Rare Earth Magnets – Hidden but Essential

Dr John Ormerod

October 27th, 2020

Los Angeles Chapter, ASM International

JOC LLC

“The Nation That Controls Magnetism Will Control The Universe”

- Dick Tracy cartoon strip, created by Chester Gould.
- Circa early-1960’s i.e. before rare earth magnets and the Chinese dominance of RE supply chain and magnet industry!

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Outline

- Introduction: Me, Rare Earths and Magnetics
- Rare Earth Magnet Markets and Applications
- Processing of NdFeB Magnets
- Summary or “Where’s the next big thing?”

Introduction - Me

- BSc, MSC and PhD in Metallurgy from the University of Manchester (1972 – 1978).
- Magnetics career began for Philips (UK and Holland) – 1979 – 1990.
  - Developed and commercialized SmCo5, 2:17 and NdFeB magnets.
- Joined Arnold Engineering (US) responsible for soft and hard magnetic materials development and GM for permanent magnets (1990 – 2002).
- 2002 - 2014 President of Res Manufacturing in Milwaukee.
  - Metal stamping and value-added assemblies to the automotive market (Toyota, GM, Nissan).
  - Major supplier to Tesla Motors for Model S and Model X.
- Provided expert testimony on key NdFeB patent challenges over the last few years.
- Advisory Board member for Bunting Magnetics, Senior Technology Advisor for MAI, CMI and Technology Advisor for Niron Magnetics.
- Founded business and technology consultancy for magnetics and metals related industries in 2015 – JOC LLC (www.jocllc.com).

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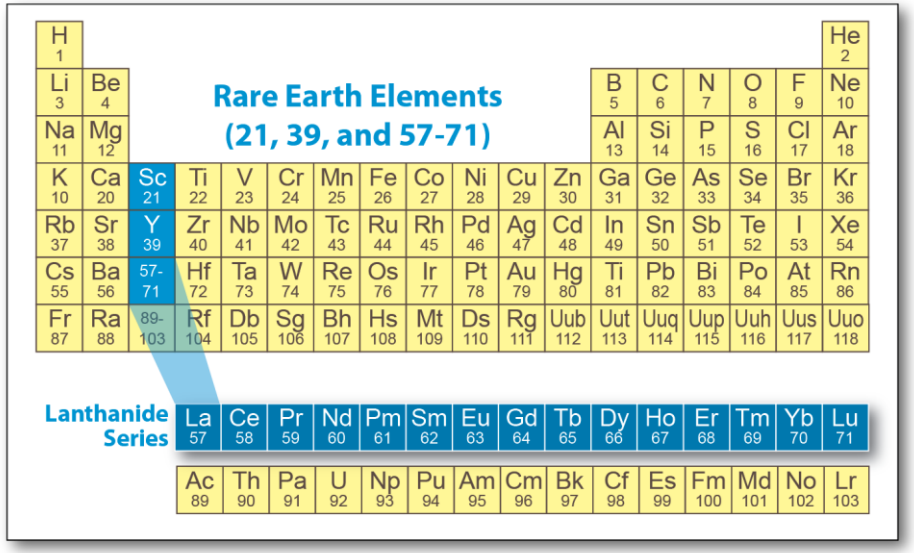
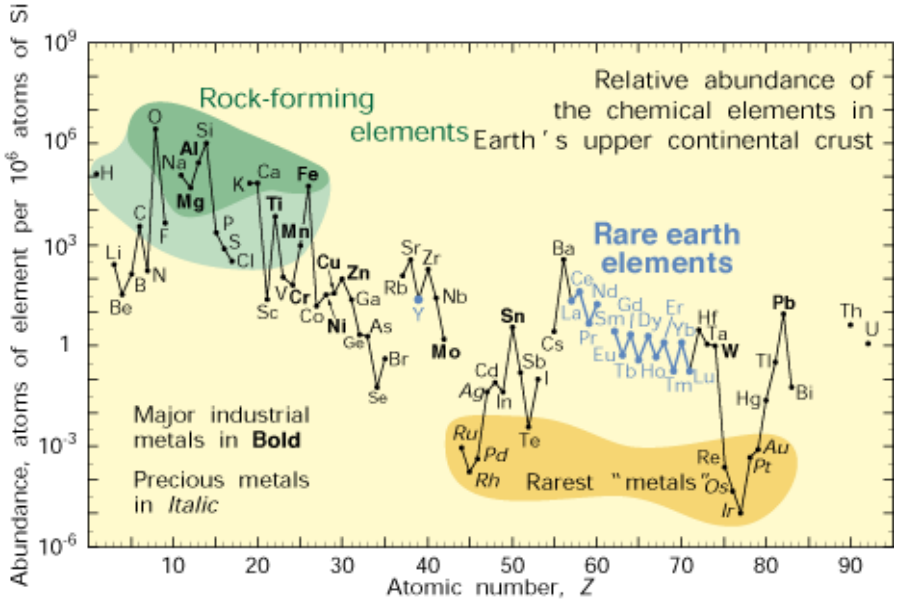
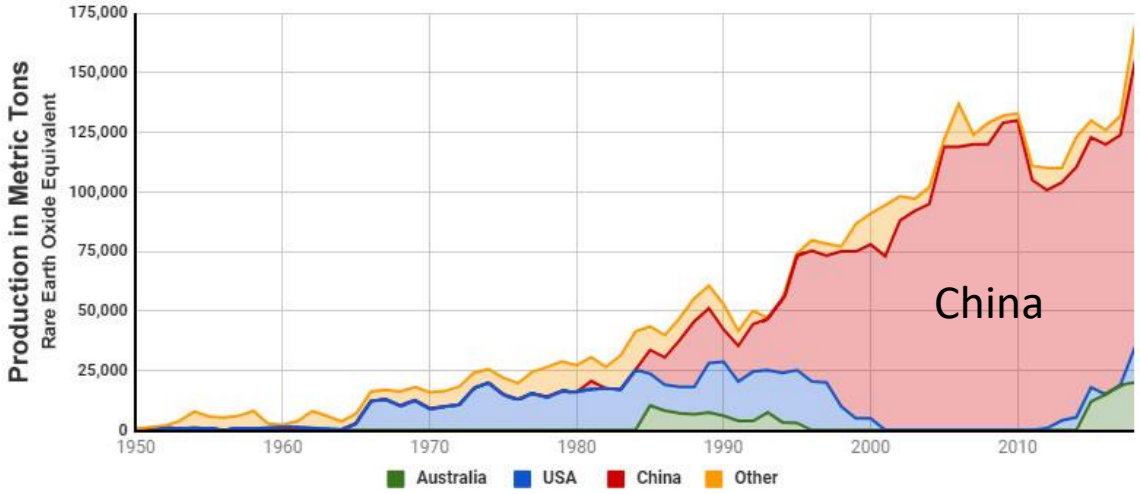
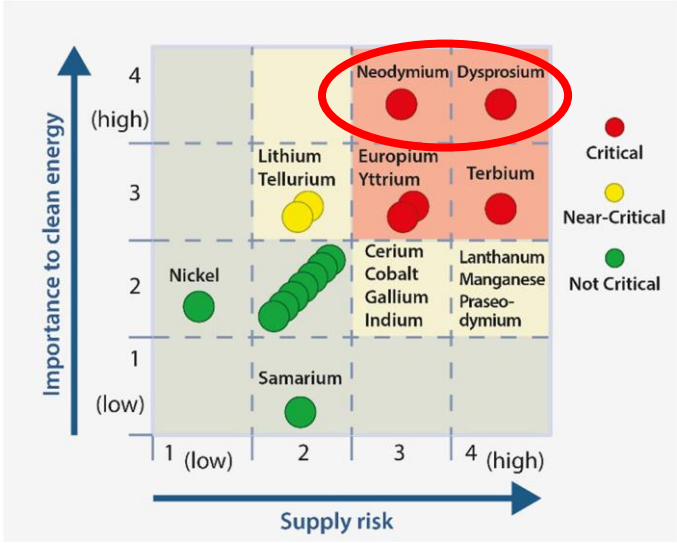
Introduction – Rare Earths









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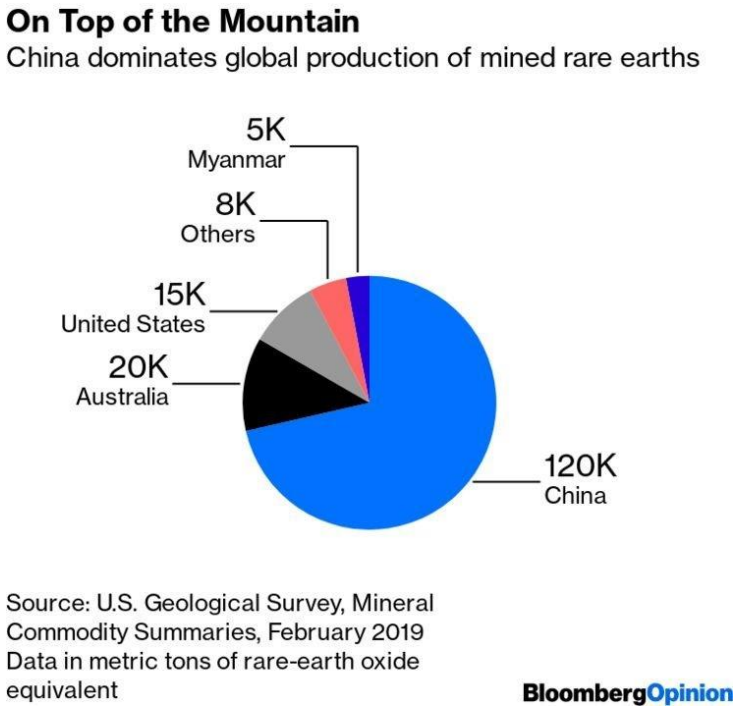
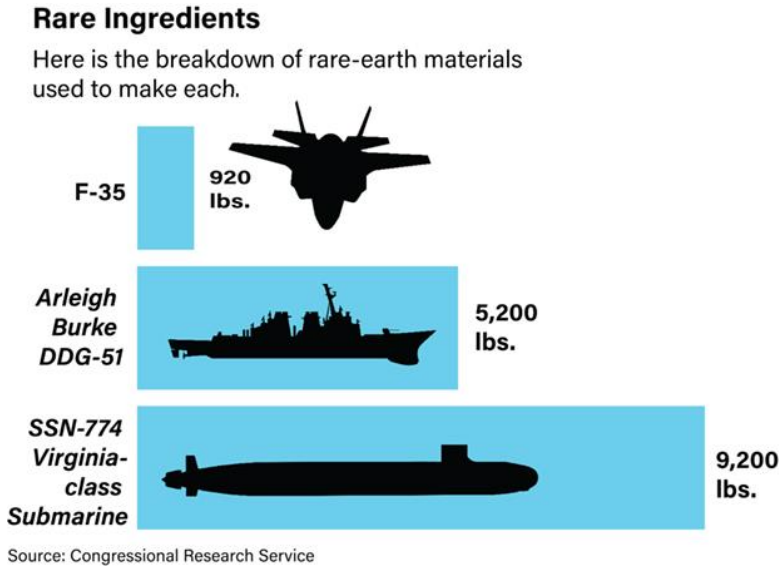


Rare-Earth Elements

Originally produced for the October 2011 issue of *Scientific American*

What Are They Used For?

Scandium	Aerospace components, aluminum alloys
Yttrium	Lasers, TV and computer displays, microwave filters
Lanthanum	Oil refining, hybrid-car batteries, camera lenses
Cerium	Catalytic converters, oil refining, glass-lens production
Praseodymium	Aircraft engines, carbon arc lights
Neodymium	Computer hard drives, cell phones, high-power magnets
Promethium	Portable x-ray machines, nuclear batteries
Samarium	High-power magnets, ethanol, PCB cleansers
Europium	TV and computer displays, lasers, optical electronics
Gadolinium	Cancer therapy, MRI contrast agent
Terbium	Solid-state electronics, sonar systems
Dysprosium	Lasers, nuclear-reactor control rods, high-power magnets
Holmium	High-power magnets, lasers
Erbium	Fiber optics, nuclear-reactor control rods
Thulium	X-ray machines, superconductors
Ytterbium	Portable x-ray machines, lasers
Lutetium	Chemical processing, LED lightbulbs



China's Downstream RE Capabilities

Separation: 75%

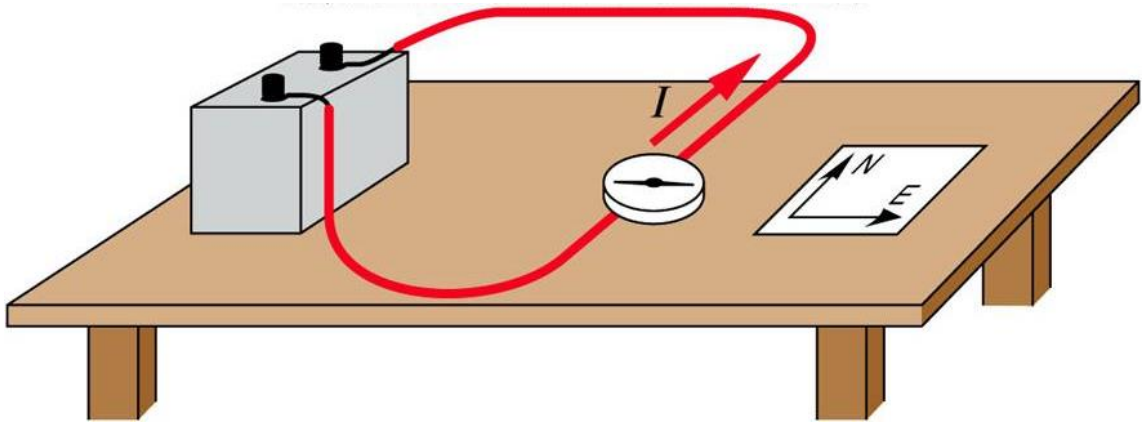
Reduction: 80%

Magnet Manufacturing: 80%

Issue is supply-demand balance

Not a good idea to be totally dependent on Chinese supply chain!

