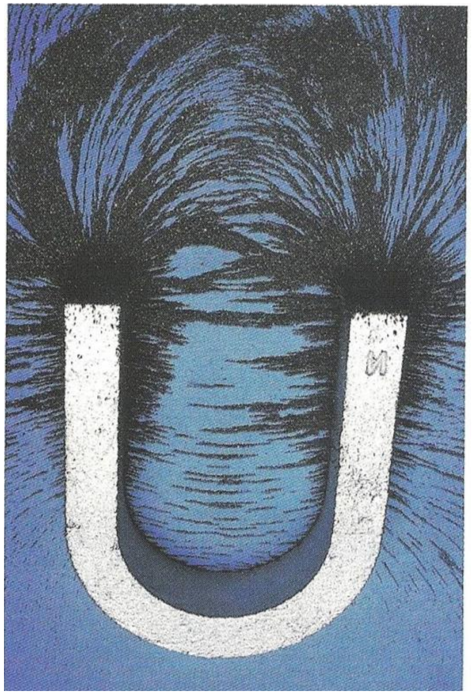
We Can See Magnetic Fields

- Iron powder aligns with the magnetic field lines





Source: Walker

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Hysteresis

- A delayed response to a stimulus
- In this case, the stimulus is an applied magnetic field and the response is the magnetization or flux density
- The *shape* of the hysteresis loop tells us what kind of material we have

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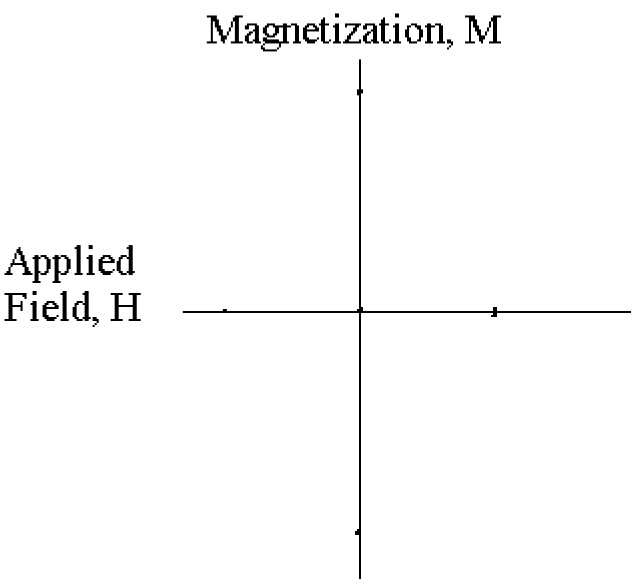
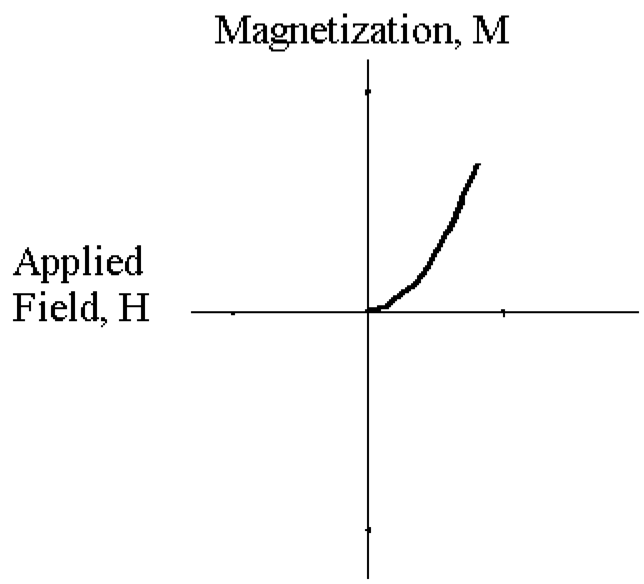

