MAGNETICS 2021

The Ideal Permanent Magnet – Myths and Realities.

Dr John Ormerod

January 20th, 2021

“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
- The Ideal Permanent Magnet
  - Magnetics
  - Other Considerations
- Recent Magnet Material Developments
- Summary

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 Magnetic Technologies (USA) 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.
- Founded business and technology consultancy for magnetics and metals related industries in 2015 – JOC LLC (www.jocllc.com) assisted clients in all aspects of the PM supply chain.
- Provided expert testimony on key NdFeB patent challenges over the last few years.
- Advisory Board member for Bunting Group, Technology/Industry Advisor for Bunting, CMI and MP Materials.

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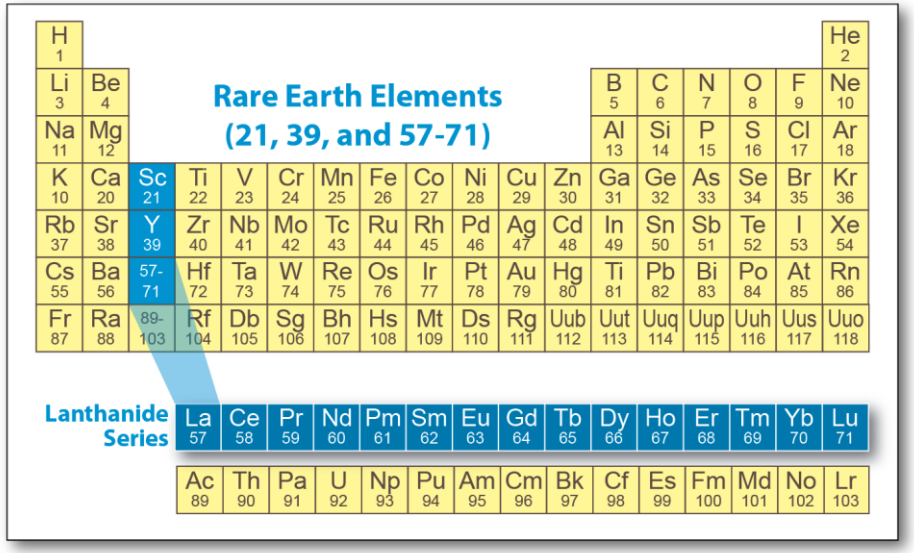
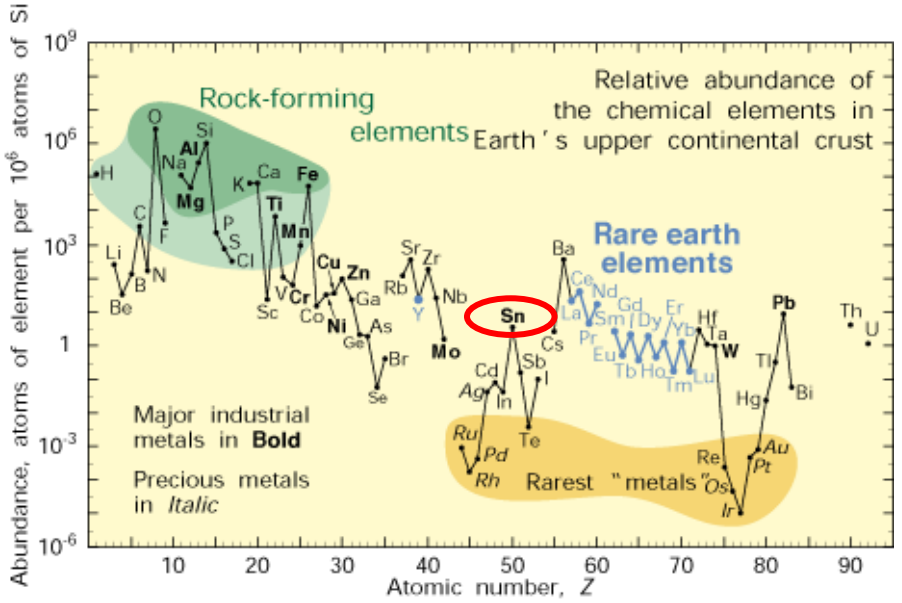
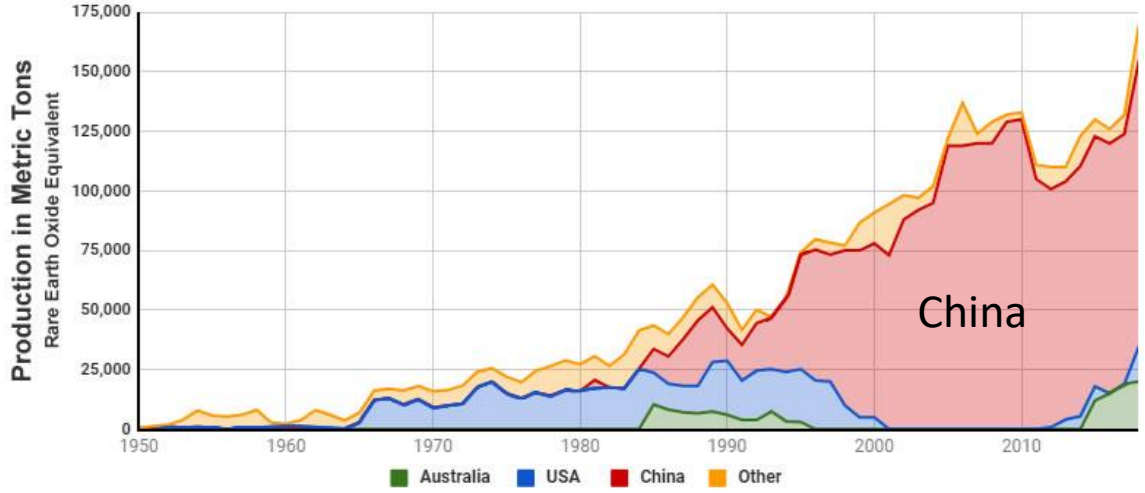
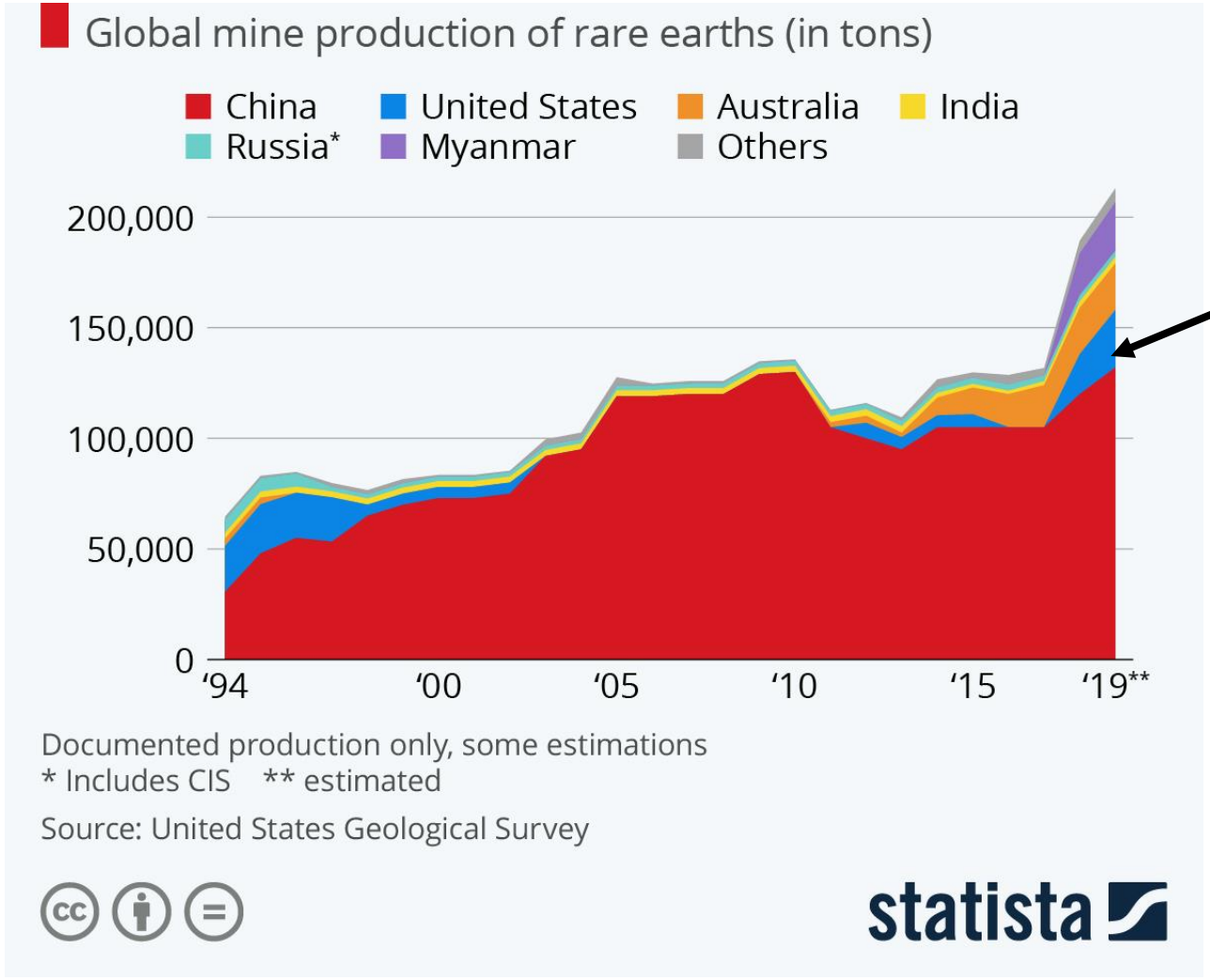
Introduction – Rare Earths