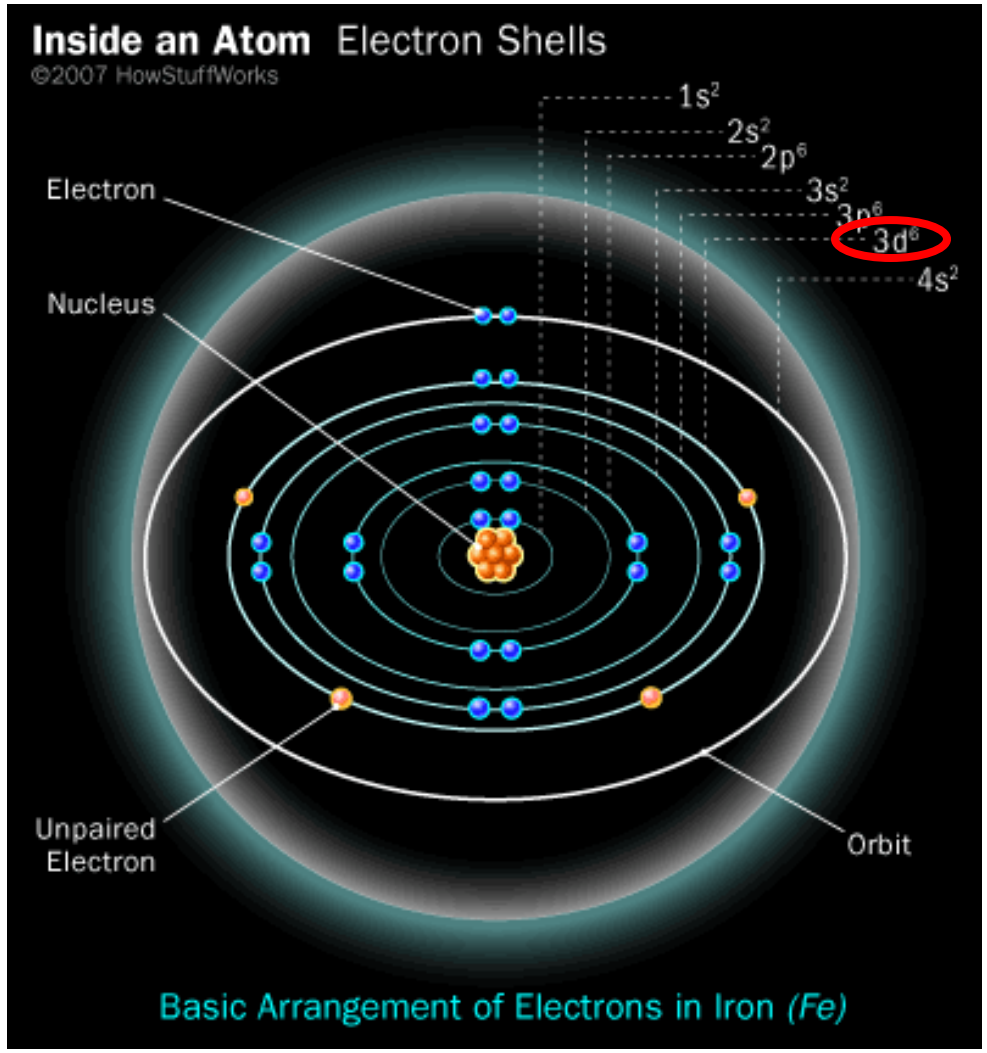
Introduction - Magnetics

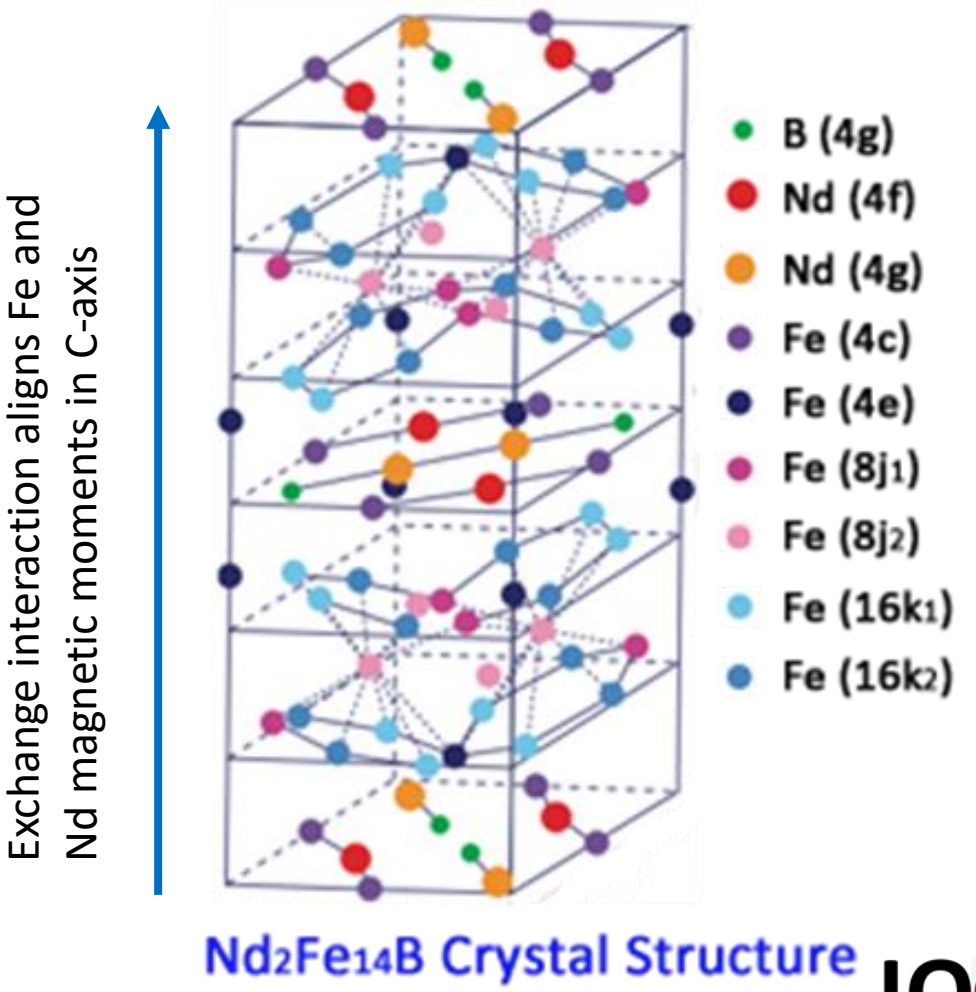


Electromagnetism accidently discovered in 1820 by Hans Oersted observed that a compass needle can be deflected by a moving electrical charge (flowing current).

What Oersted showed is that magnetic fields are created by moving charges, or currents.

Magnetism in Materials is Due to Unpaired Electron Spins





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The Three Important Magnetic Parameters

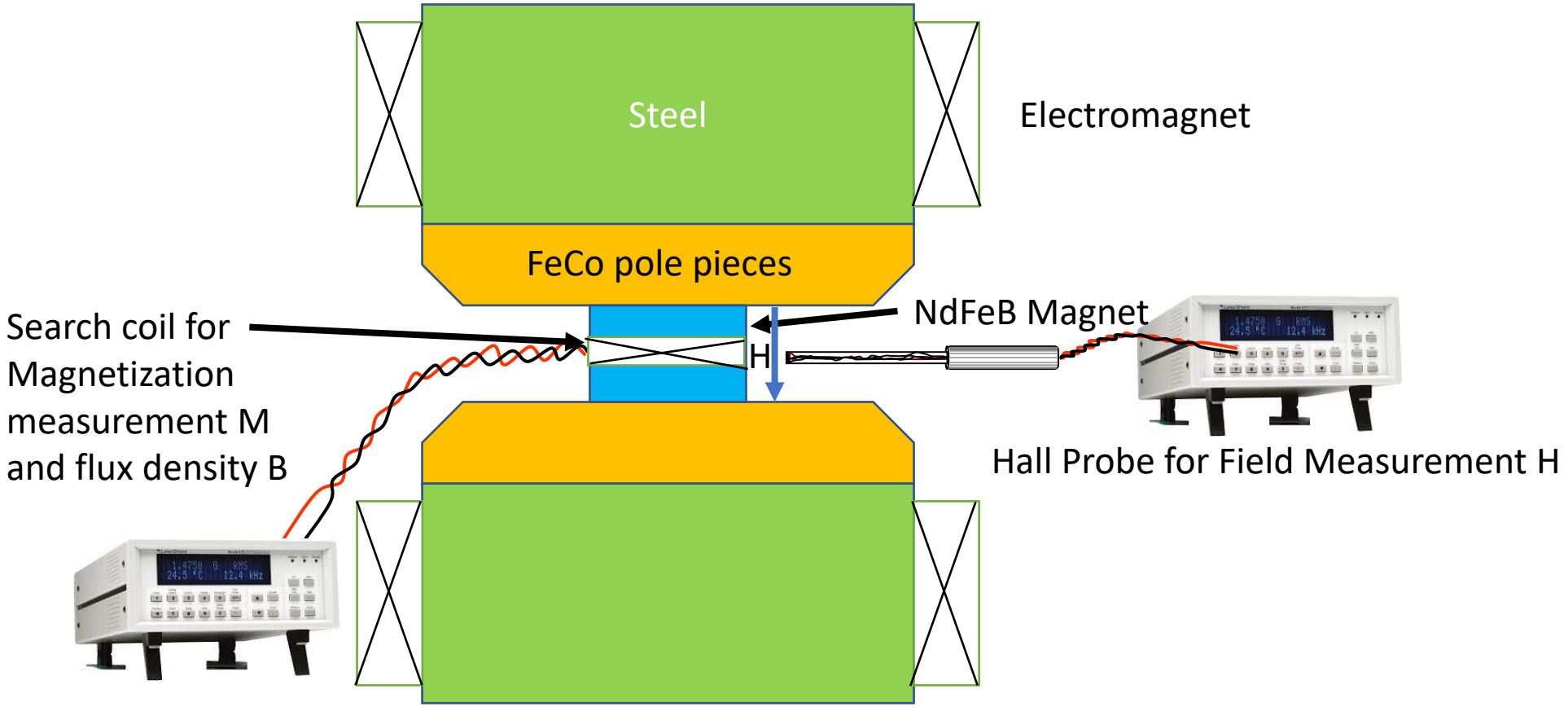
- H - Magnetic field (conventionally from current). Units of Oersted or kA/m.
- M – Magnetization (the magnetic state of a material). Units of Gauss or Tesla.
- B – Induced magnetization in a materials or flux density. Units of Gauss or Tesla.

These vectors quantities are not independent but are related.

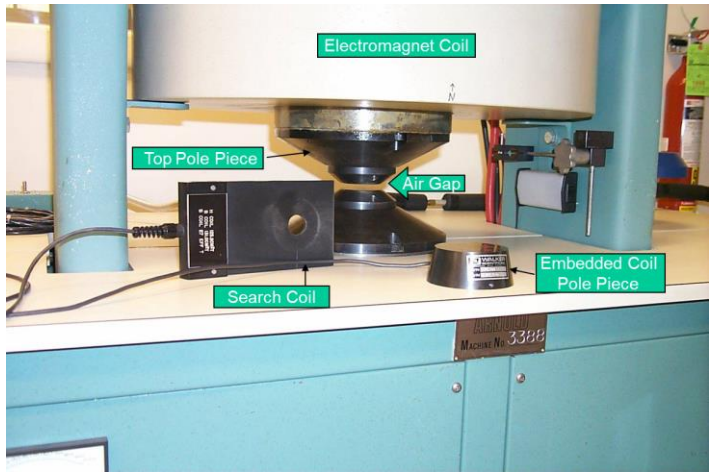
Induction (B) is the combination of magnetization (M) and magnetic field (H).