Magnetization, M
Applied
Field, H



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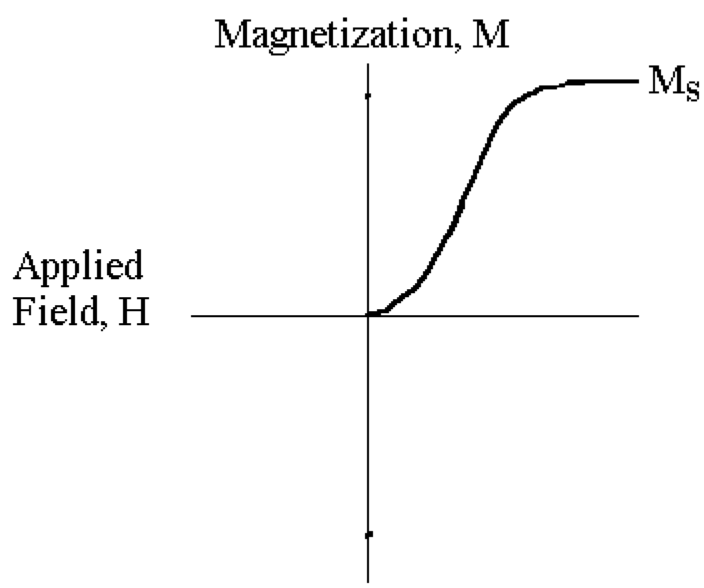

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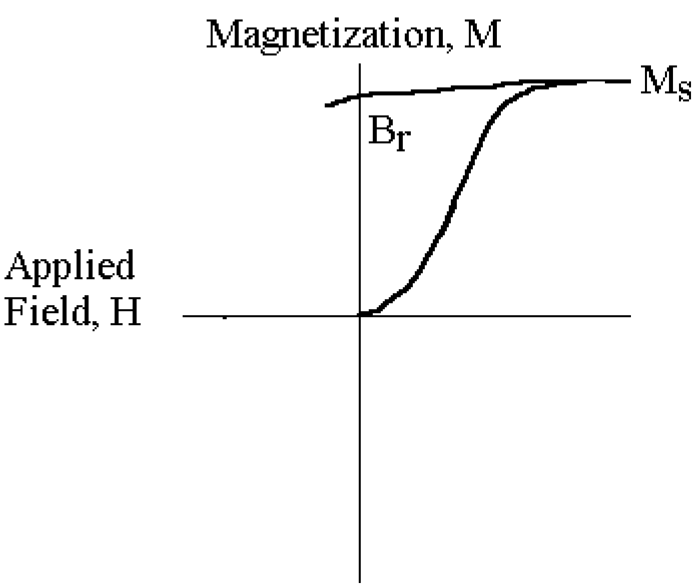

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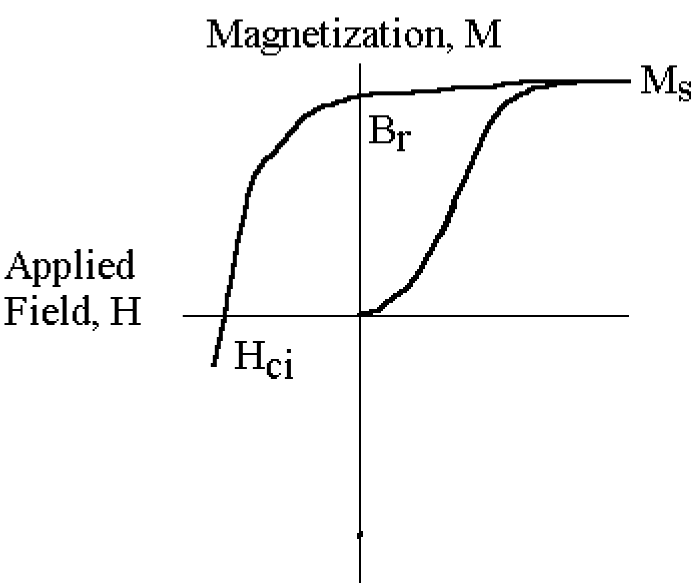
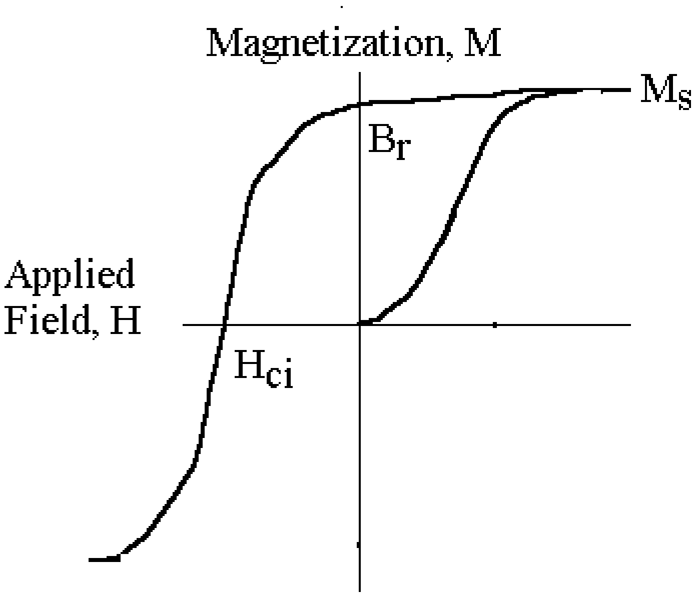

