MAGNETICS 2018

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Permanent Magnet Material Options: Why \$/kg And $(BH)_{max}$ Are Misleading Metrics!

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“The Nation That Controls Magnetism Will Control The Universe”

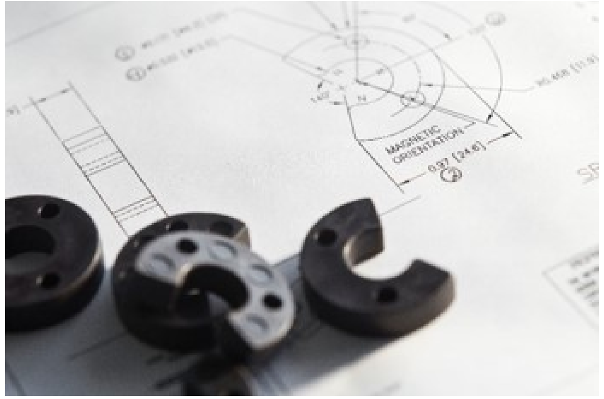
- Dick Tracy cartoon strip, created by Chester Gould.
- Circa early-1960’s i.e. before rare earth magnets and the Chinese dominance of RE supply chain and magnet industry!

Presentation Outline

- Introduction to Magnet Applications, Inc.
- Price/Performance – Niche or mass market?
- $/kg – Who buys magnets by weight?
- $(BH)_{max}$ – Is it really the best performance metric?
- NdFeB patent litigation update.

Introduction: Magnet Applications, Inc.

- Visit the latest website at: http://magnetapplications.com.
- A Bunting Magnetics Company: https://buntingmagnetics.com/.
- Only North American manufacturer of compression bonded NdFeB and injection molded ferrite, NdFeB and hybrid magnets.
- Supply full range of engineered magnets and magnetic assemblies.
- Located in DuBois, PA – Originally established in UK over 50 years ago – sister company located in Berkhamsted, UK.
- Primary applications are BLDC motors and sensors in the automotive, medical, defense and industrial markets.



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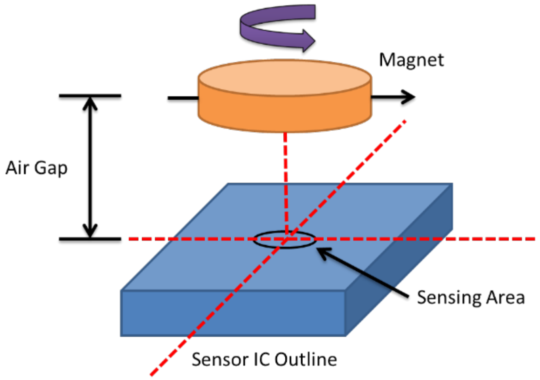
Introduction: Magnet Applications, Inc.

- Pre-production magnetic design services including 3D magnetic modeling.
- State of the art manufacturing capabilities including in-house coating and complete magnetic testing suite.
- Investing in R & D for next generation of magnetic materials e.g. high Br compression bonded, 3D printed magnets.
- The backing of strong family ownership – in business for over 55 years.
- ITAR / DFARS registered for Defense Industry.
- ISO-9001 Certified Quality System with a strong continuous improvement culture.
- Very strong international supply chain for the complete range of permanent magnet materials.