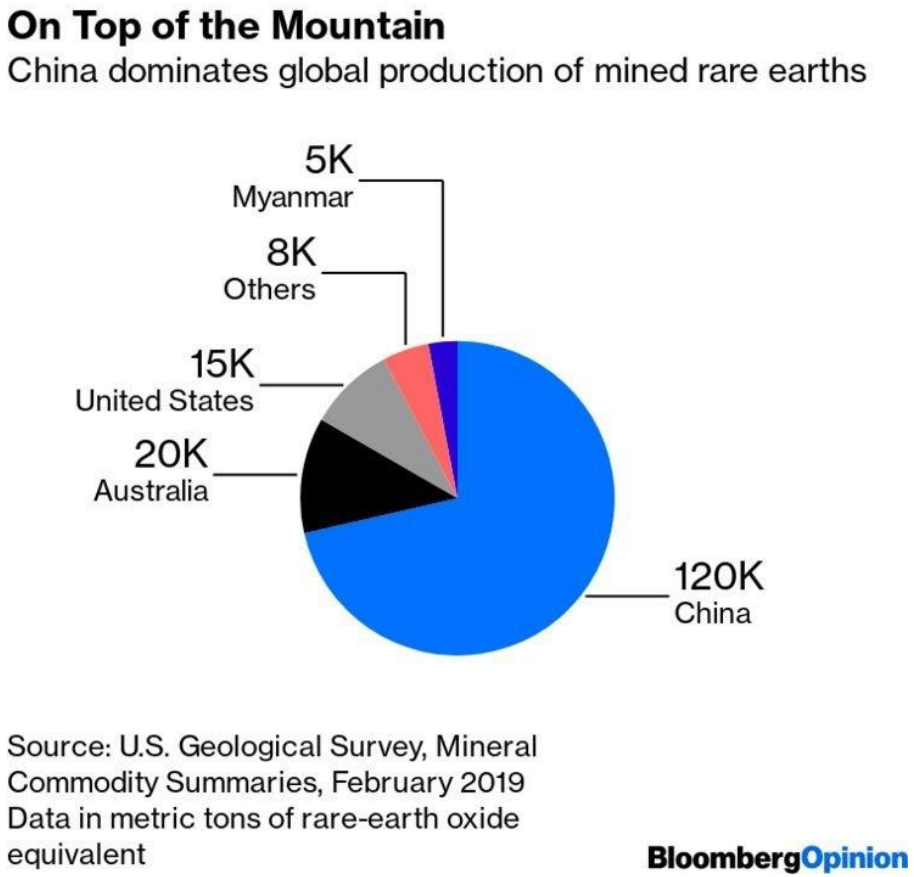


China's REE dominance is (might be) diminishing



MP Materials' Mountain Pass back online.

China's Dominance of Mining is Diminishing, but……



China Still Dominates Downstream RE Processing – Global Capacities

- Separation: 80%
- Reduction to Metals: 75%
- Magnet Manufacturing: 75%

Rare Earths – Supply Demand (out of) Balance

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

Projected Supply & Demand (2016)

2016	Demand		Supply		Surplus
Element	tonnes	%	tonnes	%	(Deficit)
La	36,750	23.0%	52,000	26.7%	15,250
Ce	65,000	40.6%	81,000	41.5%	16,000
Pr	7,500	4.7%	9,500	4.9%	2,000
Nd	30,000	18.8%	31,500	16.2%	1,500
Sm	1,000	0.6%	3,750	1.9%	2,750
Eu	780	0.5%	500	0.3%	-280
Gd	2,225	1.4%	2,750	1.4%	525
Tb	450	0.3%	350	0.2%	-100
Dy	1,650	1.0%	1,450	0.7%	-200
Er	1,000	0.6%	800	0.4%	-200
Y	13,350	8.3%	10,000	5.1%	-3,350
Ho-Tm-Yb-Lu	250	0.2%	1,400	0.7%	1,150
TOTAL	159,955	100.0%	195,000	100.0%	35,045

Texas Mineral Resources: http://tmrcorp.com/ree/market_dynamics/

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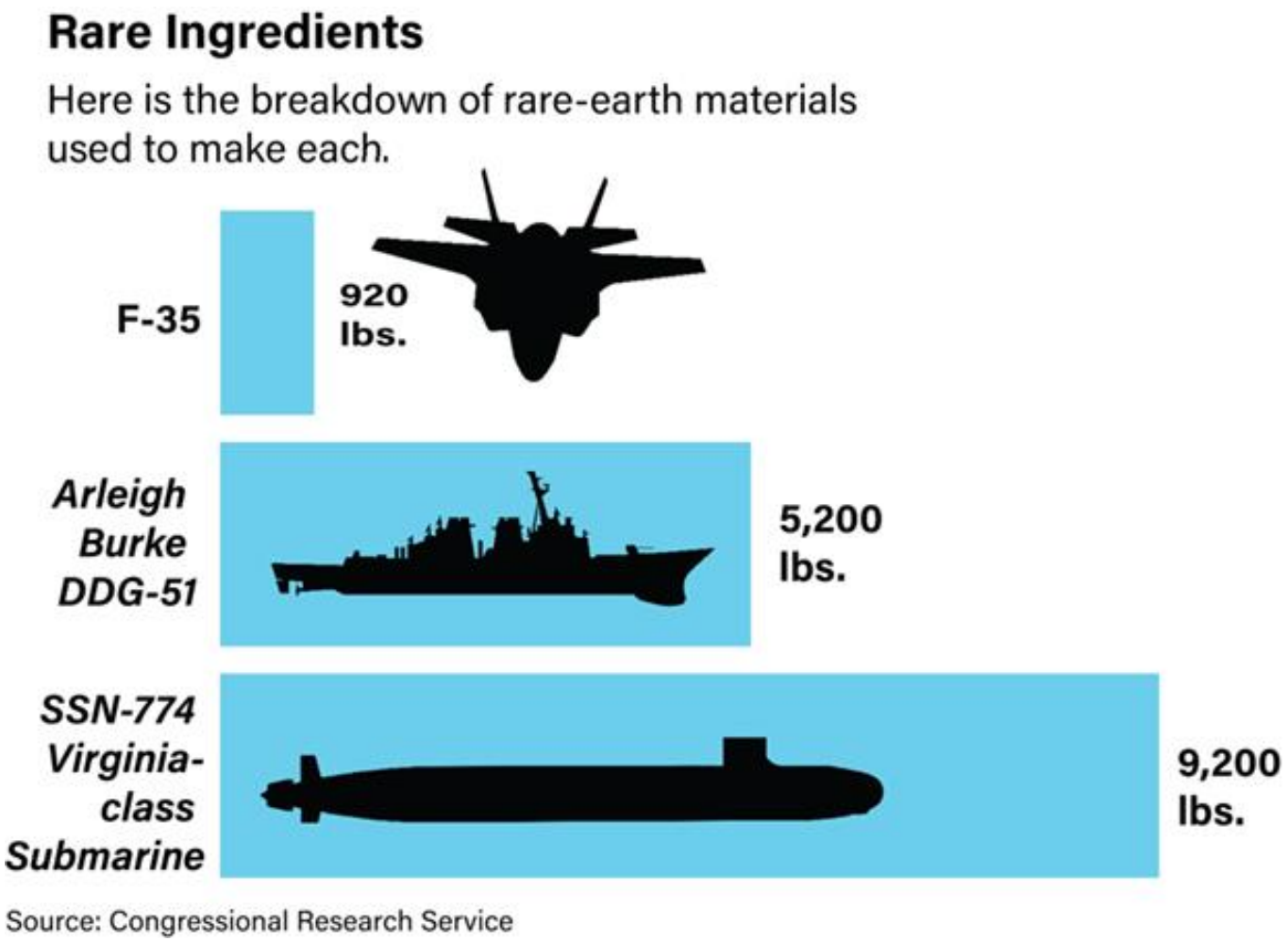
Rare Earths – DOD Systems Need REE's
Not A Good Idea To Be Dependent On China