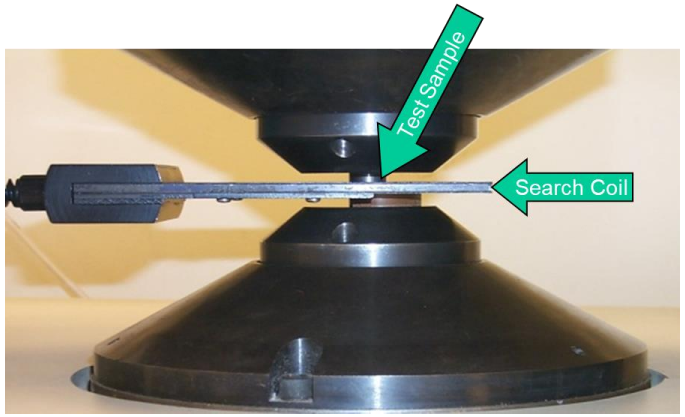
$$B=H + 4\pi M$$

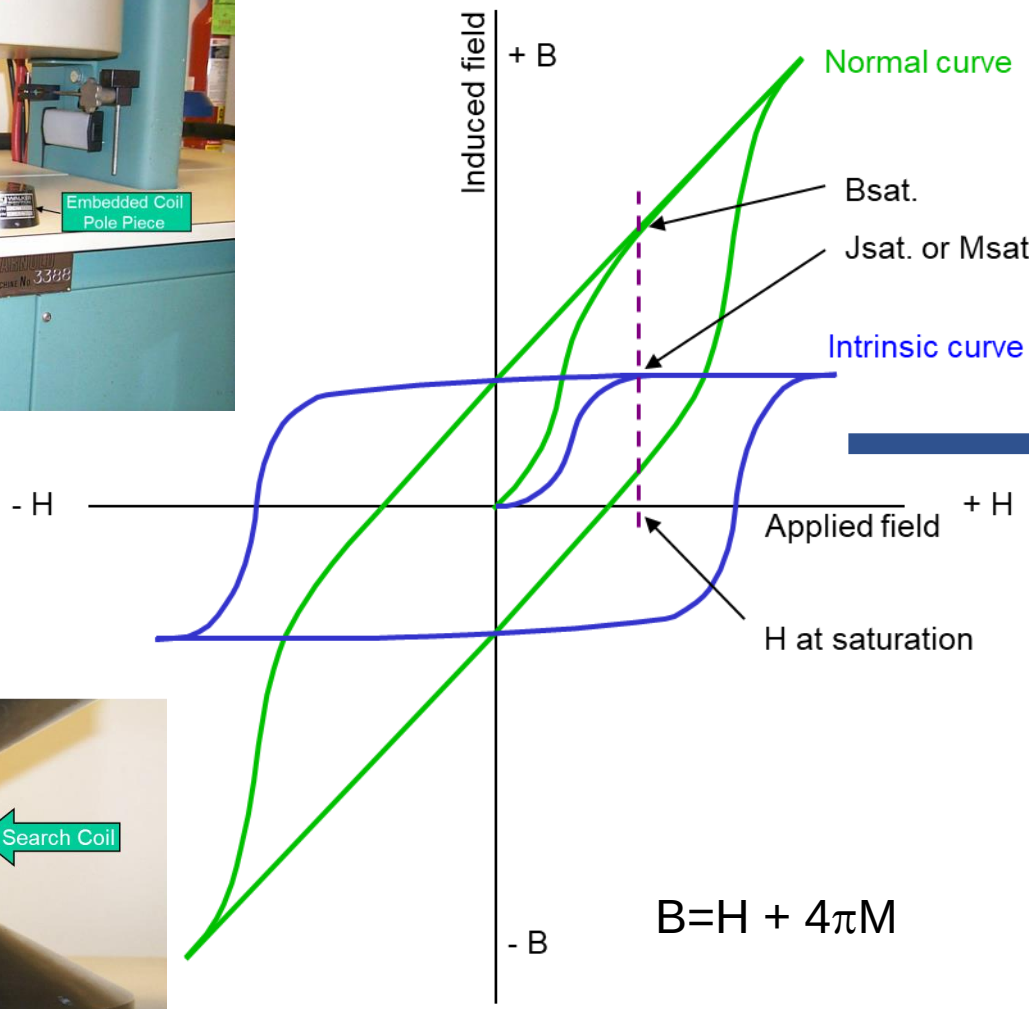
Hysteresis Measurement of NdFeB Magnet



Hysteresis Loops – Normal and Intrinsic

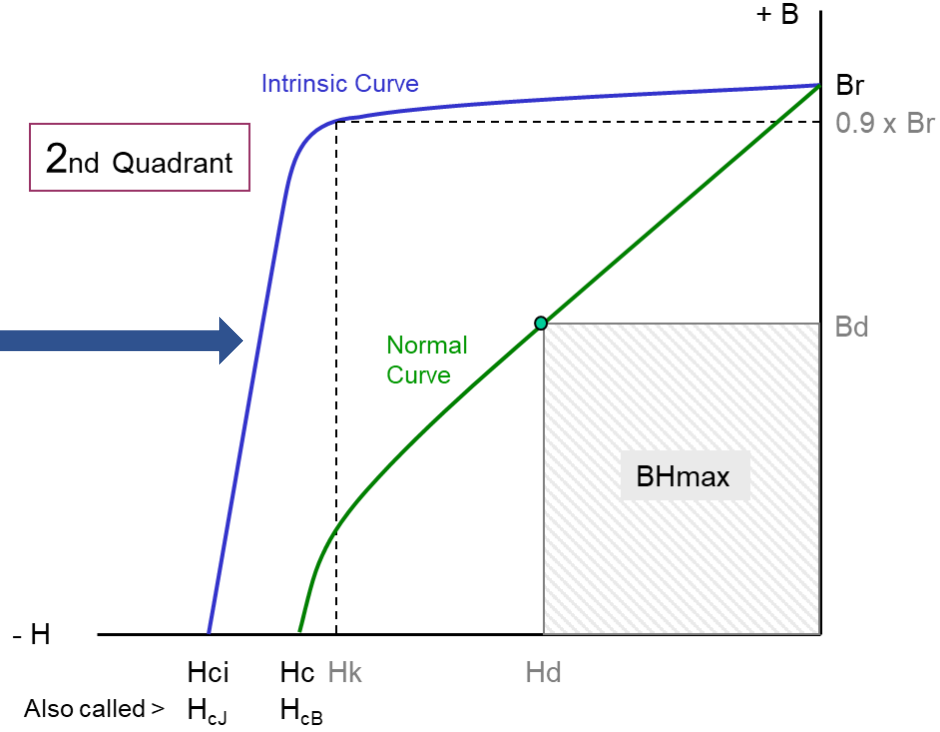






$B=H + 4\pi M$

2nd Quadrant

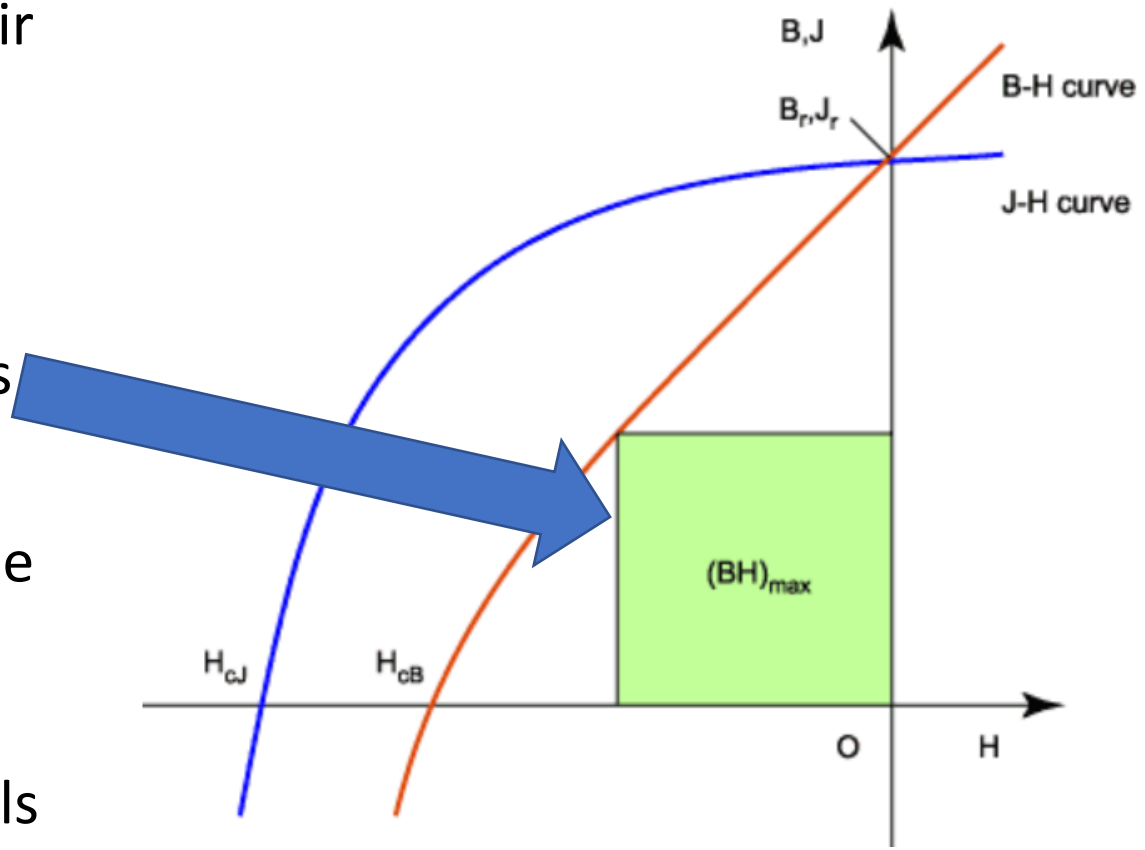


Key PM Magnetic Properties

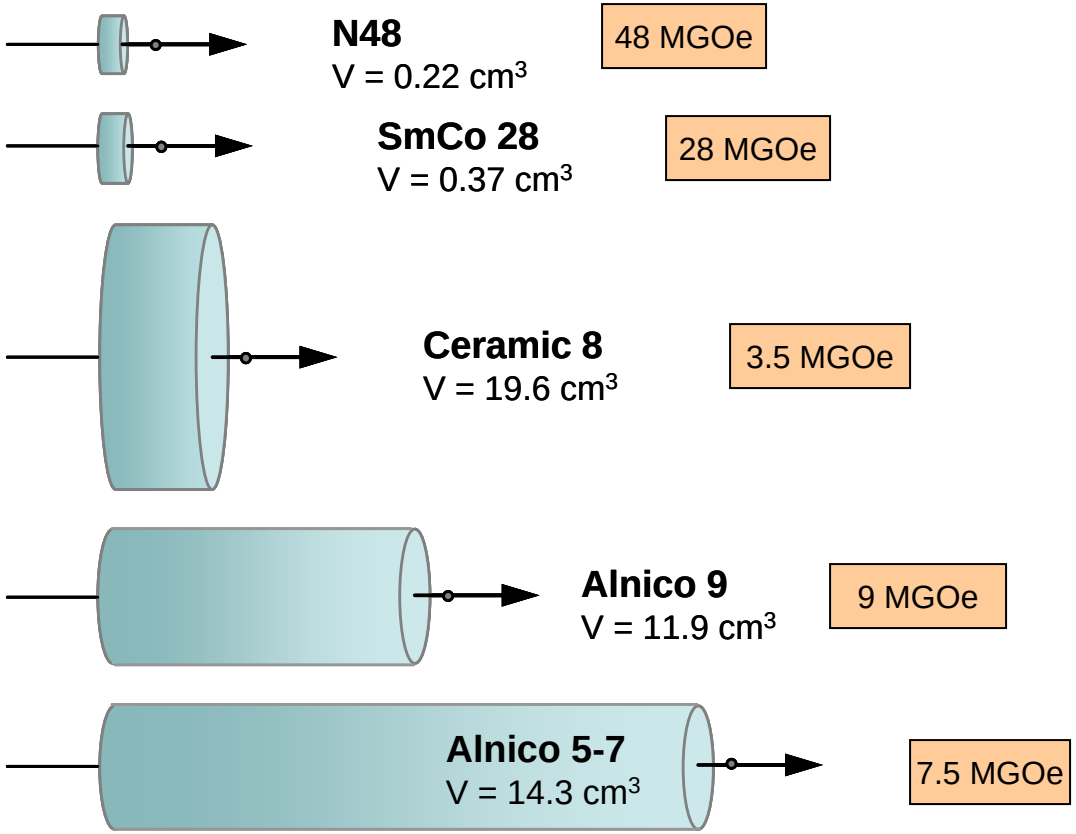
- **B_r**, Remanence or Remanent Induction – indicates available flux output from the magnet after magnetized to saturation and the field is removed. Units of Gauss or Tesla..
- **IH_c**, Intrinsic coercivity or **BH_c**, normal coercivity – indicates the magnet's resistance to demagnetization. Units of Oersted or kA/m.
- **$(BH)_{max}$**, Maximum Energy Product – a figure of merit for how much potential magnetic energy per unit volume is available in a grade/material type. Units of MGOe or kJ/m^3

What Is $(BH)_{max}$?

- The energy stored in the field in an air gap is directly proportional to the product of B and H on a point on the normal curve – BH known as energy product.
- The volume of a magnet required to produce a given field in a given gap is minimum when the product of BH is maximum – $(BH)_{max.}$
- The higher the $(BH)_{max}$ the smaller the magnet volume to generate a given flux density.
- However, if device volume or weight are not critical lower $(BH)_{max}$ materials can be used with same performance.



Relative Magnet Volumes versus $(BH)_{max}$



Relative magnet size and optimal shape to generate 1000 gauss flux density (B) at 5 mm from the pole face.

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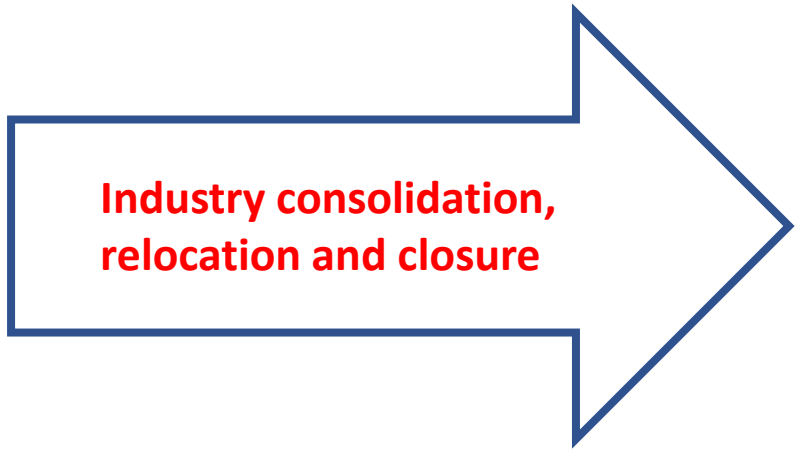
US Permanent Magnet Industry From 1995 to Today (US Manufacturing)

Arnold(Ferrite/Alnico/Smco/Bonded)
Crucible(Ferrite/Alnico/NdFeB) Closed
Kane Magnetics(Ferrite/Alnico/Bonded) Closed
Permanent Magnet Co. (Alnico) Closed
General Magnetics (Ferrite) Closed
Ugimag(NdFeB) Acquired/Closed
TDK(Ferrite)
Hitachi Metals(Alnico/Ferrite/NdFeB)
Electron Energy (SmCo)
Dynacast(Bonded Magnets) Acquired
Thomas & Skinner(Alnico/SmCo)
Magnequench(NdFeB) Relocated
Tengam(Bonded Magnets)
Magnet Applications (Bonded)
Electrodyne(Bonded)
RJF (Bonded) Acquired
Magnum (Bonded)
Magnetic Specialty (Bonded) Acquired
Flexmag Industries (Bonded) Acquired