Magnetization, M
Ms
Br
Applied
Field, H
Hci



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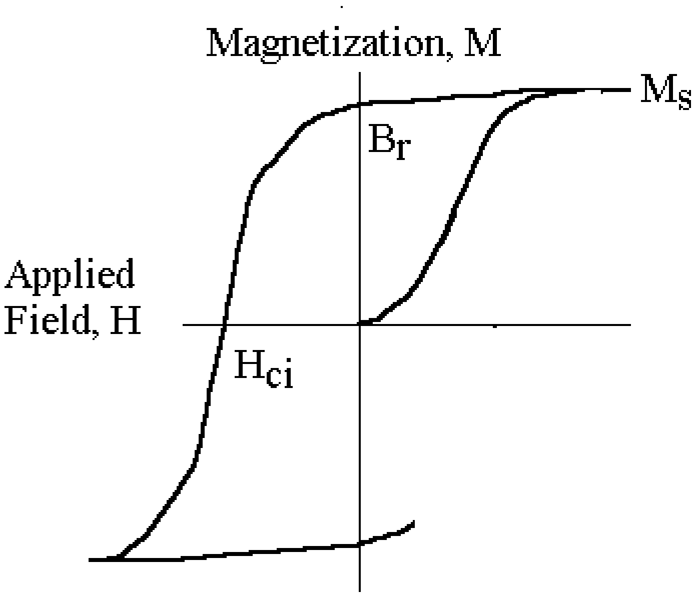
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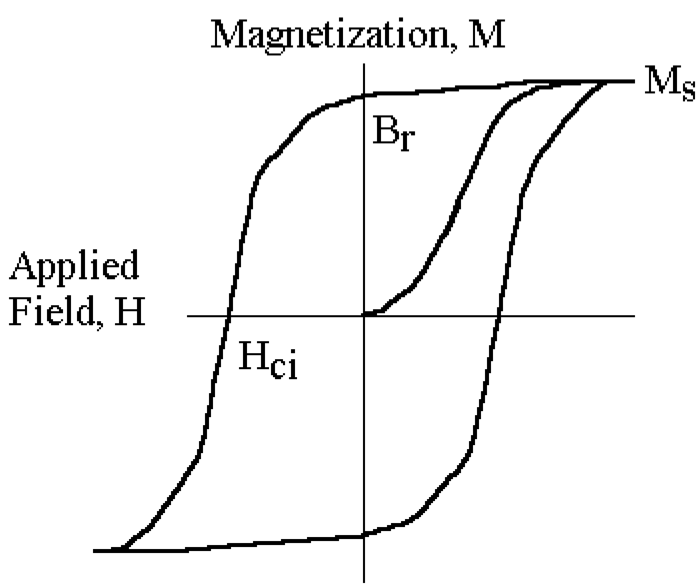