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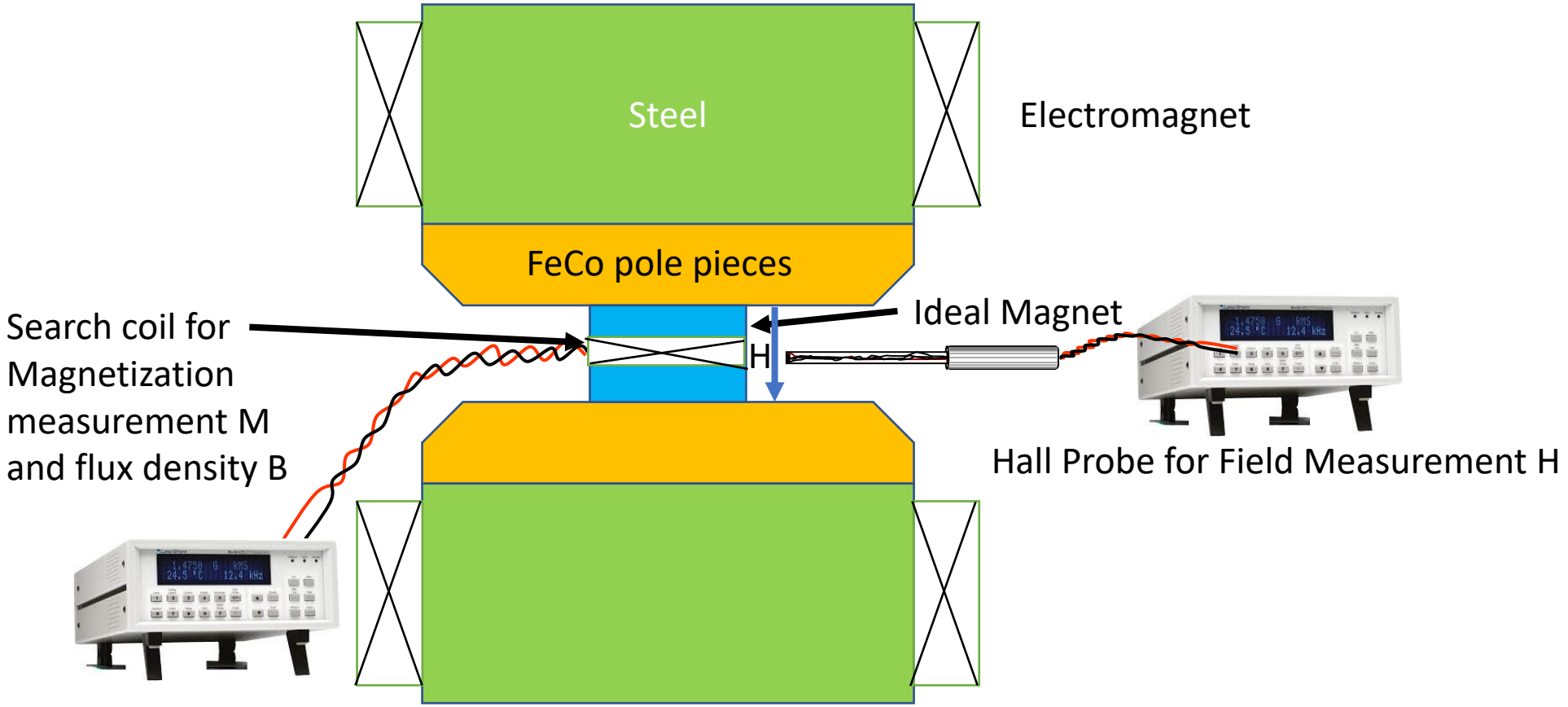
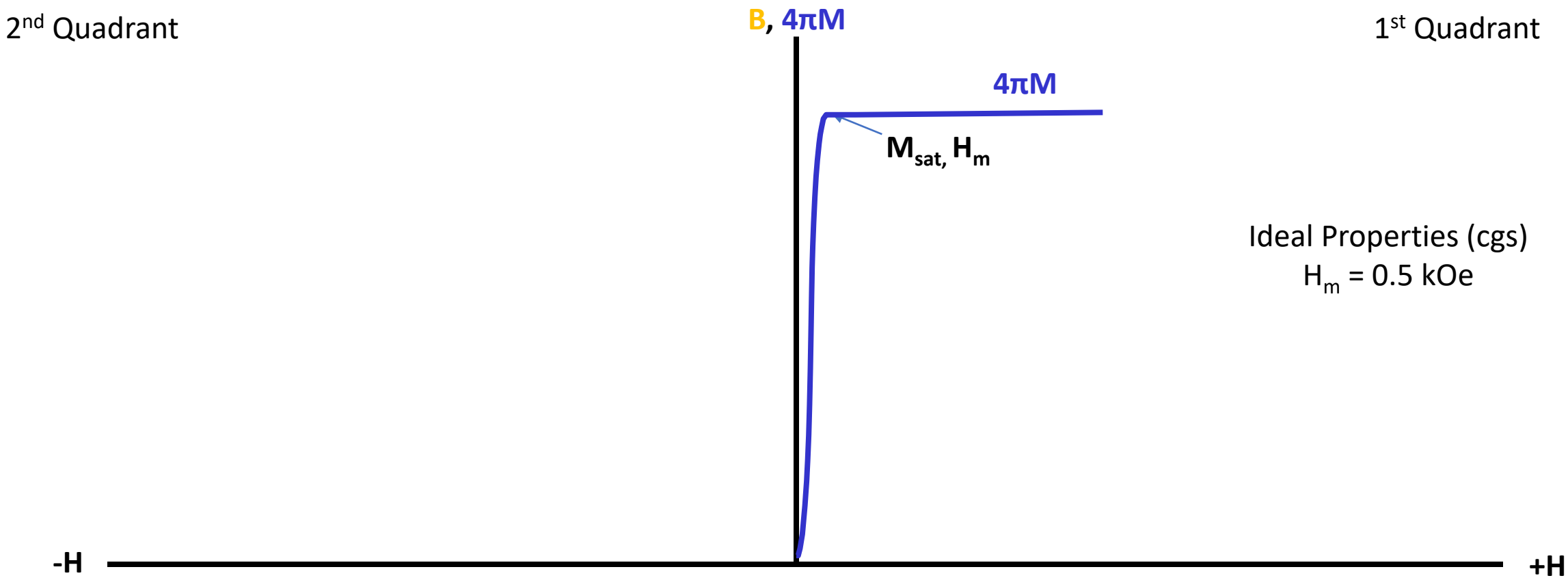
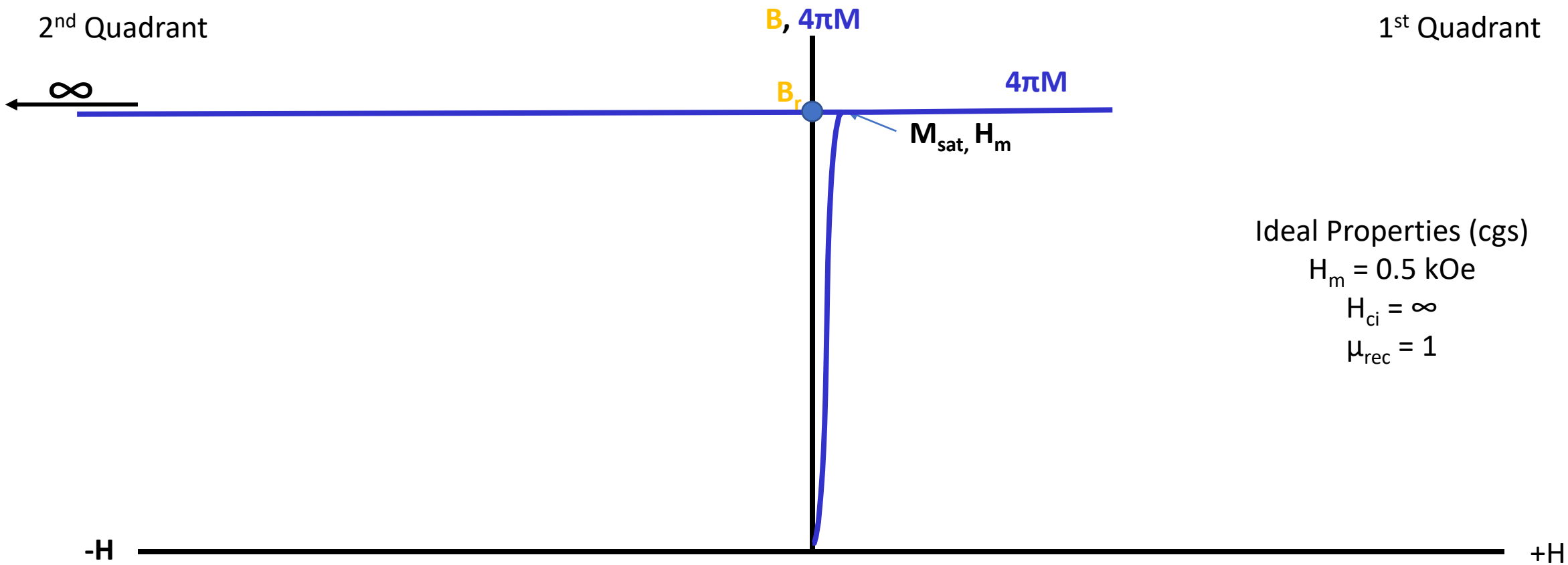
Hysteresis Measurement of Ideal Magnet



Ideal Permanent Magnet -Magnetics



Ideal Permanent Magnet -Magnetics



Ideal Properties (cgs)

H_m = 0.5 kOe

H_{ci} = ∞

μ_{rec} = 1

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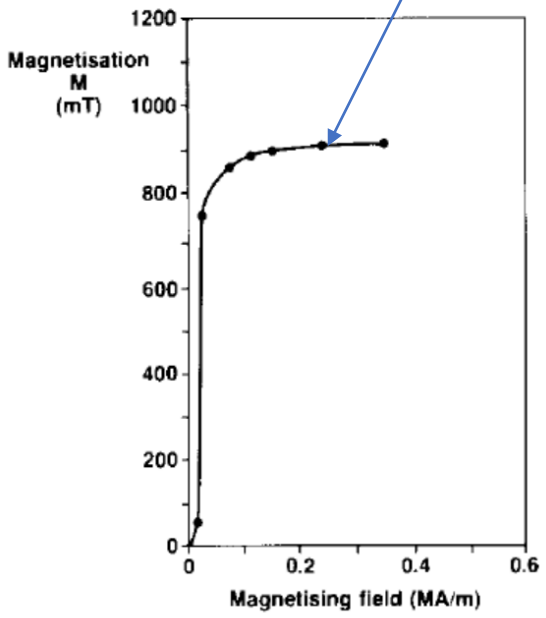
Magnetizing Field < H_c?
Grain Boundary Pinning Mechanism ($SmCo_5$ and $Nd_2Fe_{14}B$)

Saturating at 3 kOe

Hm of 10 kOe with H_{ci} of 22 kOe?



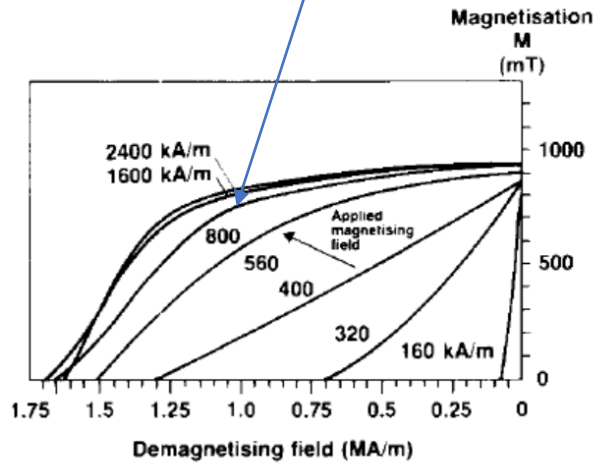


Fig. 1. Initial magnetisation curve of a thermally demagnetised $SmCo_5$ (RES 190) magnet.