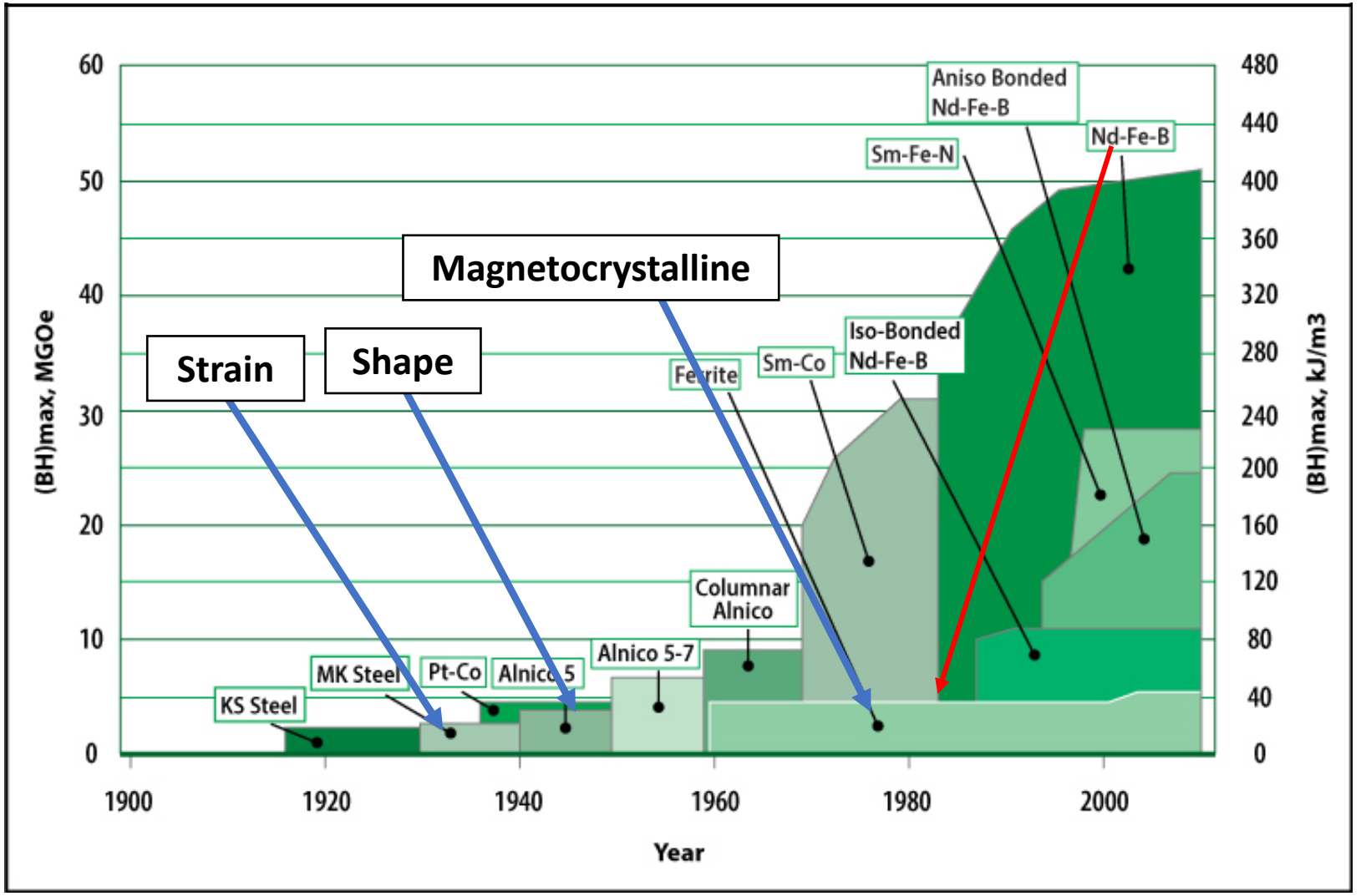
Arnold(Alnico/Bonded)

TDK(Ferrite)
Hitachi Metals (Ferrite)
Electron Energy (SmCo)

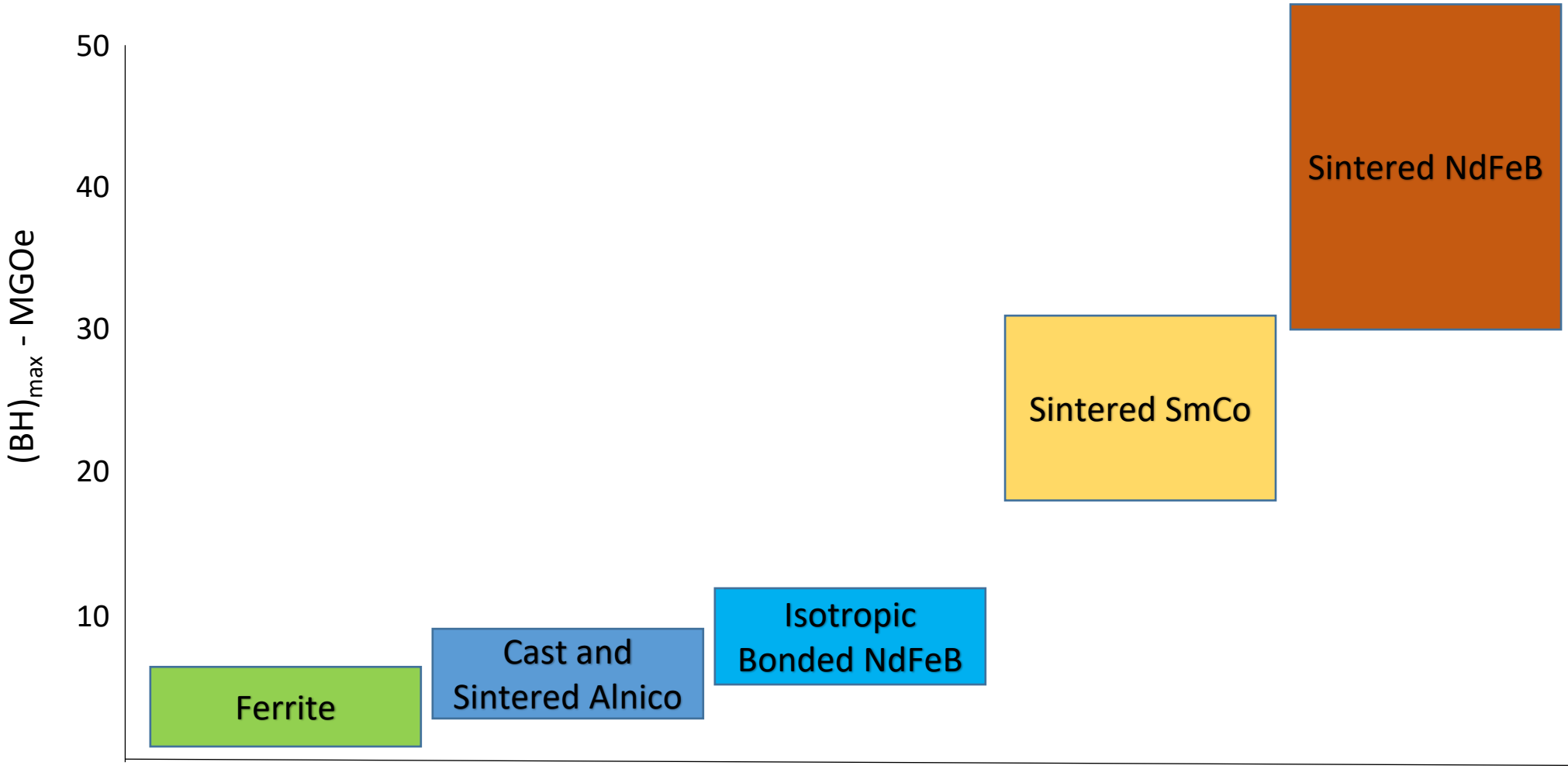
Thomas & Skinner(Alnico)

Tengam(Bonded)
Magnet Applications (Bonded)
Electrodyne(Bonded)
Magnum(Bonded)

History of Permanent Magnet Development
Is It Time For A New Breakthrough?



The 5 Commercially Important Classes Of Permanent Magnets



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Estimated Permanent Magnet Market – 2018 to 2020

	2018		2020	
Material	**Weight (000's kg)**	**Value ($ Millions)**	**Weight (000's kg)**	**Value ($ Millions)**
NdFeB	160,000	11,200	190,000	12,000
Ferrite	830,000	5,800	900,000	6,500
Bonded NdFeB	11,000	1000	12,000	1100
SmCo	4,200	400	4400	450
Alnico	6,300	350	6750	400
Other	2000	150	2200	175
	Total	Approximately $19 B		Approximately $21 B

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Estimated Permanent Magnet Market – 2020 to 2040

	2020	2030	2040
Material	**Weight (000's kg)**	**Weight (000's kg)**	**Weight (000's kg)**
NdFeB	190,000	450,000	600,000
Ferrite	900,000	950,000	1,000,000
Bonded NdFeB	12,000	14,000	18,000
SmCo	4,400	4,700	5,000
Alnico	6,750	6,850	7,000
Other	2200	2,500	3,000

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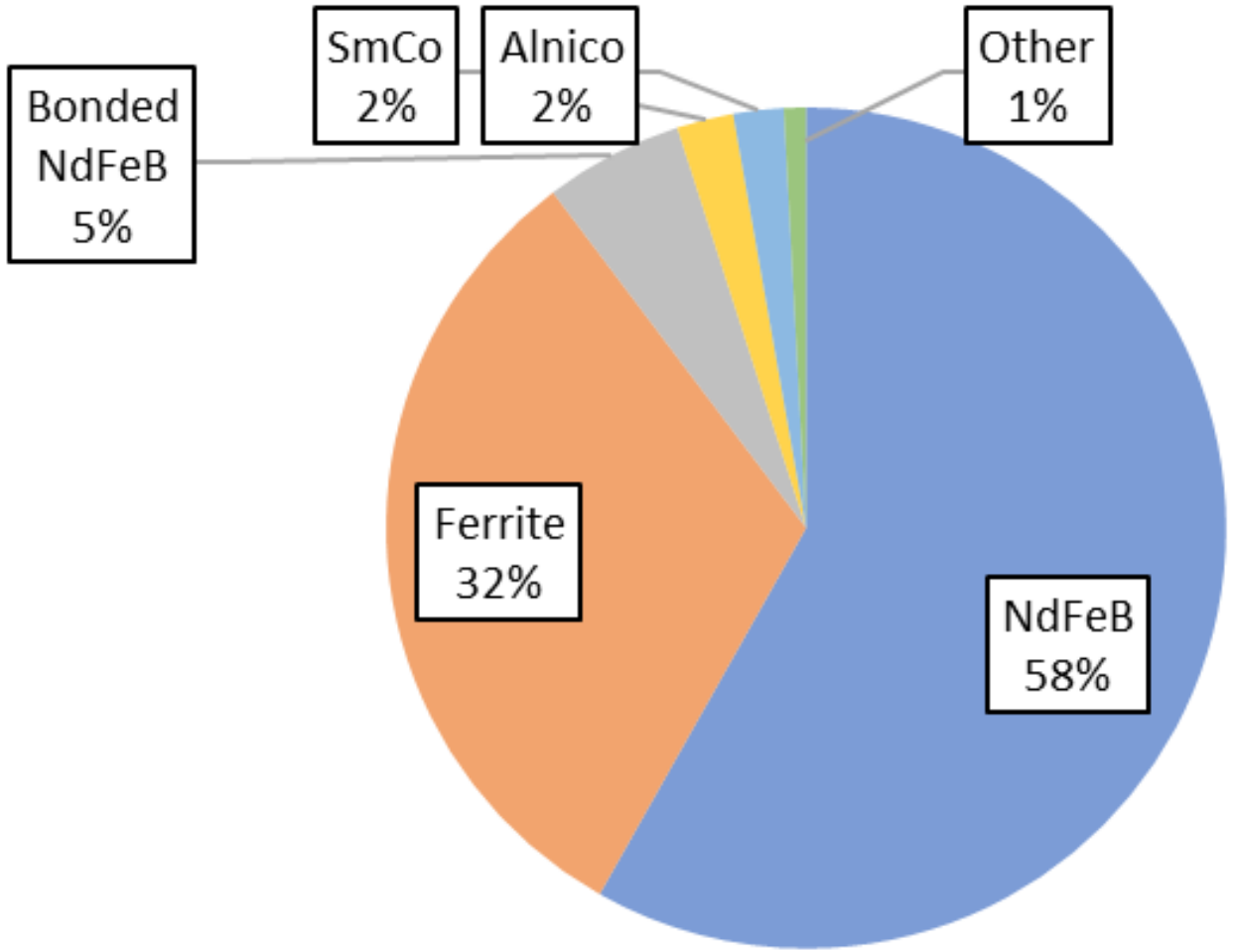
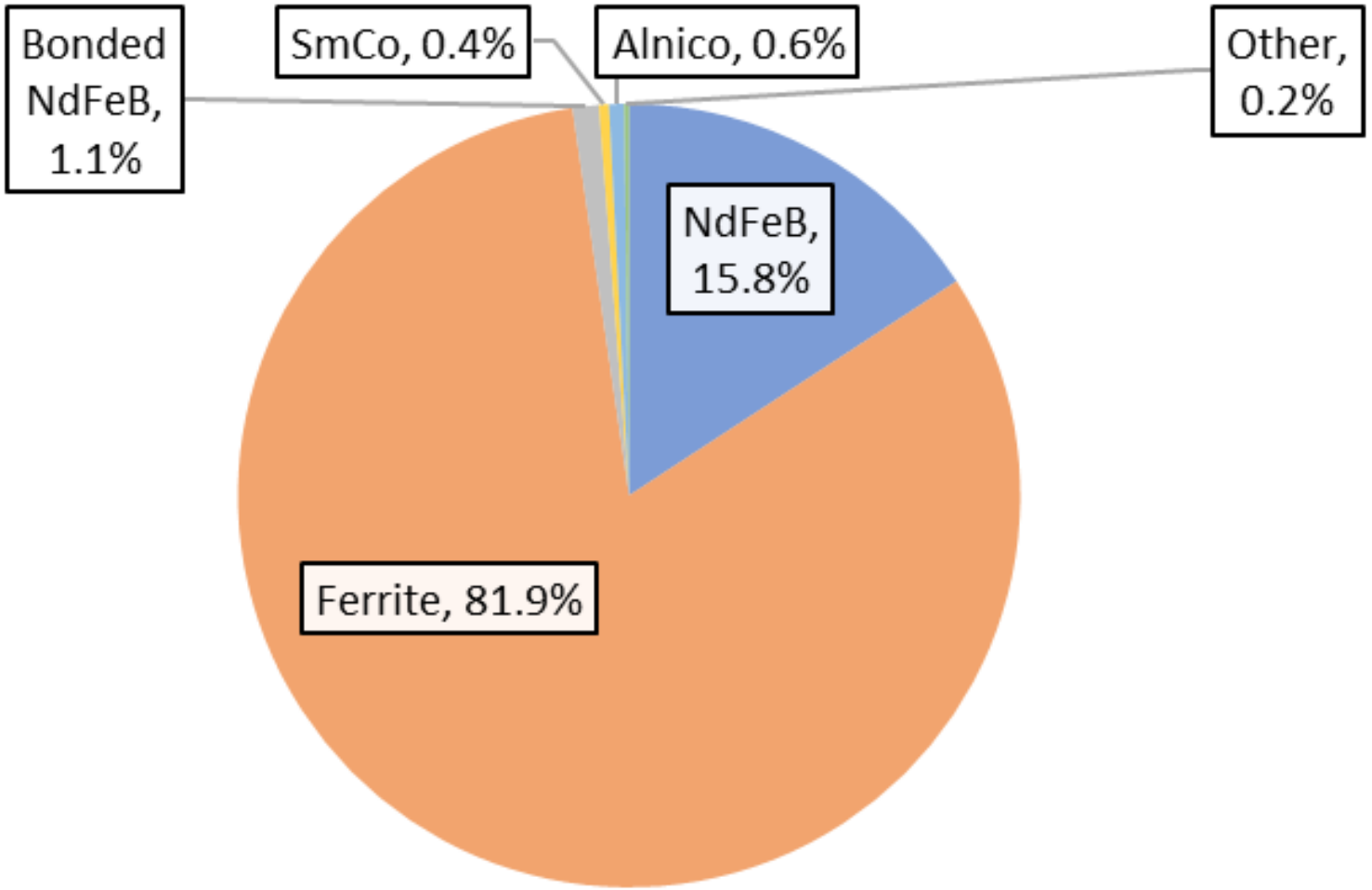
Market ($) Is Dominated By NdFeB And Ferrite