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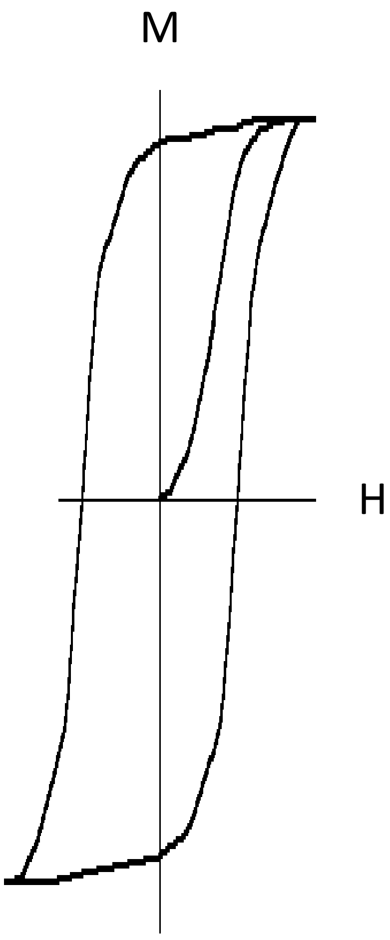
Soft Materials

- Low H_{ci}
- High Saturation (M_s)
- High Permeability (μ)
- Applications
  - Transformers
  - Inductors
- Materials
  - Low Frequency (<1 kHz)
    - Fe, Si-Fe, Ni-Fe, Fe-B
  - High Frequency (>1 kHz)
    - Zn-ferrite