Fig. 2. Dependence of coercivity on initial magnetising field of thermally demagnetised $SmCo_5$ (RES 190) magnets.

Source: J. Ormerod, Journal of the Less-Common Metals, 111 (1985) 49 - 69

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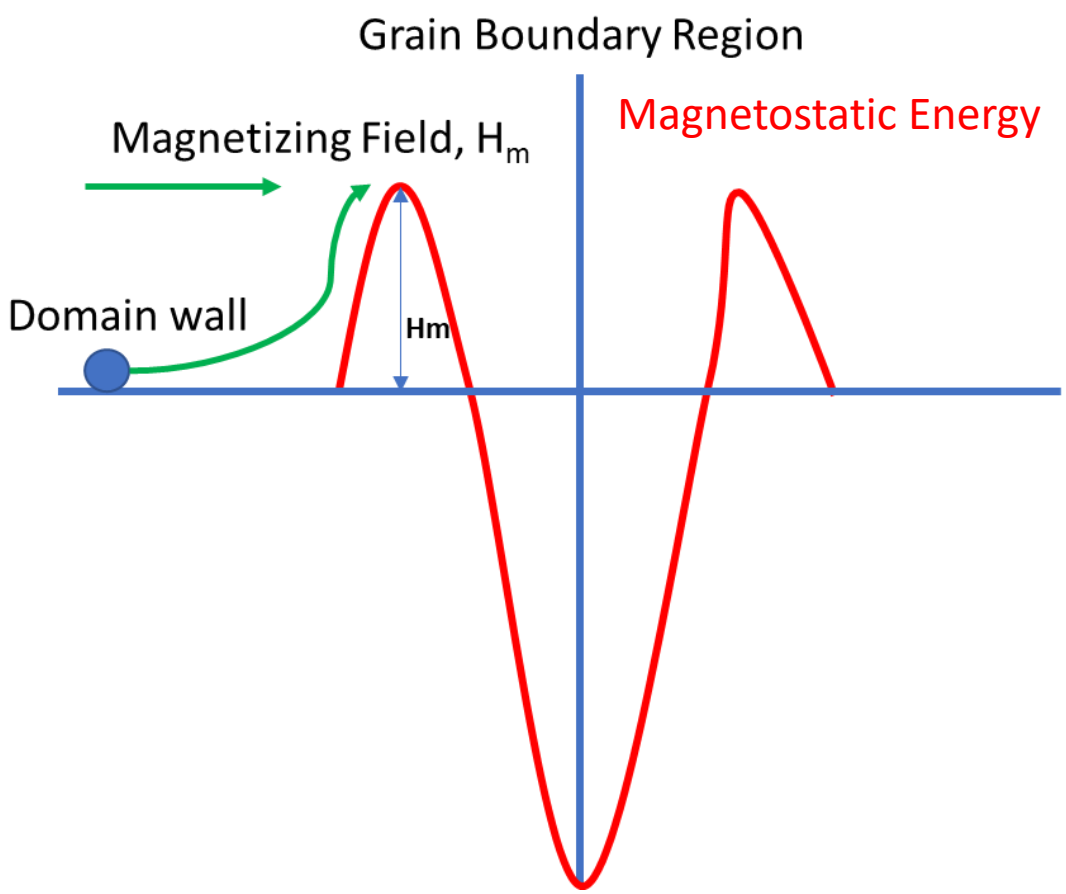
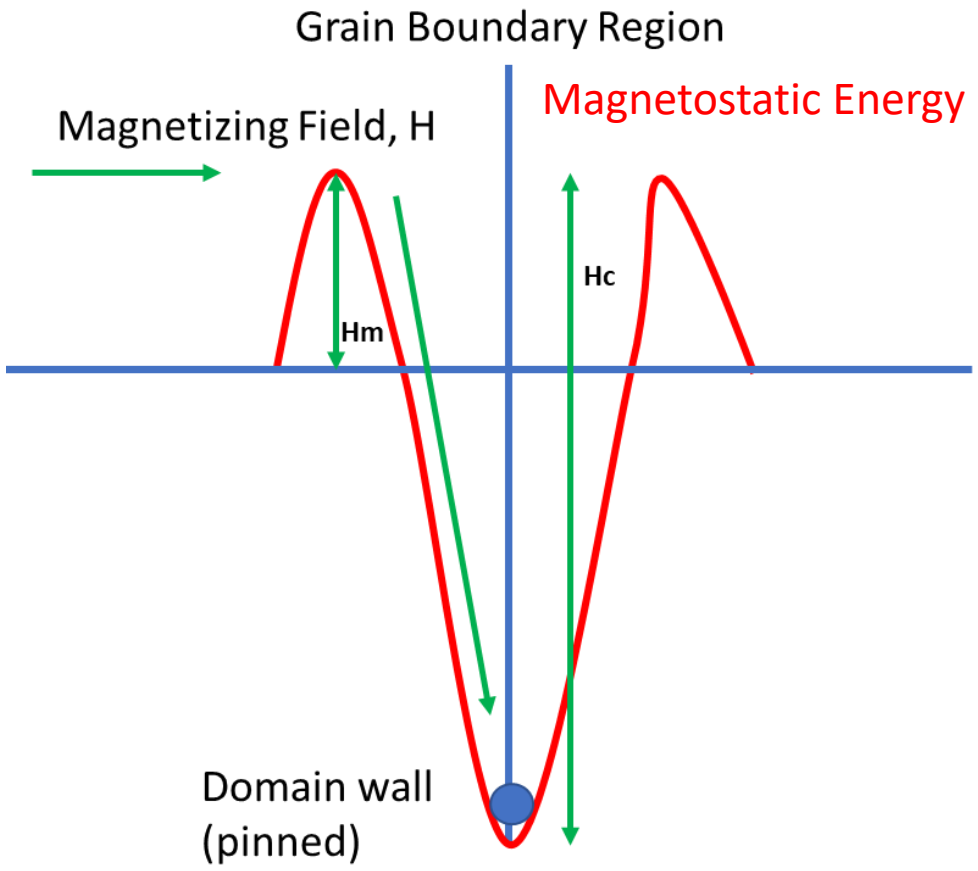
It's all About the Grain Boundaries (and Energy Wells)

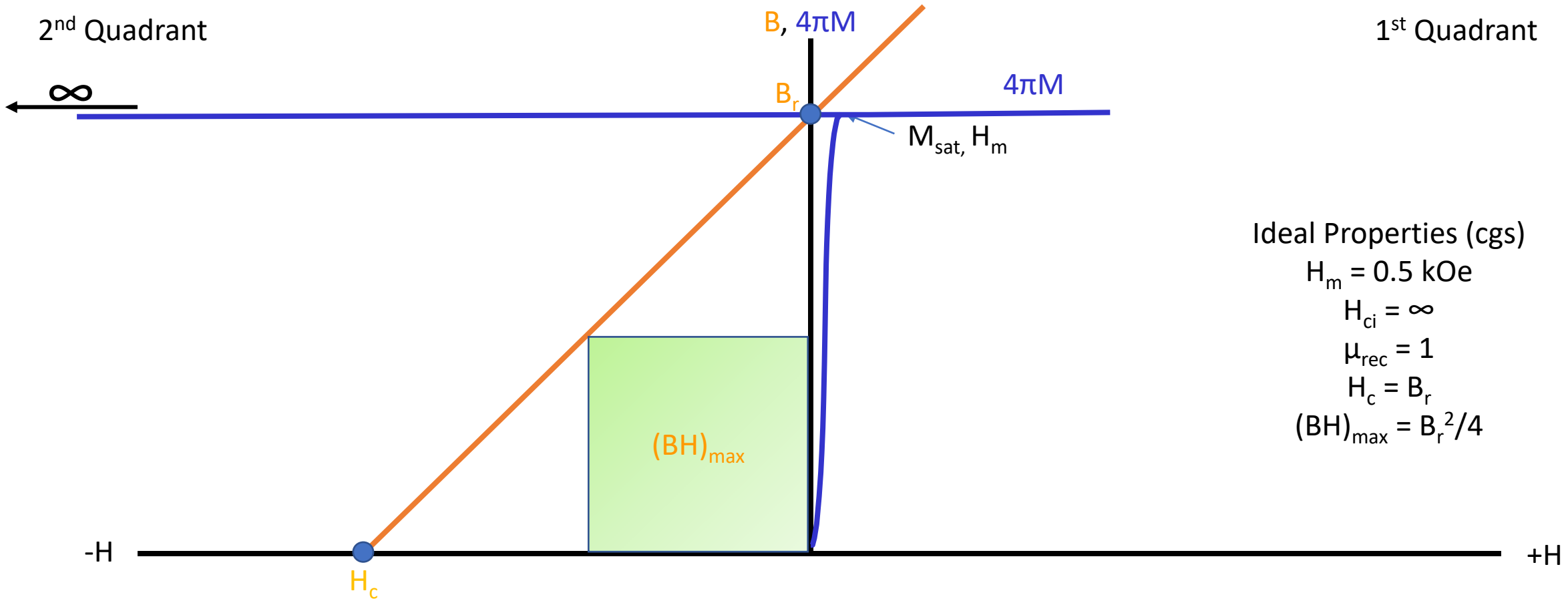


Initial Magnetizing Field



Maximum Coercivity

Ideal Permanent Magnet -Magnetics



Ideal Properties (cgs)