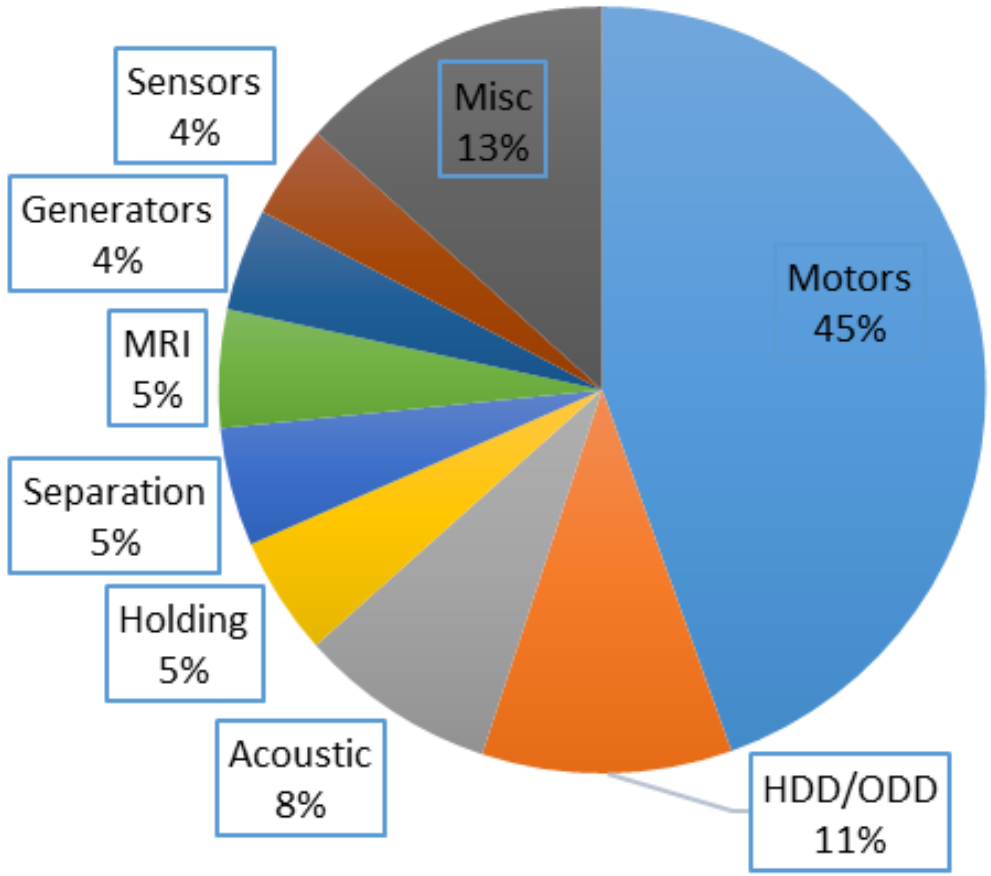
Production (Tons) Is Dominated By Ferrite



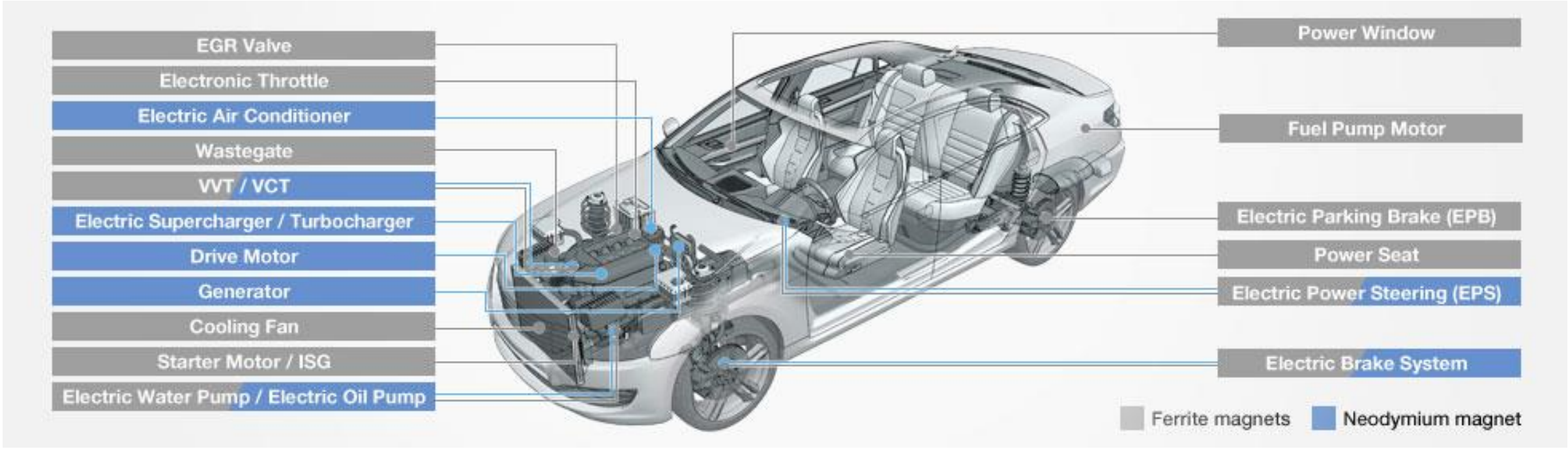
Major Functions Of A Magnet

Application Category	Physical Law	System Function is Proportional to	Application Examples
Electrical to Mechanical (with solid conductor)	Lorentz Force law	B	Loudspeakers, PM motors, HDD/ODD VCM
Mechanical to Electrical	Faraday's Law of Induced voltage	B	Generators, Alternator, Tachometer, Magneto, Microphone, Eddy current devices, sensors
Magnetostatic Field Energy to Mechanical Work	Coulomb Force Principles	B^2	Magnetic Chucks, Conveyors, Magnetic Separators, Reed Switches, Synchronous Torque Couplings
Electrical to Mechanical (with free charged particles)	Lorentz Force law	B	Travelling Wave Tubes, Magnetrons, Klystrons, MRI

Market By Major Application Type



Automotive Applications – NdFeB Is Gaining Ground!



Source: TDK: https://product.tdk.com/info/en/products/magnet/technote/ap_automotive.html

Current And Future Major Applications

- Hybrid and electric cars & trucks are in a rapid growth phase:
  - 22,000 tons of RE magnets in 2020.
  - Forecast to be largest consumer of RE magnets by 2030.
- Electric bicycles is another large and growing application.
  - estimated 17,000 tons in 2020
- HDD (servers, cloud storage):
  - RE magnet estimated in 2018 is 8,000 tons.
  - Future demand flat to declining.

Source: Magnetics and Materials LLC, WTBenecki LLC, numerous industry sources

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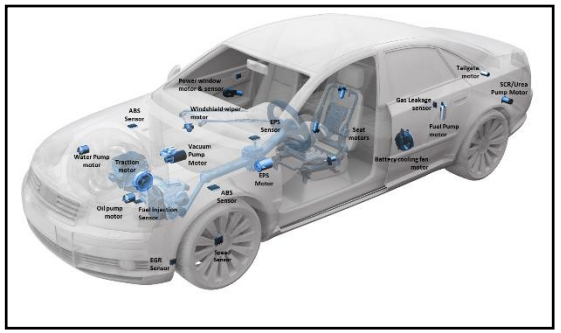
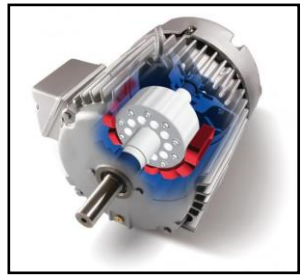
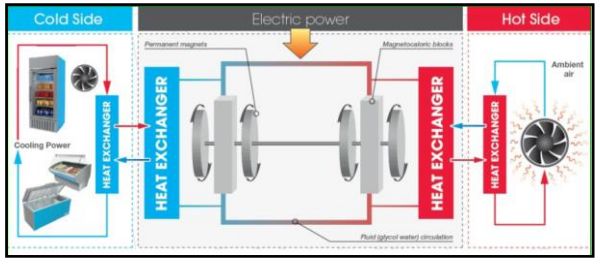
Current And Future Major Applications

- Direct Drive wind turbines:
  - RE magnet weight forecast in 2020 is 38,000 tons.
- Automotive (ICE):
  - Over 100 PM devices in a typical car.
  - Estimated 12,000 tons usage in 2020.
- General industrial and commercial motors for robotics, appliances, HVAC etc.
  - Estimated 15,000 tons in 2020
- Acoustic transducers.
  - Micro magnets (> 5 billion magnets)
  - Estimated 5,000 tons in 2020
- Magneto calorific cooling for refrigeration and HVAC is a potential major application.







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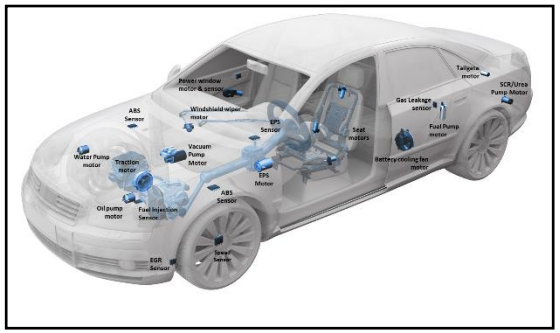

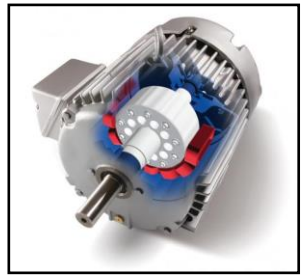

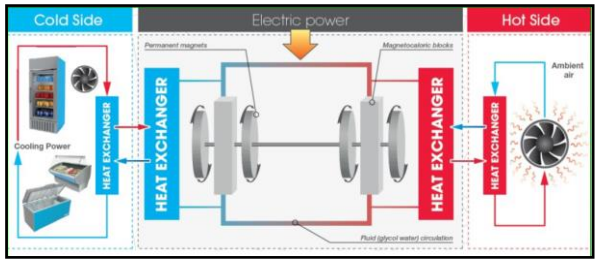

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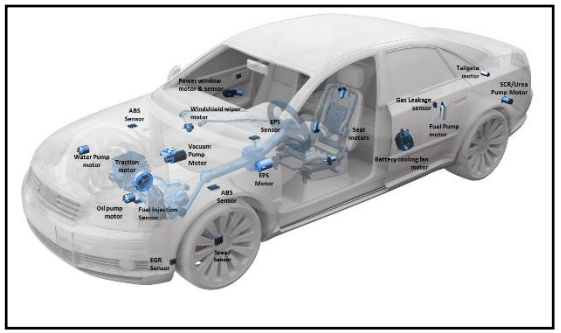

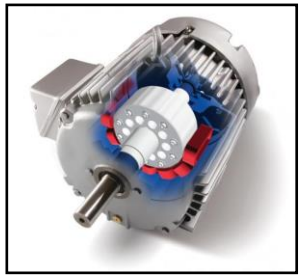

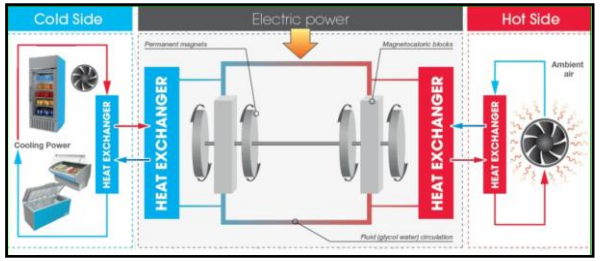

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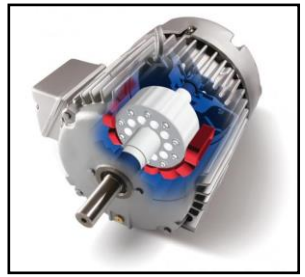

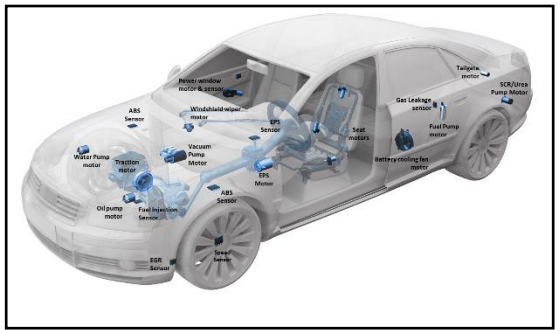

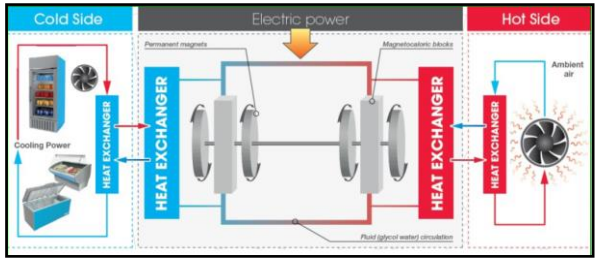

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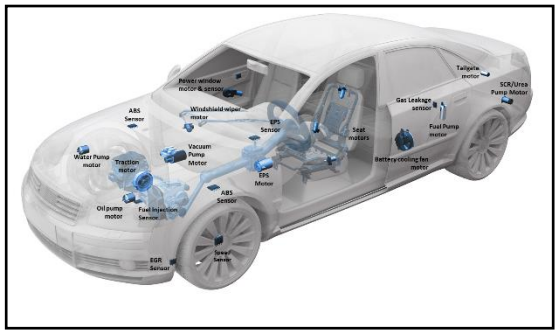
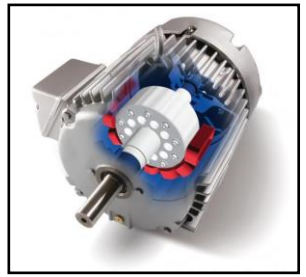
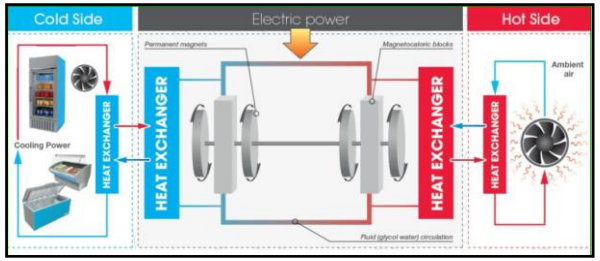






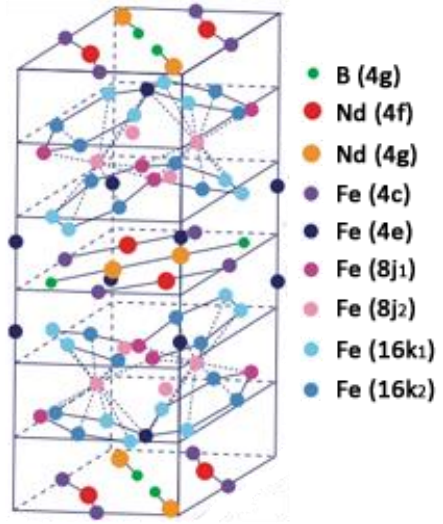
Source: Magnetics and Materials LLC, WTBenecki LLC, numerous industry sources

Outline

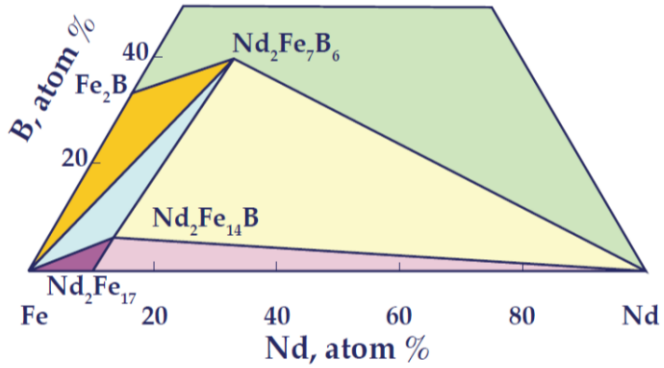
- Introduction: Me, Rare Earths and Magnetics
- Rare Earth Magnet Markets and Applications
- Processing of NdFeB Magnets
- Summary or “Where’s the next big thing?”