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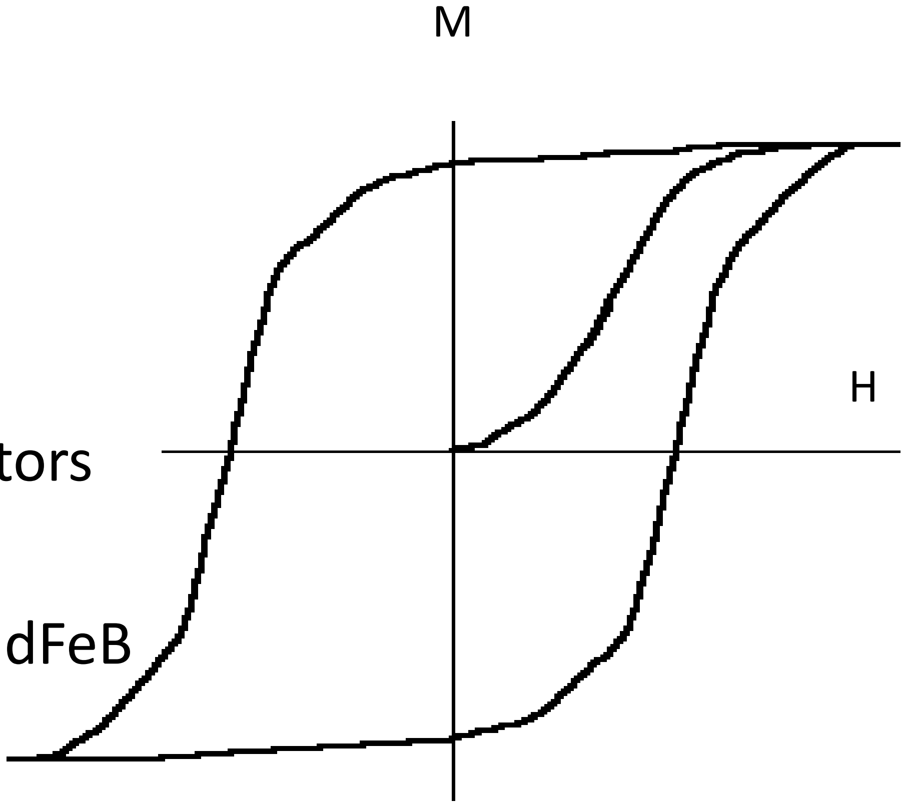
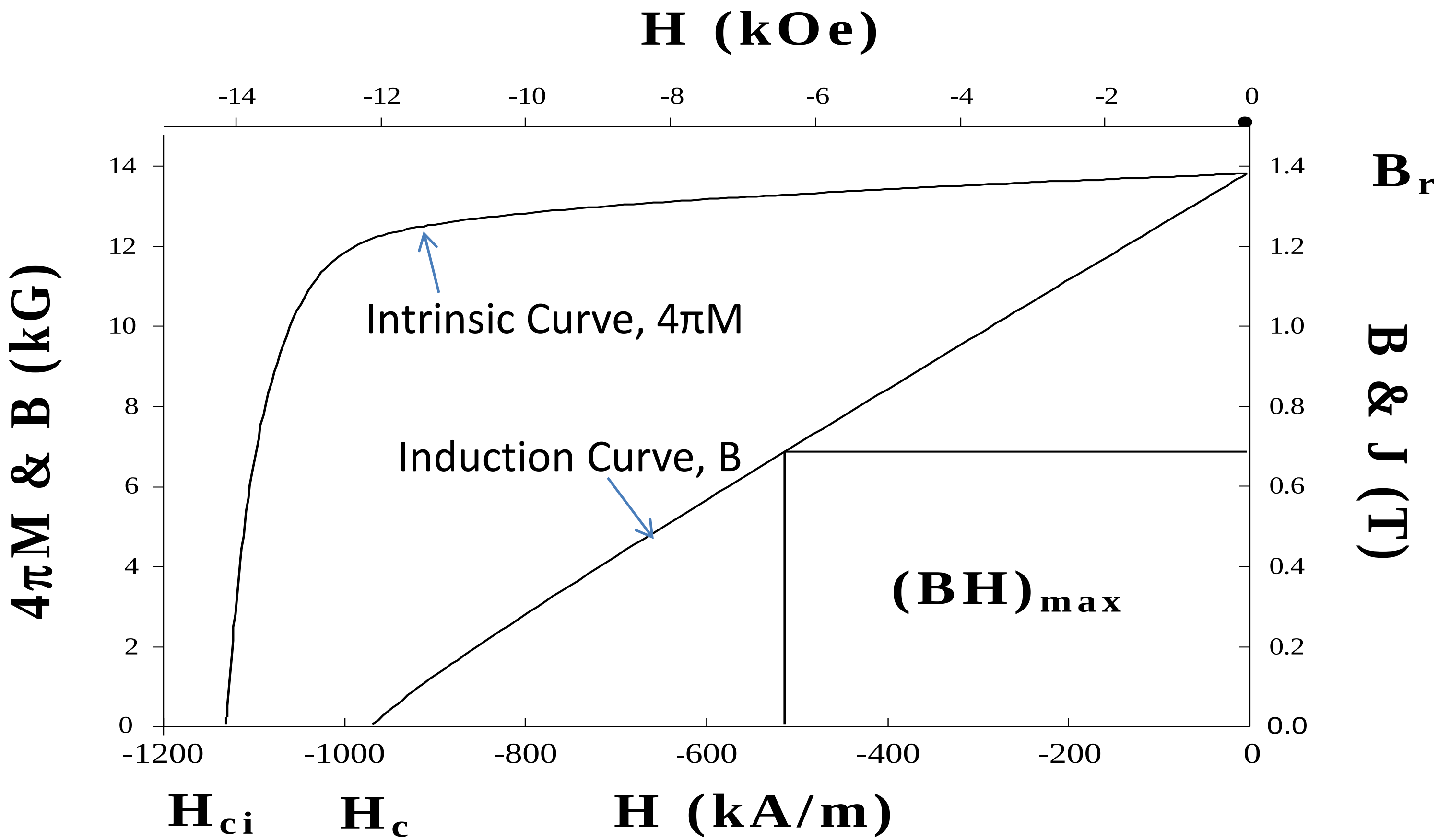
Permanent Magnets

- High H_{ci}
- High B_r
- Very square H_k
- Applications
  - Motors, sensors, actuators
- Materials
  - Alnico, ferrite, SmCo, NdFeB