H_m = 0.5 kOe

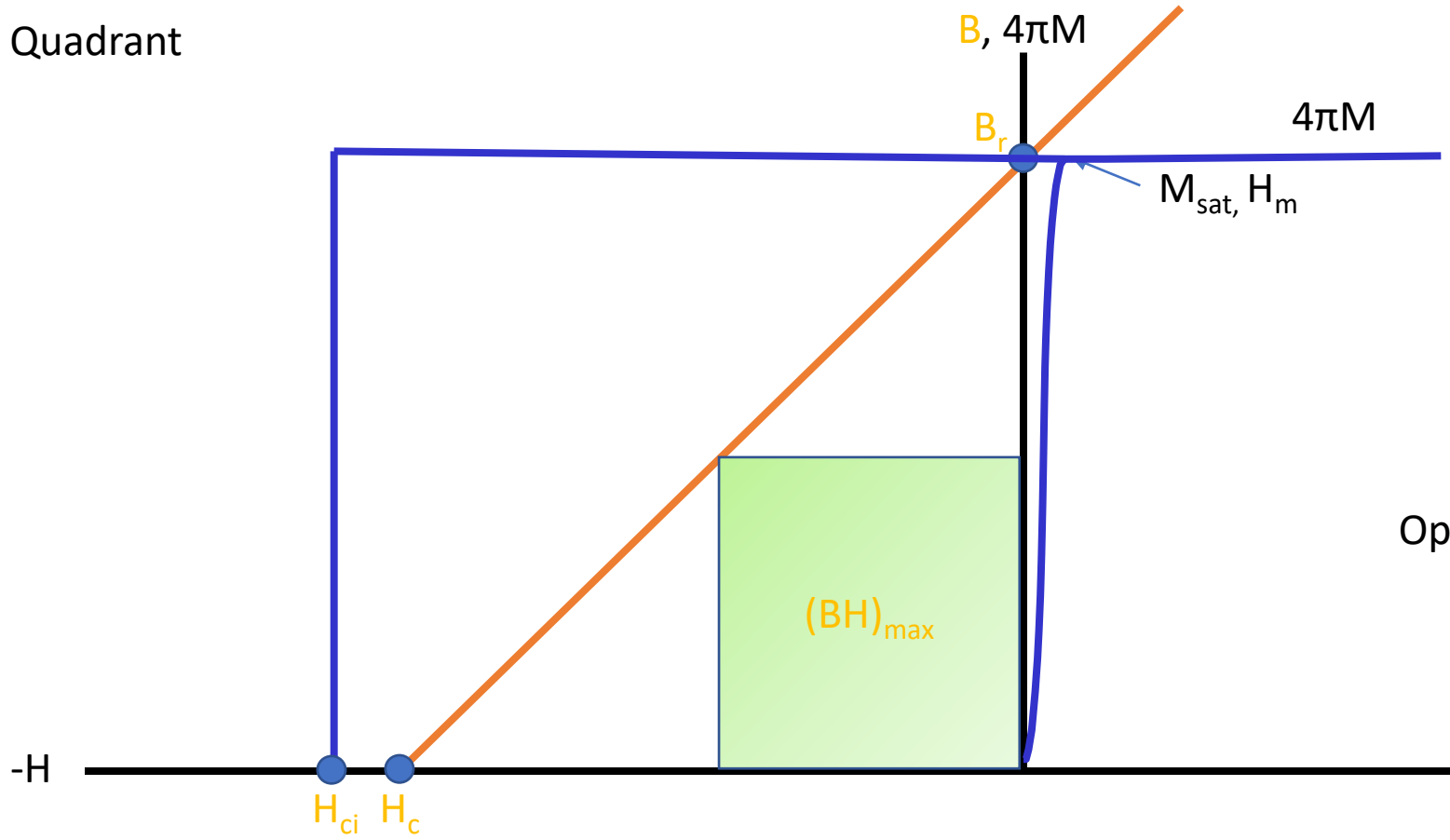
$H_{ci} = \infty$

$\mu_{rec} = 1$

$H_c = B_r$

$(BH)_{max} = B_r^2/4$

Ideal Permanent Magnet -Magnetics



Ideal Properties (cgs)

H_m = 0.5 kOe

μ_{rec} = 1

$H_c = B_r$

$(BH)max = B_r^2/4$

$H_{ci} = 1.1\ H_c$

Operate at 1000°C with zero reversible losses of B and H

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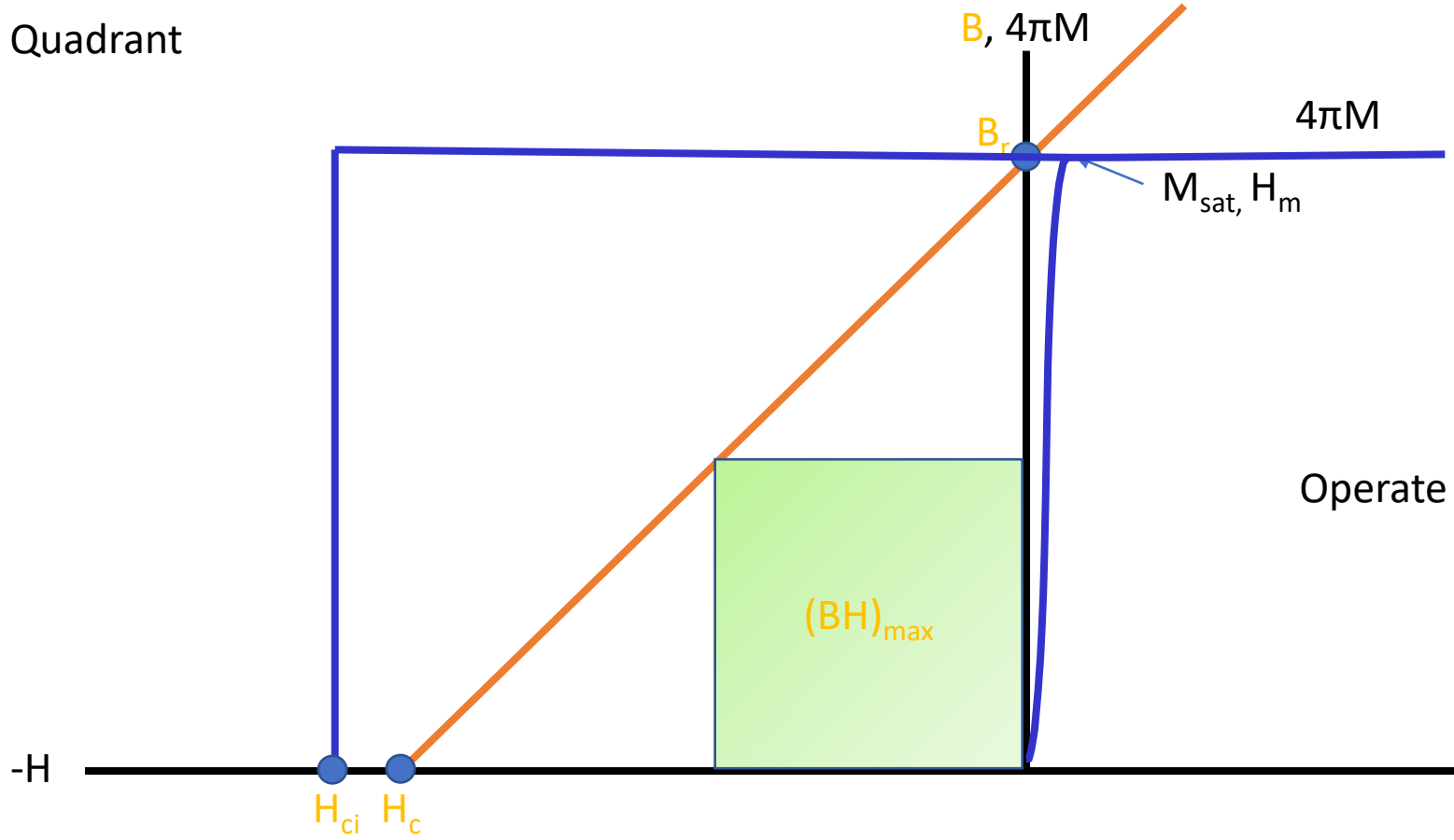
Ideal Permanent Magnet -Magnetics



Ideal Properties (cgs)

$H_m = 0.5$ kOe

$\mu_{rec} = 1$

$B_r = 24$ kG

$H_c = 24$ kOe

$(BH)_{max} = 24^2/4 = 144$ MGOe

$H_{ci} = 1.1\ H_c = 26.4$ kOe

Operate at 1000°C with zero reversible losses of B and H

The ideal permanent magnet depend on the application and numerous other considerations