The NdFeB Era

- By a strange coincidence permanent magnets based on the Nd2Fe14B tetragonal compound were discovered, and the key inventive claims were filed, during 1982 by both General Motors Corporation (GMC) and Sumitomo Special Metals Corporation (SSMC). SSMC was later to form a JV with Hitachi and eventually merged as Hitachi Metals in 2007. GMC spun off the NdFeB magnet business as Magnequench; today part of Neo Materials.
- The Hitachi process is based on powder metallurgical processing whereas the Magnequench process is based on melt spinning or jet casting.

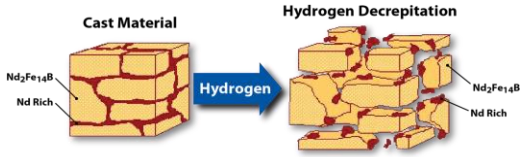


$Nd_2Fe_{14}B$ Crystal Structure

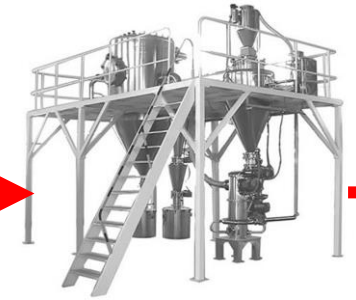


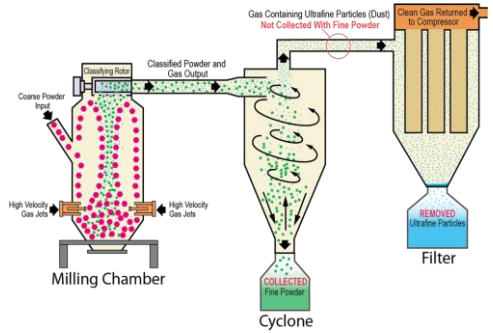
Typical Powder Metallurgical Processing of NdFeB

Strip Casting

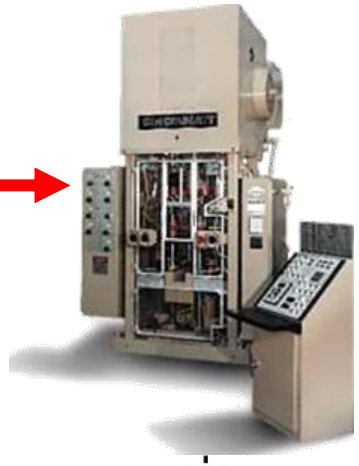


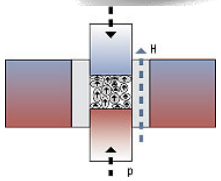
Hydrogen Decrepitation





Jet Milling

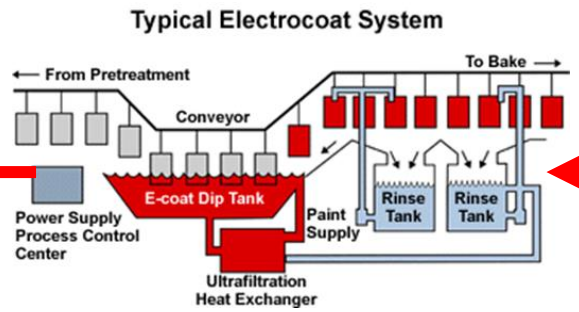




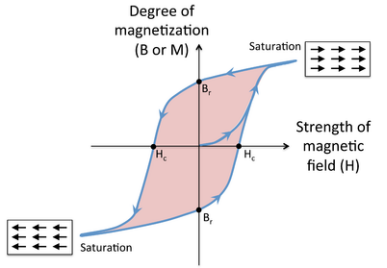
Pressing in Magnetic field

Sinter and Heat Treat

Machining

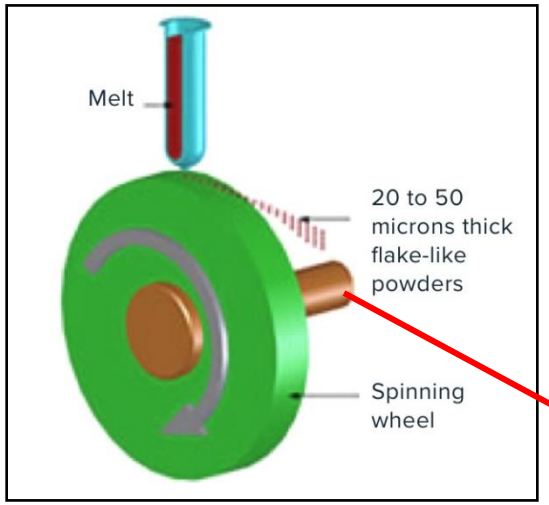


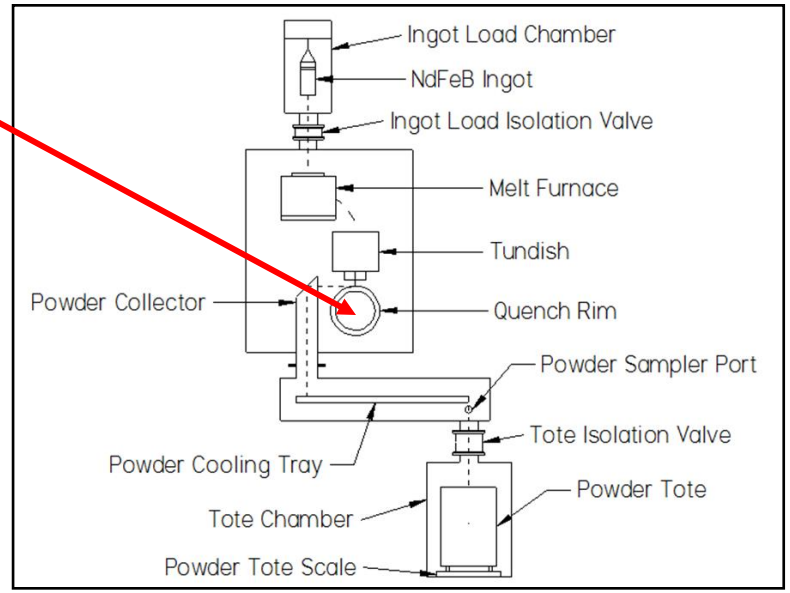
Plating



Magnetize

Melt Spinning (Jet Casting) Of NdFeB





- This method of melt-spinning consists of melting the alloy or elements in a tube either under vacuum or inert gas. The melt, under argon pressure, is sprayed through an orifice in the tube onto a rotating, water-cooled copper wheel or disc. Cooling rates in excess of 10^6 K/s are achieved.
- GM commercialized this technology for the production of magnets, known as Magnequench.
- The isotropic powders are mainly used in bonded magnet production.

Source: J.J. Croat, Rapidly Solidified NdFeB PM's, Woodhead Publishing, 2018.

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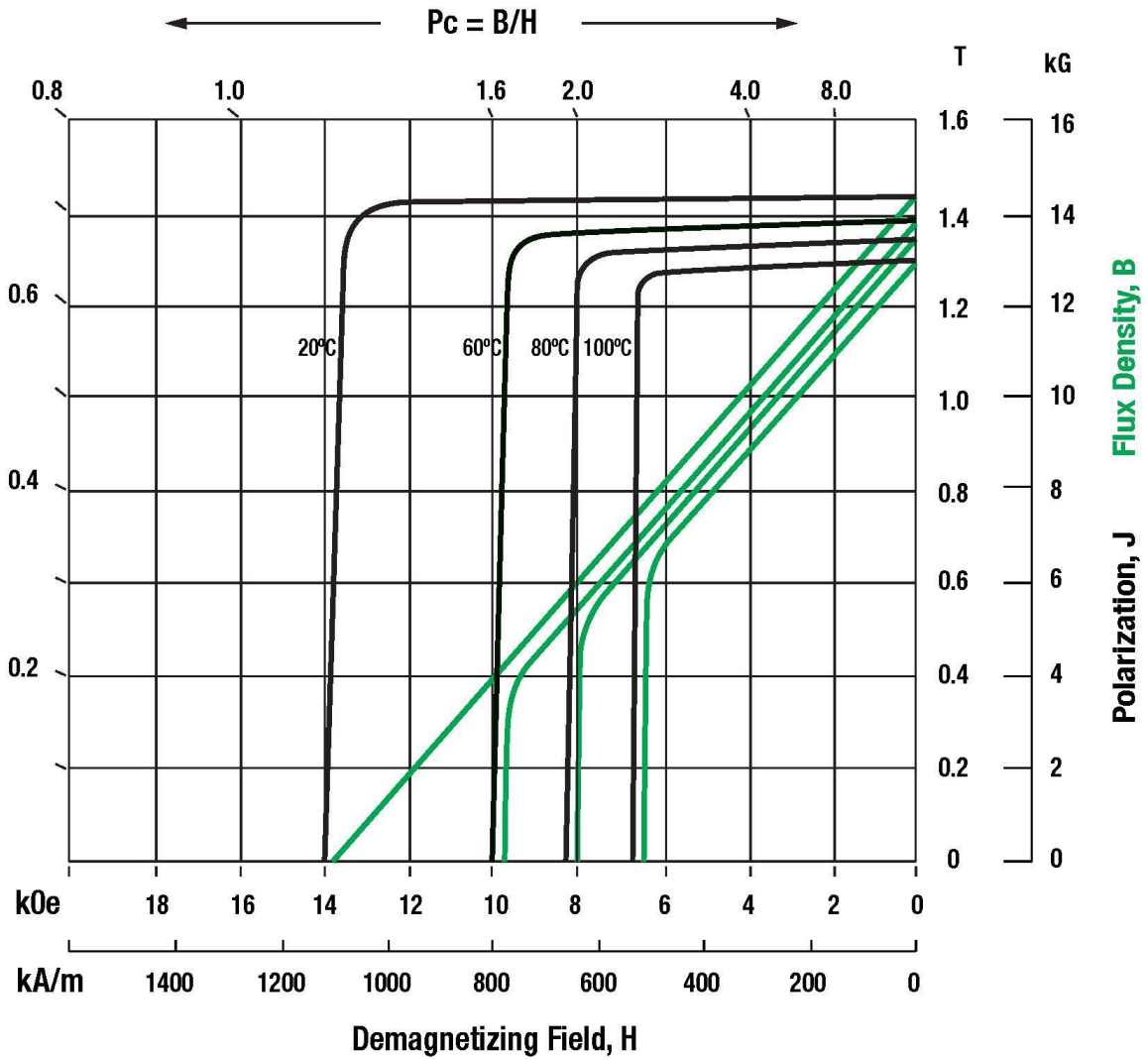
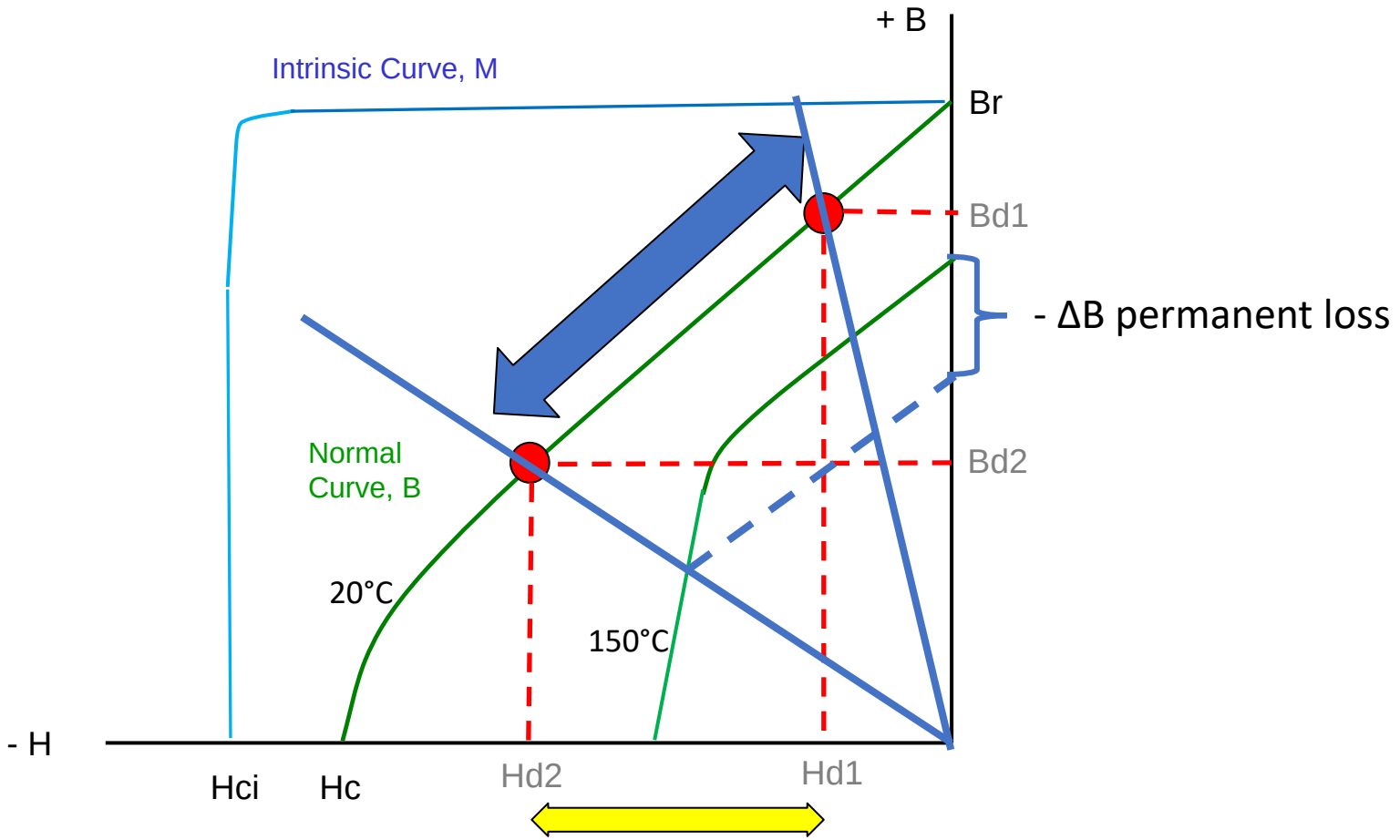
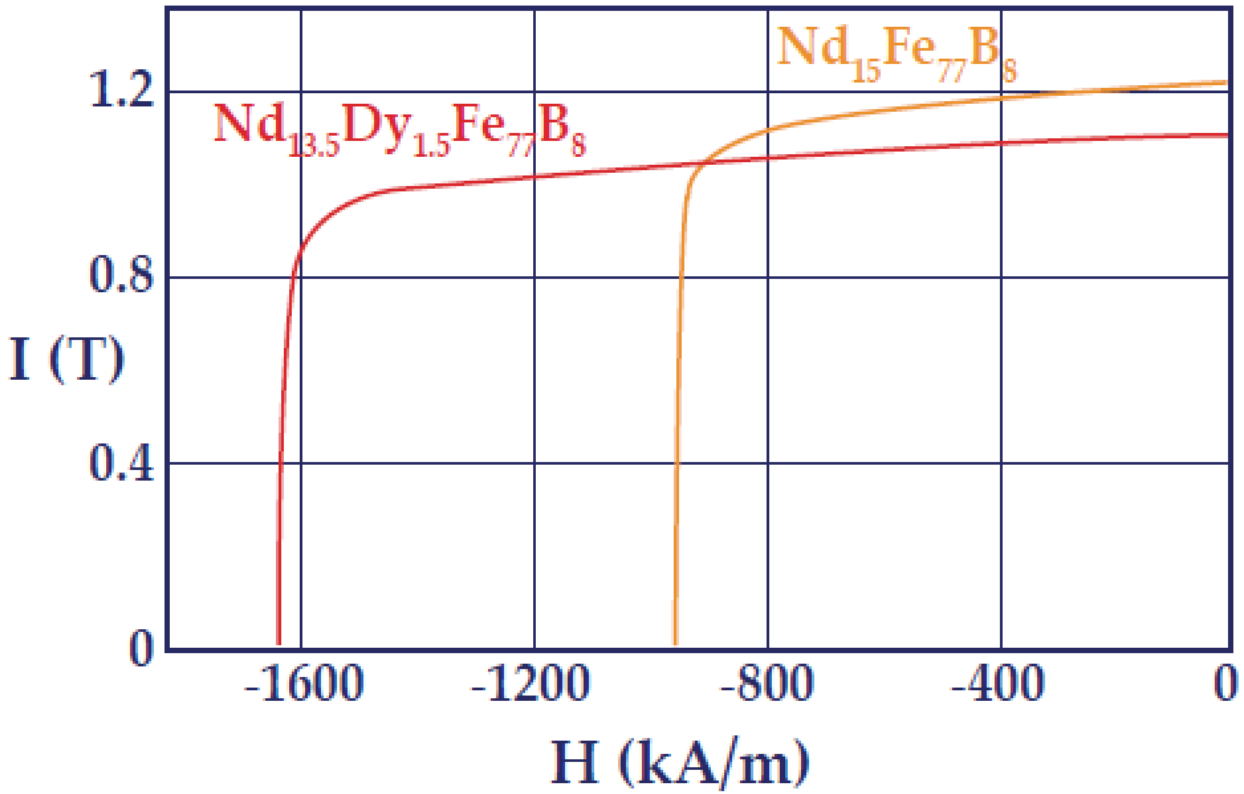
Demagnetization Behavior At Temperature for NdFeB (N55M)