Demagnetization Curves



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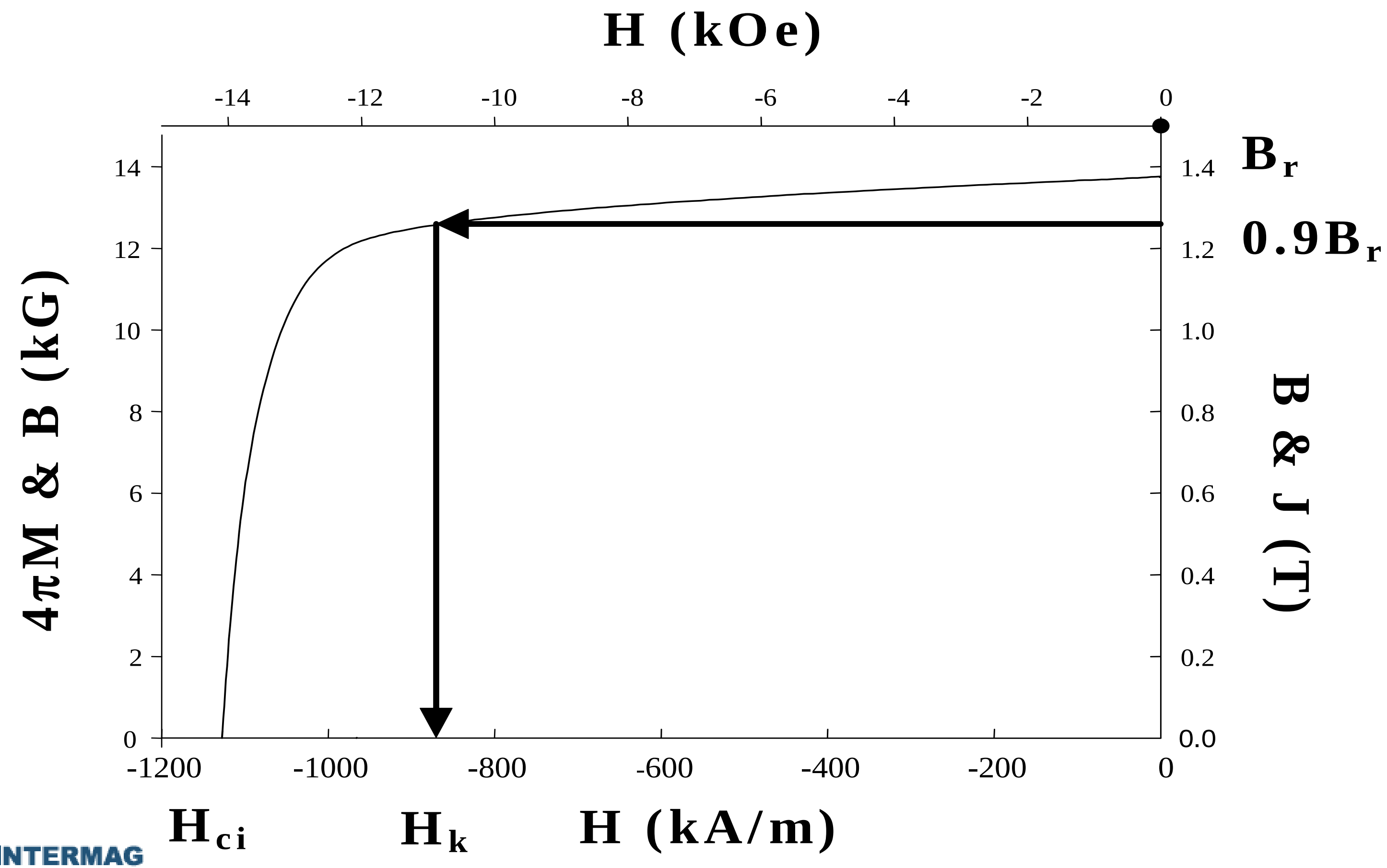
Definition of H_k



Electron Spin

- Spinning electrons produces tiny magnetic moments
- The moments are often "quenched" (cancel out) except when electrons are unpaired, 3d and 4f levels
- Favors transition (3d) and rare earth (4f) elements