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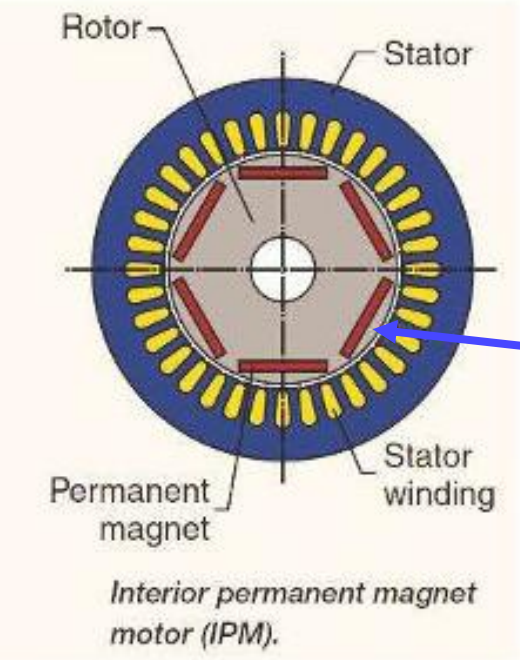
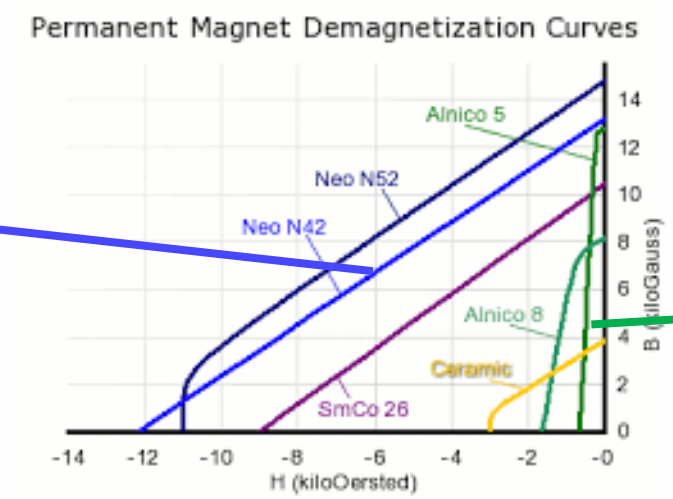
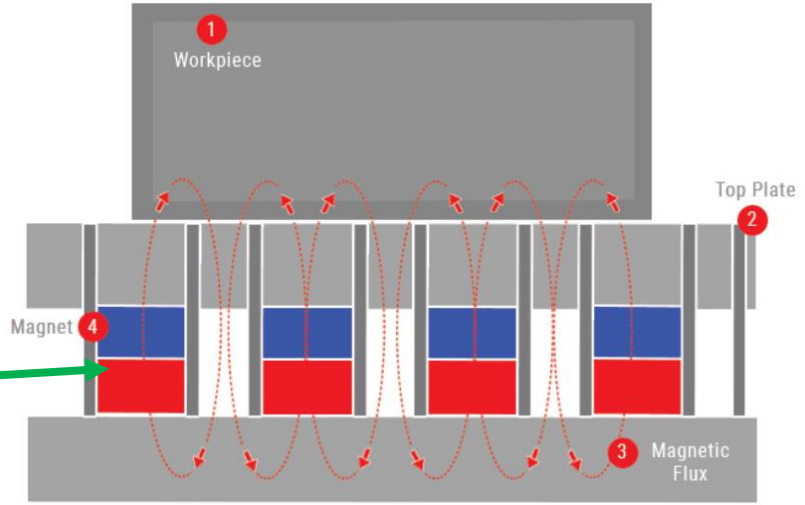
The Ideal Magnet Depends On Application – Duh!



Interior permanent magnet motor (IPM).





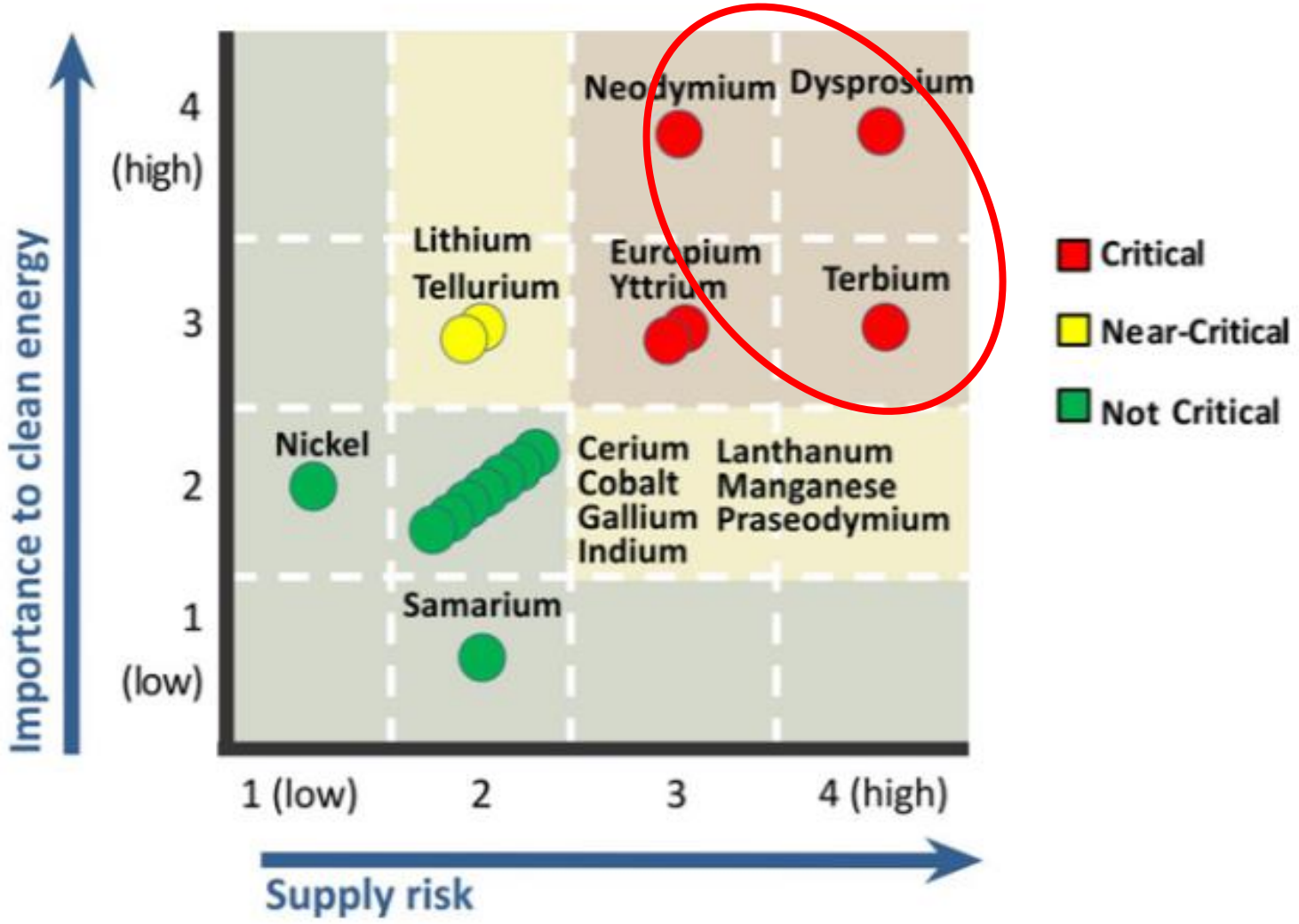
Sintered NdFeB IPM machines with a Br of 10 kG at 150°C with a straight-line B versus H characteristic.

Work holding application using alnico magnets with a B_r of 13 kG and H_c of 1.0 kOe

The Ideal Permanent Magnet – Other Considerations

- Critical Material Content
- Uniformity
- No toxic or environmental damaging processes
- Usable temperature range
- Magnetization change with temperature (RTC)
- Corrosion resistance
- Physical strength
- Electrical resistivity
- Available sizes, shapes, and manufacturability
- Raw material cost and availability
- Net shape processing

US DoE Critical Materials Assessment – 2015 - 2025



EU 2020 Critical Raw Materials List

2020 critical raw materials (new as compared to 2017 in bold)		
Antimony	Hafnium	Phosphorus
Baryte	Heavy Rare Earth Elements	Scandium
Beryllium	Light Rare Earth Elements	Silicon metal
Bismuth	Indium	Tantalum
Borate	Magnesium	Tungsten
Cobalt	Natural graphite	Vanadium
Coking coal	Natural rubber	**Bauxite**
Fluorspar	Niobium	**Lithium**
Gallium	Platinum Group Metals	**Titanium**
Germanium	Phosphate rock	**Strontium**

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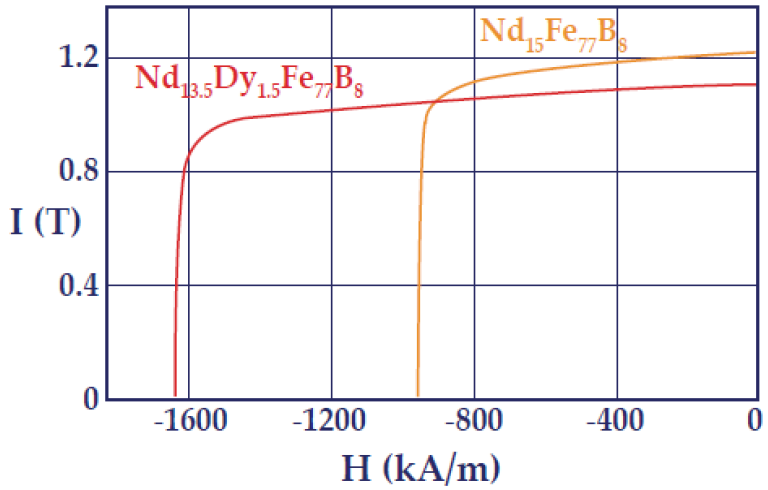
Dysprosium, Coercivity and Higher Application Temperatures