An ideal magnet is like a spring

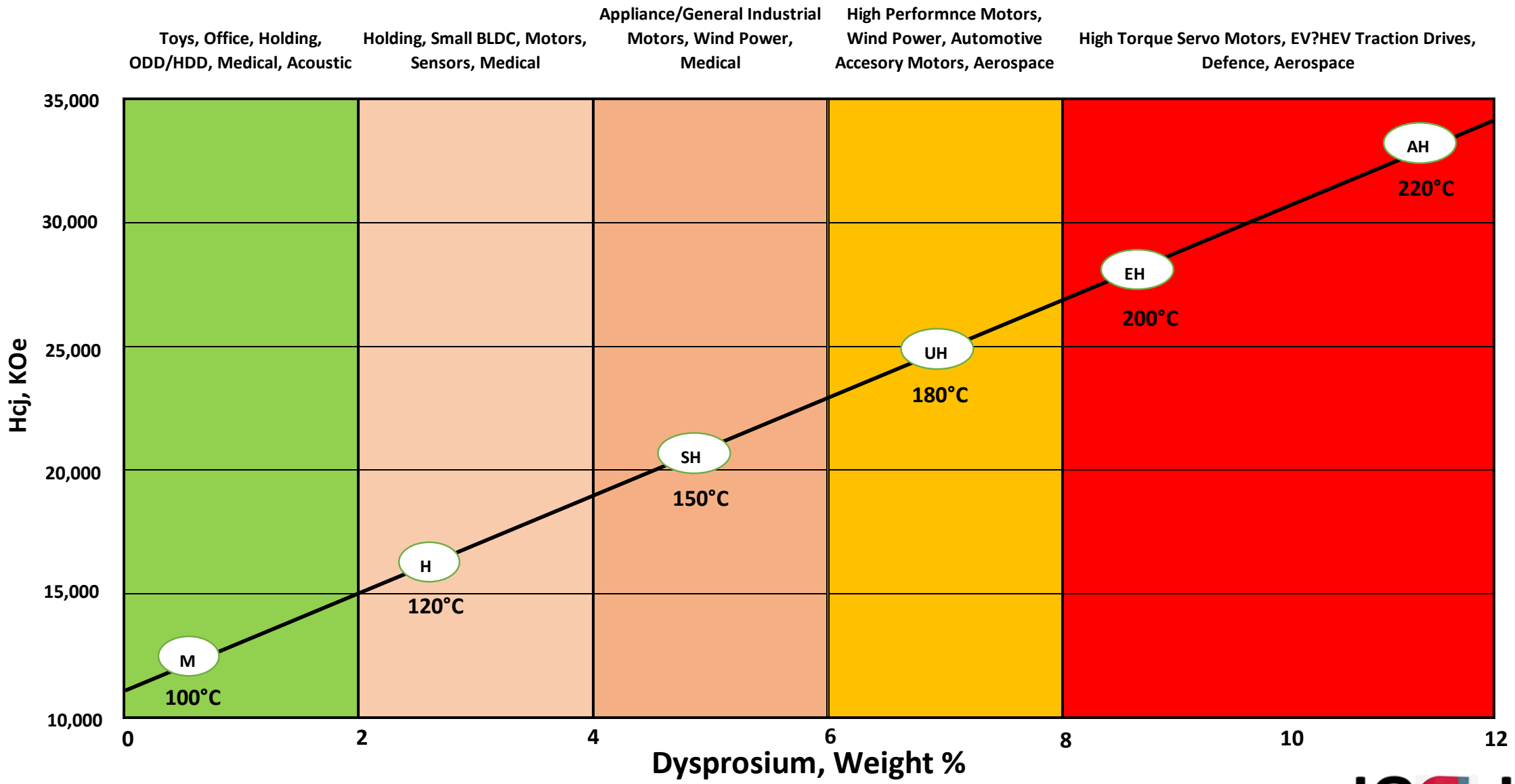


Effect Of Dy On Coercivity

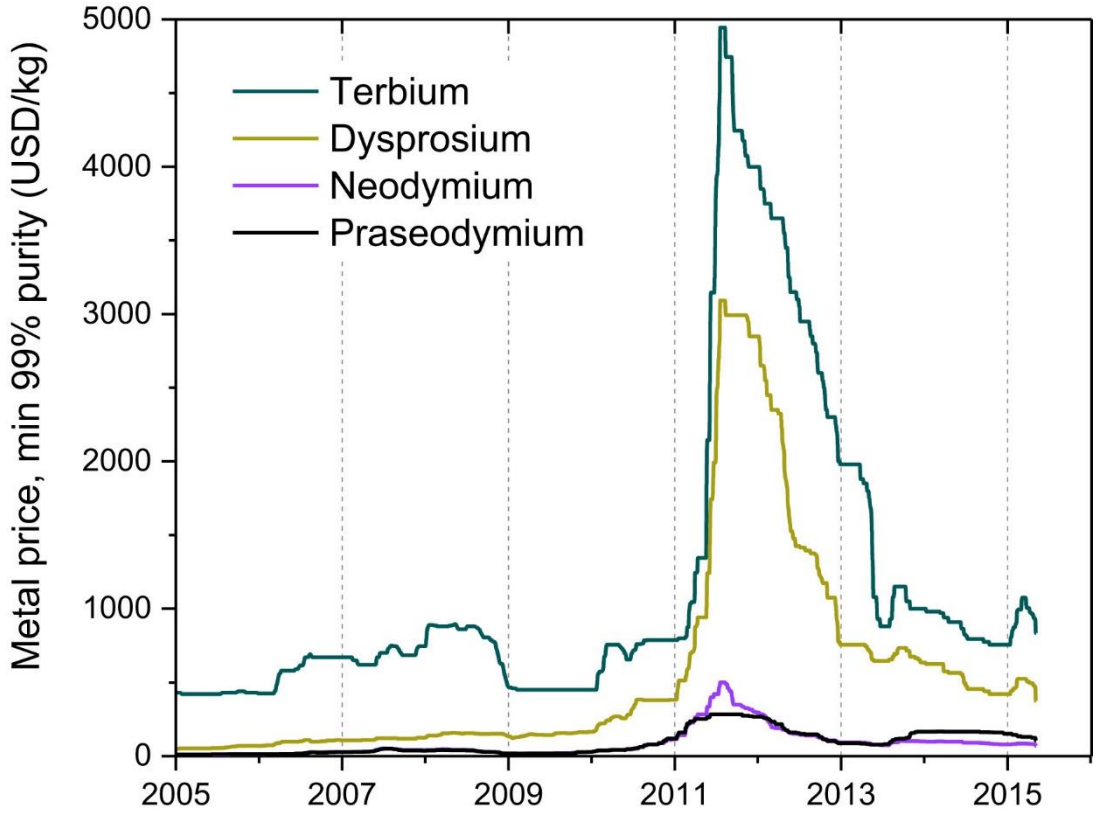


Reference: IEEE Transactions on Magnetics, Volume 20, Issue 5, September 1984, pp. 1584-1589

Typical Applications



Rare Earth Price And Supply Disruption



- Rare Earth prices spiked in 2011/2012 e.g. Dy2O3 price increased 50-fold.
- Major investment in search for RE-free substitution and application redesign.
- Drove efforts to reduce Dy content for higher temperature/coercivity grades

Reference: Ressources Policy, Volume 52, June 2017, Pages 349-357

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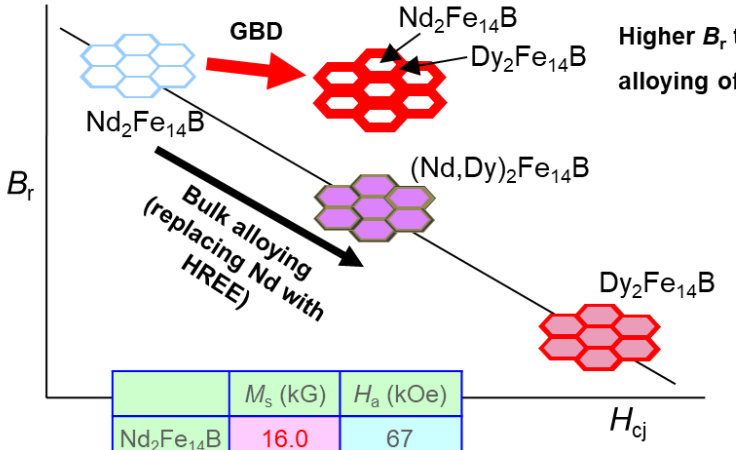
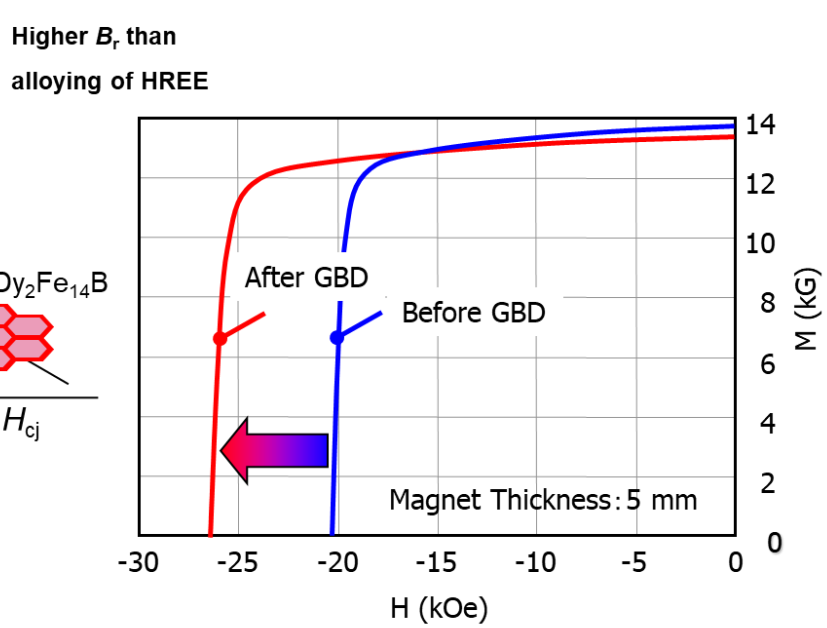
Dy Diffusion At Grain Boundaries