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Exchange Interaction

- Interaction between neighboring atoms
- Cooperative effect, favors ordering of spins
  - Parallel, ferromagnetism
  - Anti-parallel, antiferromagnetism, ferrimagnetism
  - Complex
- Exchange competes with thermal energy
  - Gone once we reach the Curie Temperature, T_c

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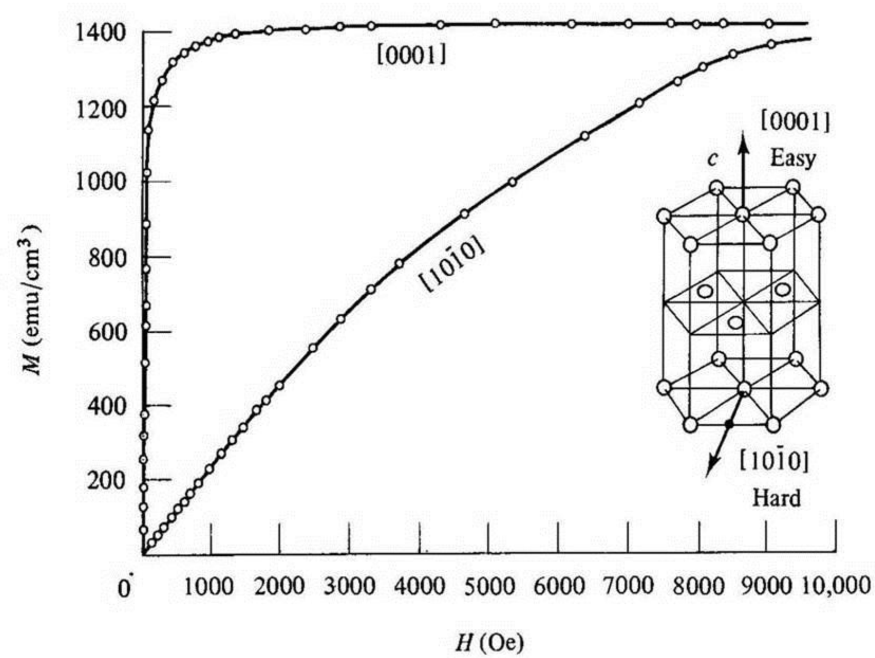
Anisotropy

- Many properties vary with direction of measurement
- Not just magnetic
- Often hard to see in polycrystalline materials
- High anisotropy enables high coercivity