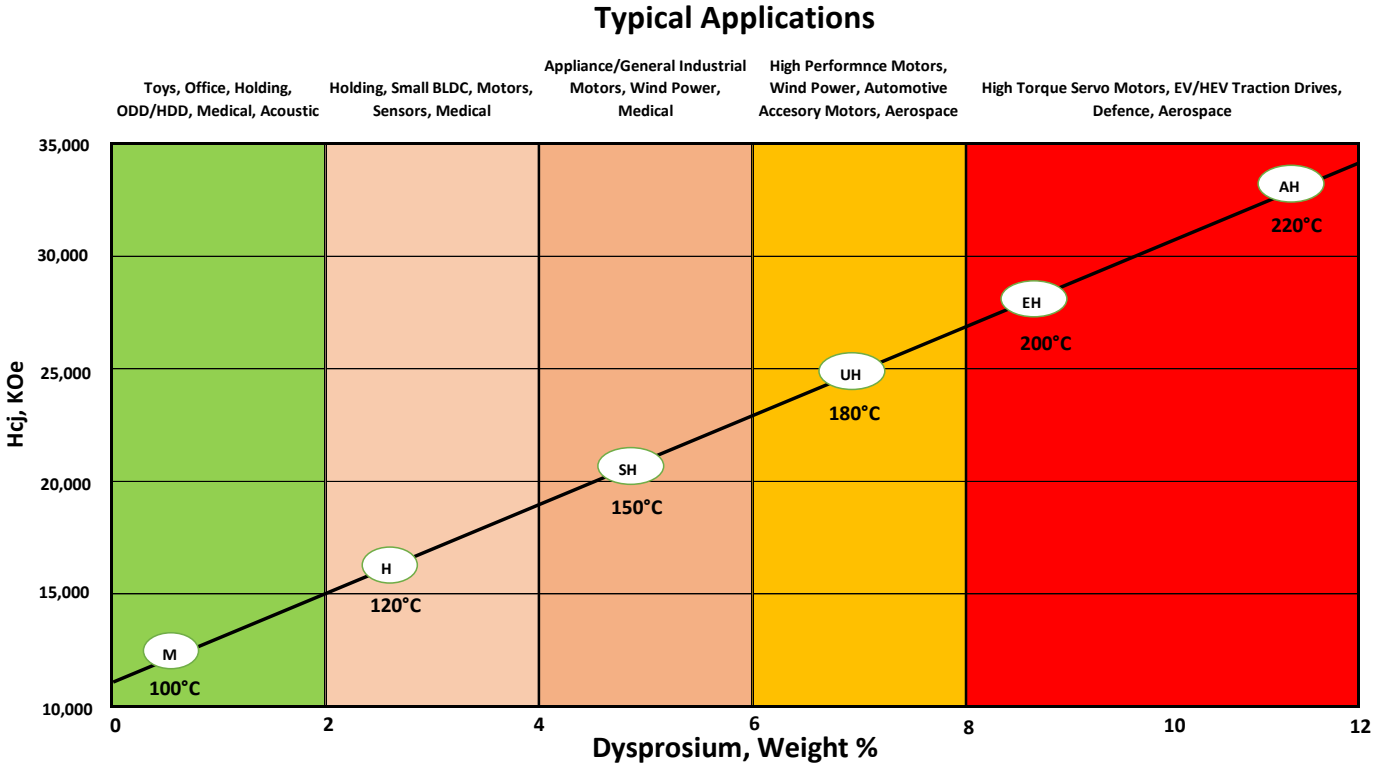


Reference: IEEE Transactions on Magnetics, Volume 20, Issue 5, September 1984, pp. 1584-1589

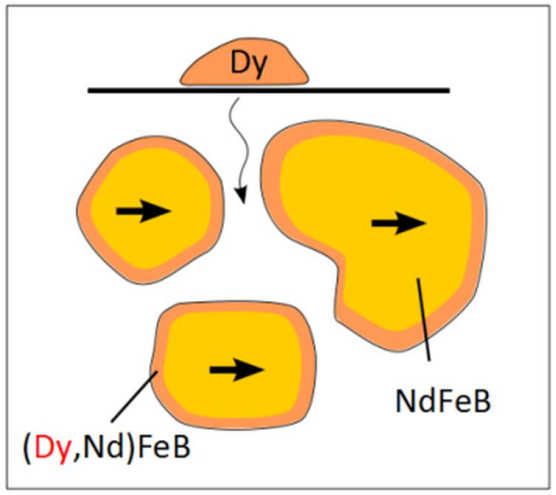
Table 2 Consumption of the different REEs in 2012, with the relative part of the total consumption being compared with the relative abundance of these elements in REE ores [33]

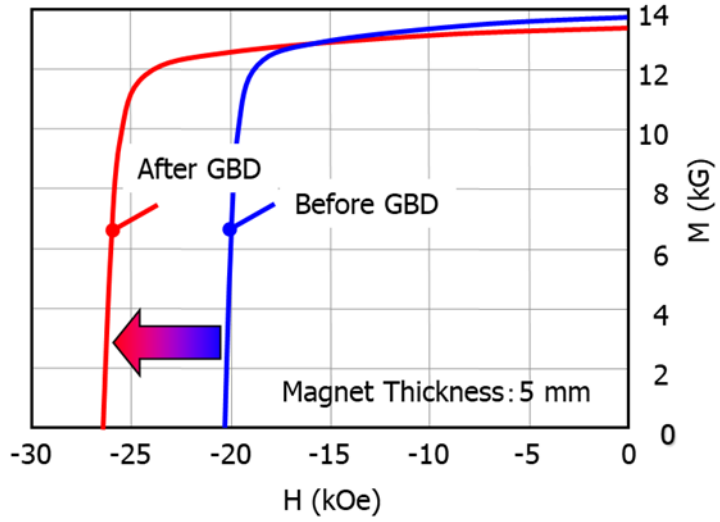
REE	Consumption in 2012 (tons of REOs)	Relative part of the total consumption (%)	Relative abundance (%)[a]
Lanthanum	31,495	27.8	24.9
Cerium	45,525	40.2	43.2
Praseodymium	4945	4.4	4.6
Neodymium	19,925	17.6	16.2
Samarium	515	0.5	2.2
Europium	425	0.4	0.3
Gadolinium	1020	0.9	1.4
Terbium	290	0.3	0.2
Dysprosium	845	0.7	0.9
Erbium	540	0.5	0.2
Holmium–thulium–ytterbium–lutetium	75	0.1	0.8
Yttrium	7650	6.8	4.9
Total	113,250	100	

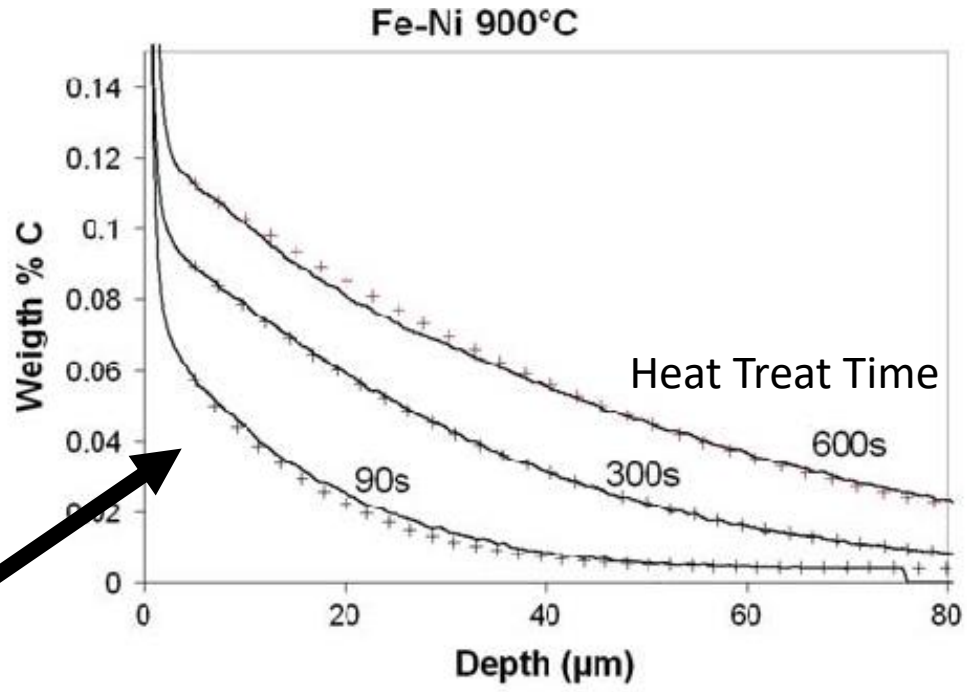
[a]Average of 51 REE deposits



Dy-Diffusion of NdFeB magnets



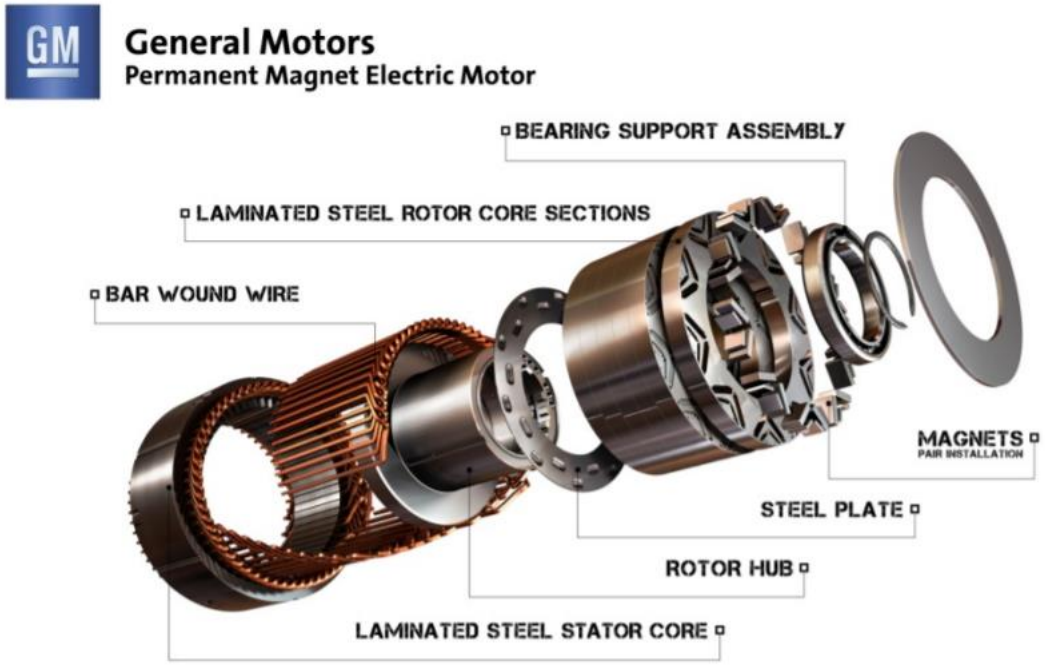




- Dy-diffusion technologies produce grades with approximately 50% Dy content and 5% improvement in Br.

- However, this is low temperature solid state diffusion process limiting the cross sectional that can be treated and tends to develop a concentration profile.