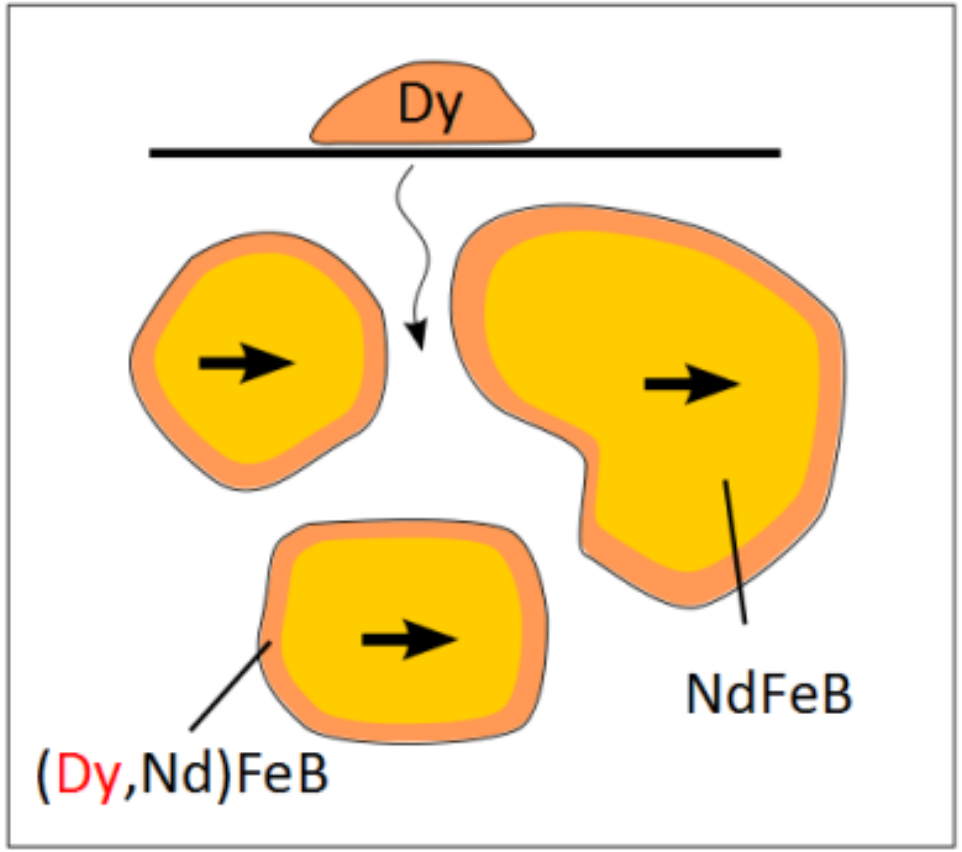
Enhancement of coercivity with small degradation of remanence by diffusing HREE into grain boundary phases and surfaces of grains



	M_s (kG)	H_a (kOe)
$Nd_2Fe_{14}B$	16.0	67
$Pr_2Fe_{14}B$	15.6	87
$Dy_2Fe_{14}B$	7.1	149
$Tb_2Fe_{14}B$	7.0	218



GBD can increase *Hcj* with minimum decrease in *Br*.



Reference: Yotaka Yoshida, Daido Steel, Magnetics 2016.

Outline

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New Permanent Magnet Materials
It's A Challenge To Hit The Sweet Spot

Extrinsic properties:
Br, Hc, (BH)max,
Thermal, Chemical and
Mechanical properties
plus $$$$

Composition and Crystal Structure

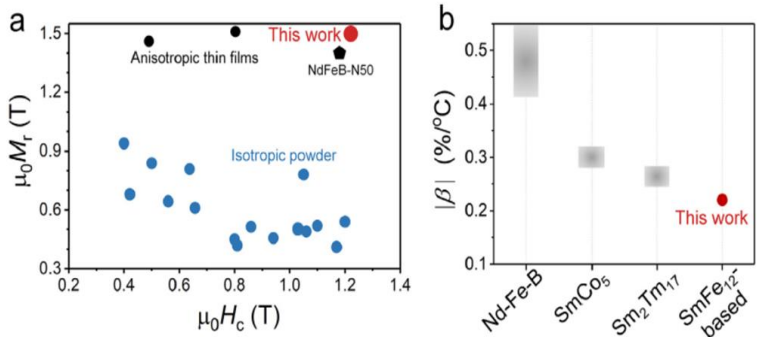
Intrinsic properties: (Ms, Ha, Tc)

Microstructure

Phase distribution, grain size. texture etc.

Bulk Fabrication

Powder metallurgical, casting, polymer bonding, hot pressing etc.



$SmFe_{12}$ announcement 8/2020

Is There An Optimum Price-Performance Metric (2016)? Niche And Mass Market Materials

Material	Average $(BH)_{max}$ (MGOe)	Average price ($/kg)	Price/Performance ($/kg per MGOe)	Market %
NdFeB	40	75	1.9	60
Ferrite	3.8	7.1	1.9	31
Bonded NdFeB	8	90	11.3	5
SmCo	25	100	4.0	2
Alnico	7	58	8.3	2

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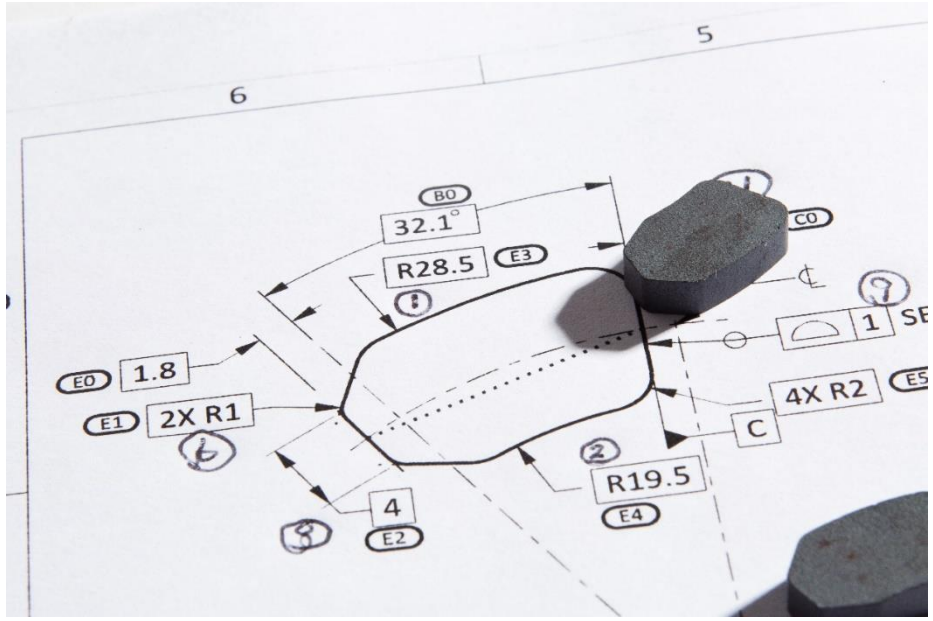
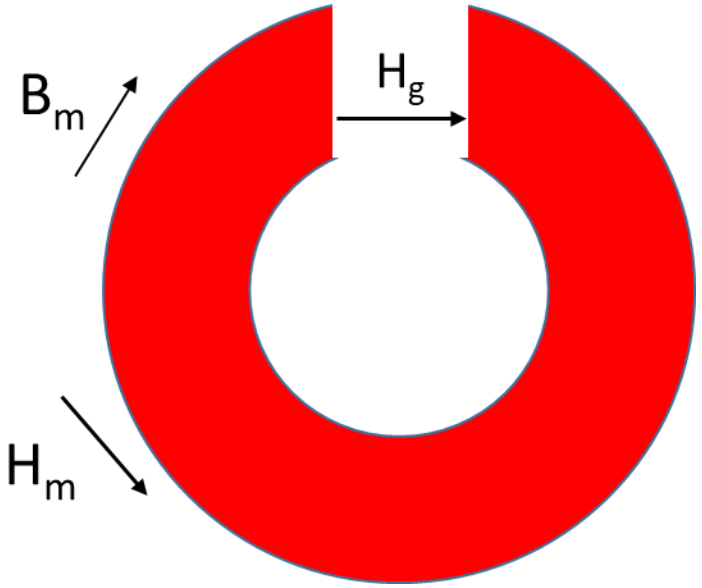
It’s Magnet Volume Not Weight!

- By experience we specify magnets by dimensions and geometry not weight.
- We buy and use a volume of magnet material.



$$H_g^2 = (B_m H_m) V_m / V_g$$



Optimum Price-Performance Metric Based On Magnet Volume

Material	Average $(BH)_{max}$ (MGOe)	Average Price ($/kg)	Density (g/cm^3)	Average Price ($/$m^3$ x 10^3)	Price/Performance ($/$m^3$ per MGOe x 10^3)
NdFeB	45	70	7.5	525	12
Ferrite	3.5	6.4	5.0	32	9
Bonded NdFeB	8	91	5.1	464	58
SmCo	25	95	8.4	798	32
Alnico	7	56	7.3	409	58

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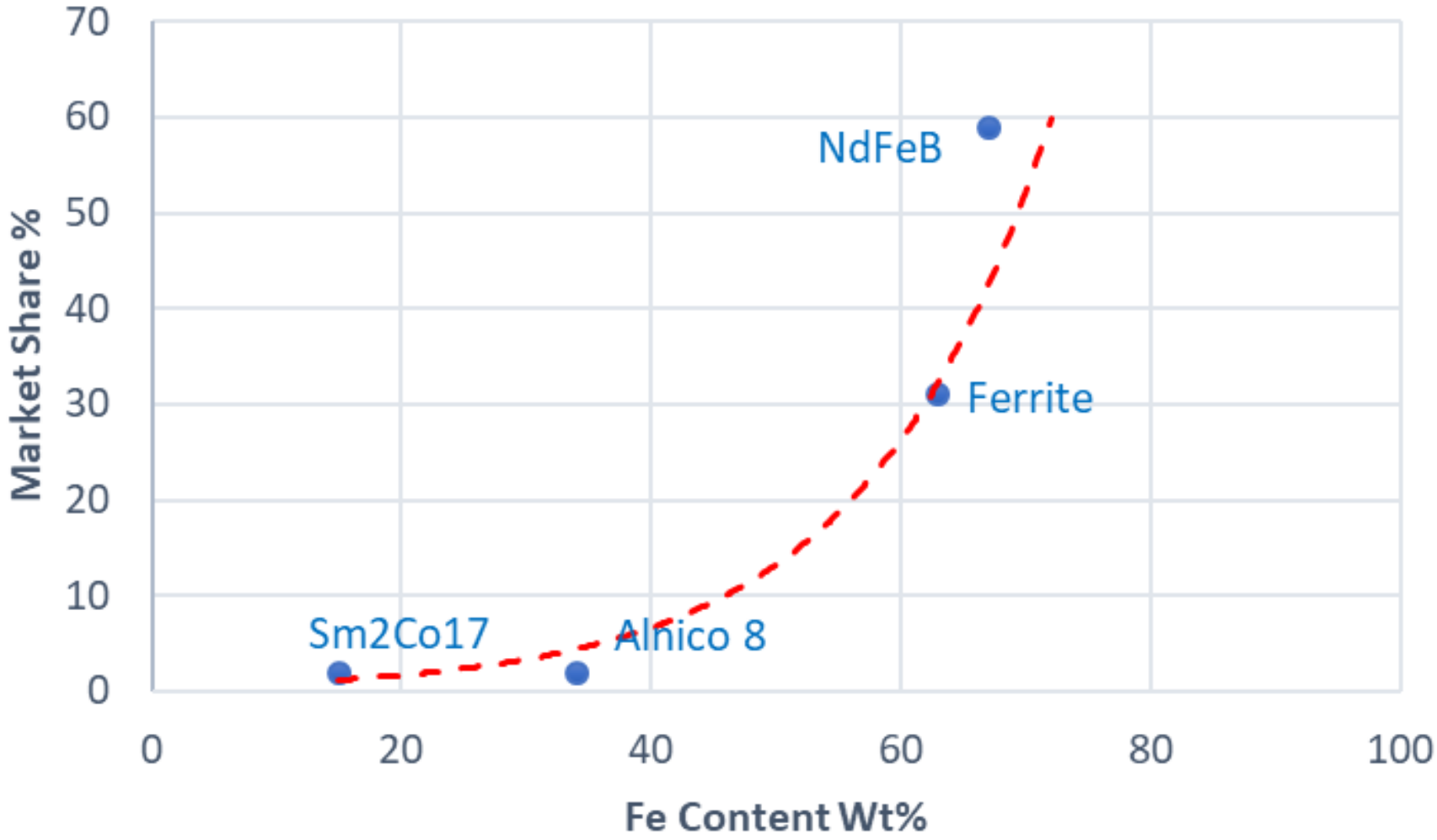
Fe Is Really A Good Magnetic Element

Price/Performance Metric For Elements!

Element	Crystal Structure	Atomic Magnet Moment (μ_B)	Curie Temperature (°C)	Price per Atomic Moment ($/$\mu_B$ x10^{-26})
Fe	BCC	2.22	770	6
Co	HCP, FCC	1.72	1115	319
Ni	FCC	0.61	354	188
Gd	HCP	7.62	19	69
Dy	HCP	10.2	-185	623

Market Share Versus Fe Content

Fully Dense Magnet Materials



Next Mass Market PM Material Composition

My Prediction

- Composition:
  - $Fe_{(1-n)}(A,B,C,D.....Z)_n$
  - Includes at least one other known element A,B,C,D…….Z
  - Where n = weight fraction
  - n << 0.4
  - In other words lots of Fe

JOC LLC

Thank you for your attention
Any Questions?

Dr. John Ormerod

JOC LLC

Loudon, Tennessee

https://www.linkedin.com/in/jormerod/

+1 414 899 2859

Jormerod8@gmail.com

John@jocllc.com