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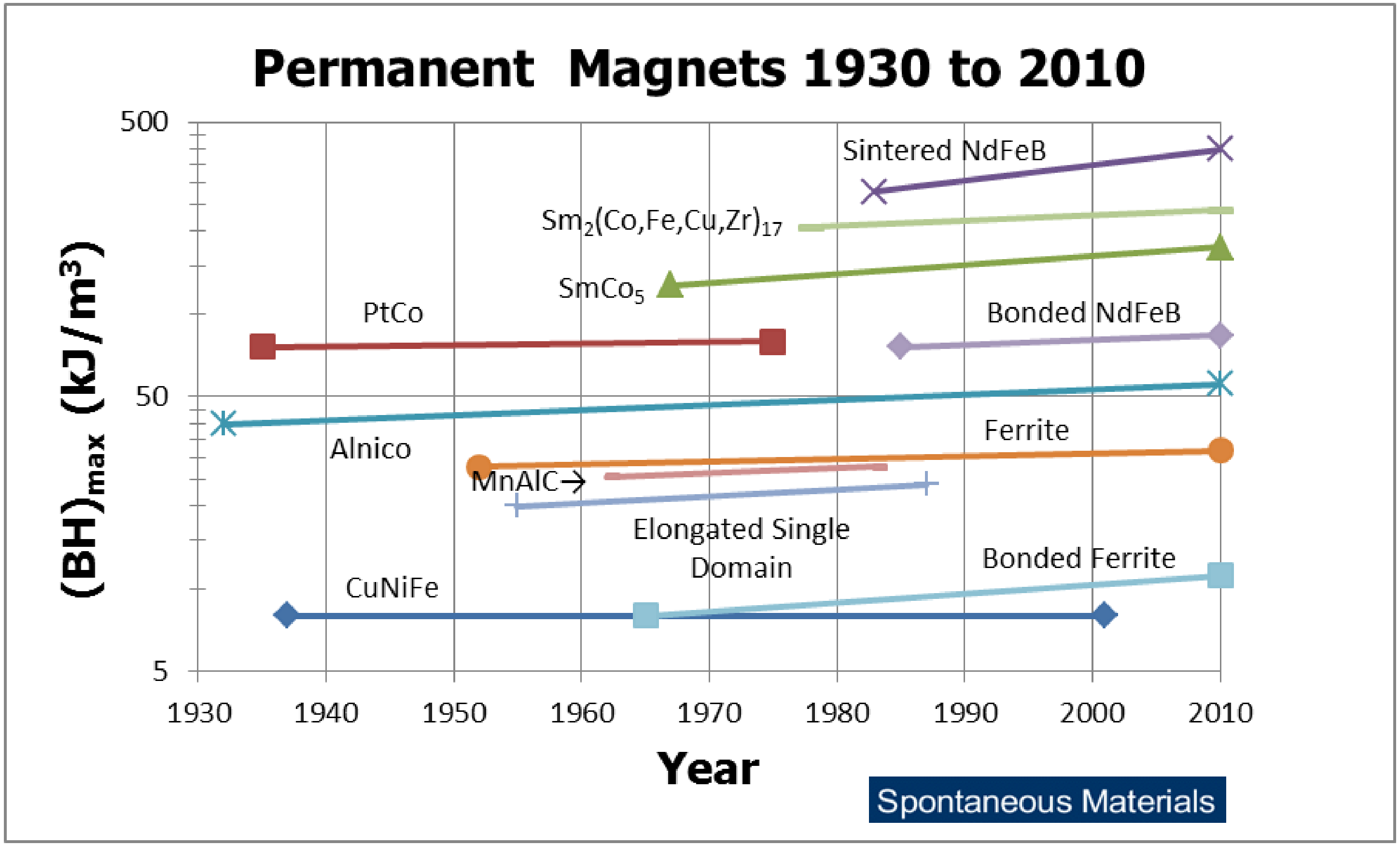

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Material Properties

	Ferrite	Alnico	SmCo		NdFeB	
Property	Ceramic 8	Alnico 5	1-5	2-17	Bonded	Sintered
B_r (Tesla)	0.40	1.25	0.90	1.05	0.69	1.34
α (%/°C)	-0.18	-0.02	-0.045	-0.035	-0.105	-0.12
$(BH)_{max}$ (kJ/m^3)	30	44	160	210	80	340
H_{ci} (kA/m)	260	51	2400	2000	720	1200
β (%/°C)	+0.4	-0.015	-0.3	-0.3	-0.4	-0.6
H_s (kA/m)	800	240	1600	2400	2800	2800
T_c (°C)	450	890	727	825	360	310

Notes : The quantity α is the reversible temperature coefficient of B_r.
The quantity β is the reversible temperature coefficient of H_{ci}.
The field required to saturate is H_s.

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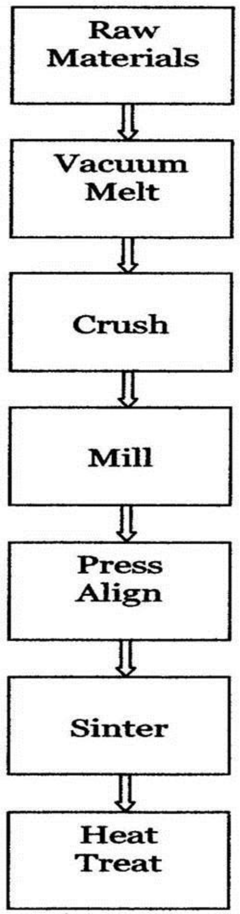
How are magnets made?



- Powder metallurgy
- Commonly used for SmCo and NdFeB
- Similar process is used for ferrites

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