Dy-diffused magnets in IPM EV drivetrains (GM Research Center)



HEVs and EVs frequently have interior permanent magnet-type motors where the permanent magnets are embedded inside the rotor in one or more layers with V-shaped poles

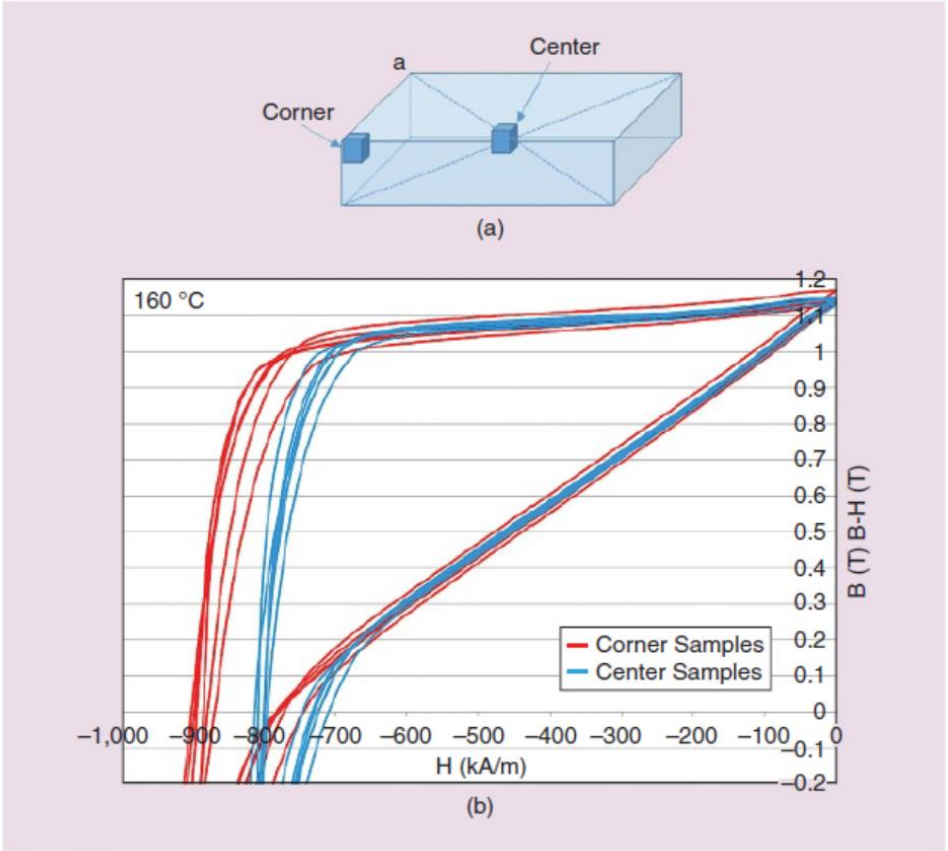


Figure 5. (a) A schematic of magnet locations of samples for VSM measurements. (b) The second quadrant BH curves for corner and center 2-mm cubic samples machined from magnets with Tb GBD measured by VSM.

M. P. Thompson et al, IEEE Electrification, March 2017

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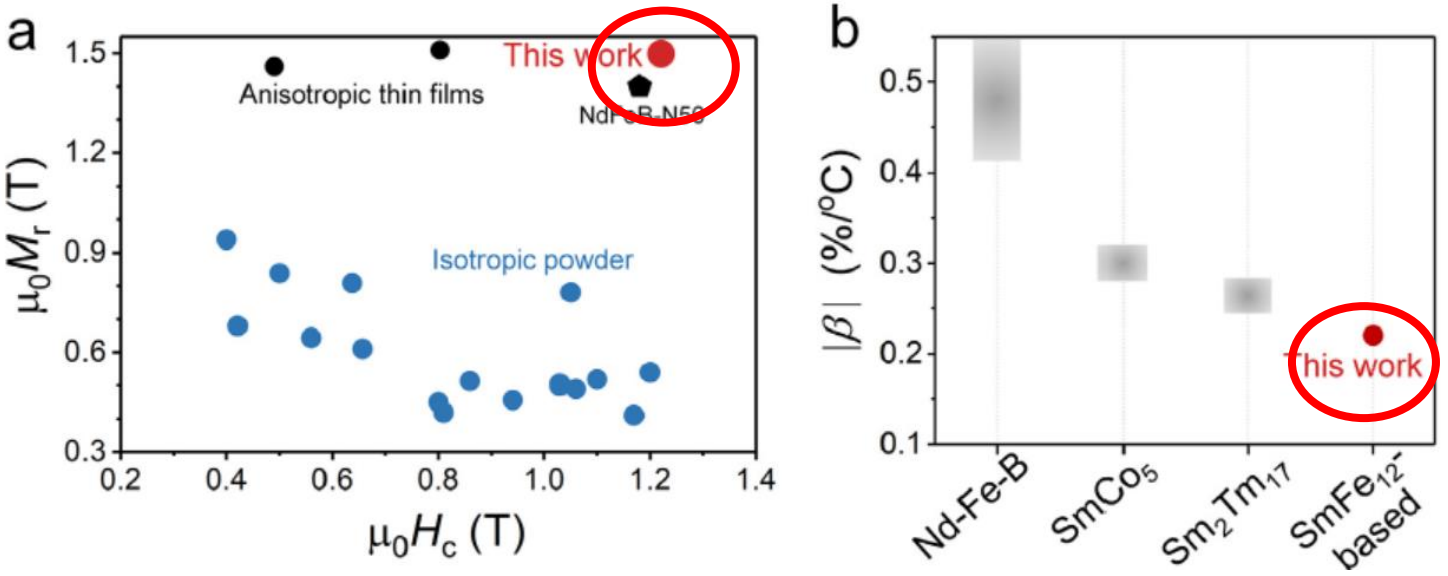
Achievement of High Coercivity in $Sm(Fe_{0.8}Co_{0.2})_{12}$



Acta Materialia, Volume 194, 1 August 2020, Pages 337-342

- Sputtered 100 nm films?
- Sm supply issue?
- Interesting but a long way from prime time.

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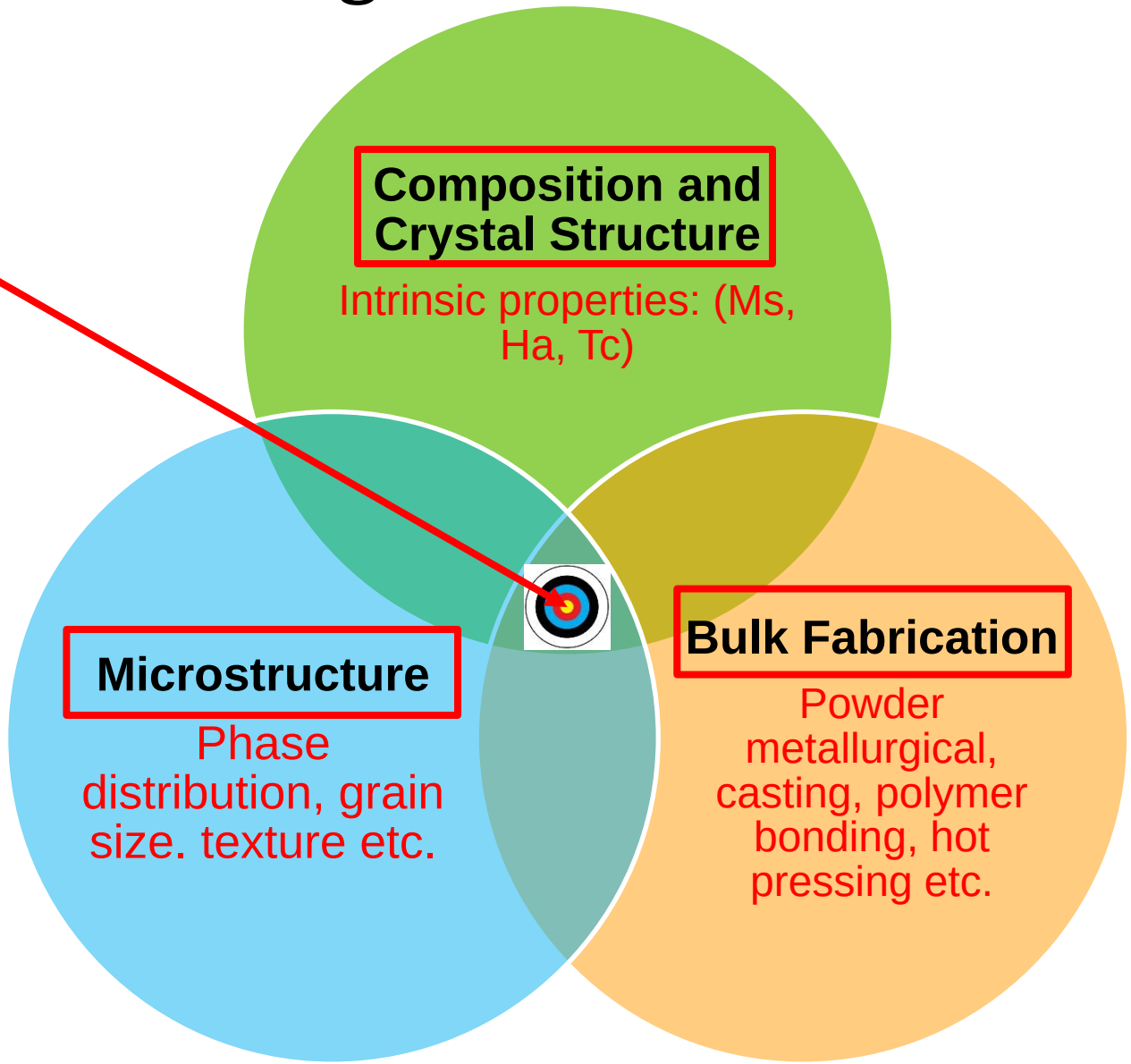
New Permanent Magnet Materials
It's A Challenge To Hit The Sweet Spot

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



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Thank you for your attention
Any Questions?

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