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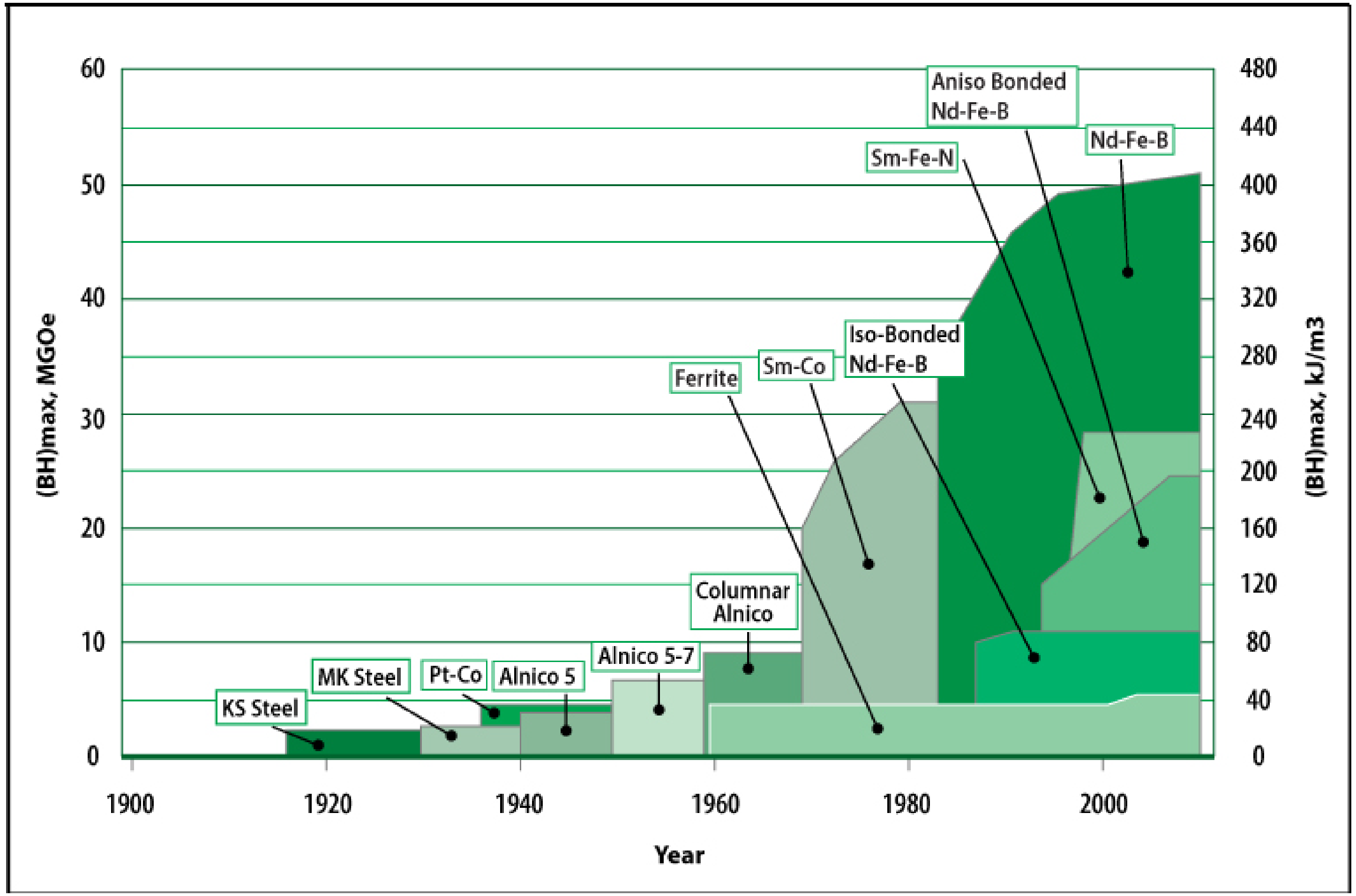
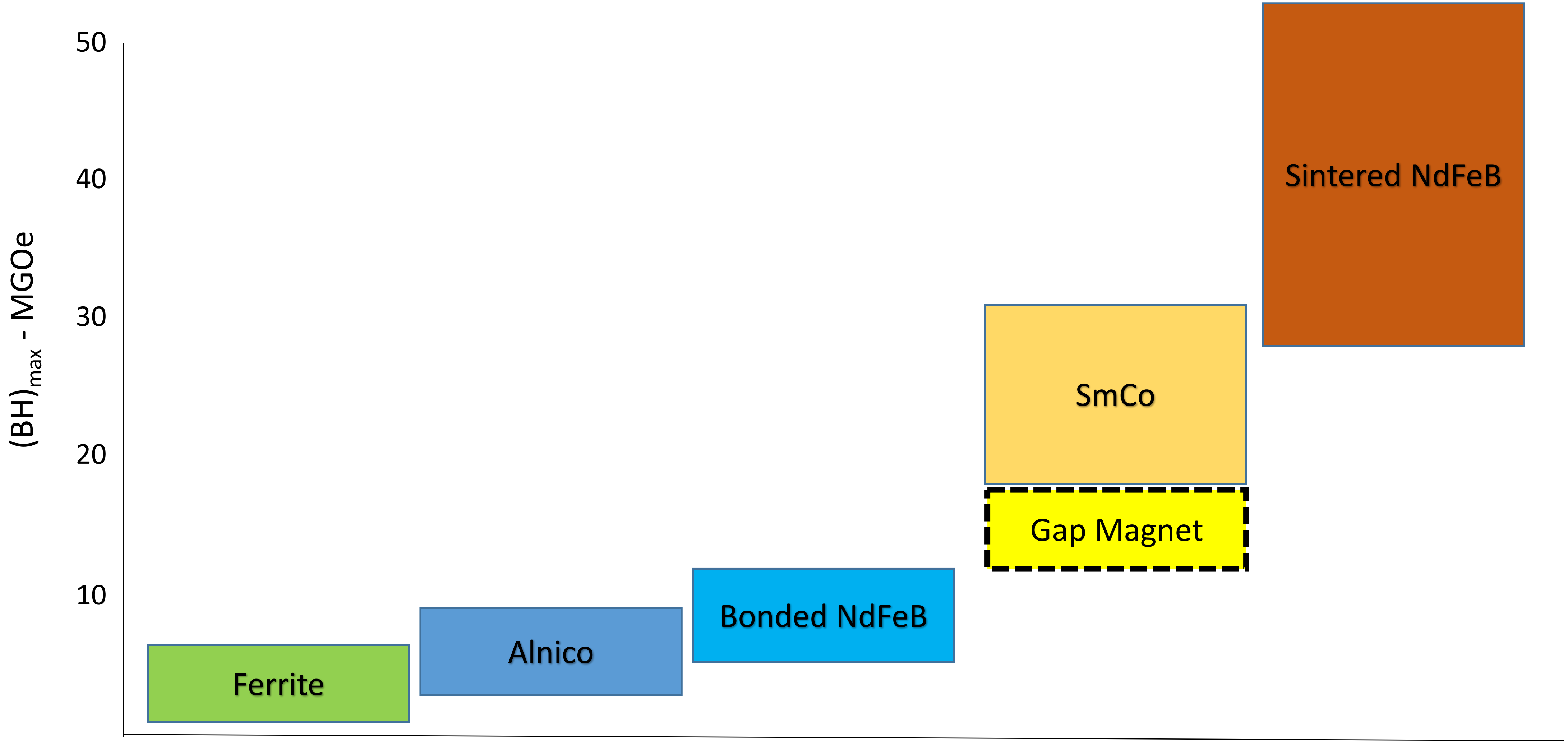
Historical Development Of Permanent Magnets



Commercially Important Permanent Magnets



Permanent Magnet Market Estimates – It's A Challenge

- Fragmented Industry with 100's of suppliers (over 800 in Asia Pacific region) – for NdFeB there are 20 Top tier, 50 mid-level and 100's third tier suppliers.
- Opaque supply chain - manufacturer – trader – master distributor/value adder – distributor – web shop.
- Installed capacity versus sales.
- In house production.
- Value added assemblies.
- Exchange rate fluctuations.
- RE raw material price volatility.

Permanent Magnet Market (2016) – Don't Mistake Precision For Accuracy!

• Markets and Markets	$14.76B
• Grandview Research	$23.37B
• Global Market Insights	$23.32B
• Transparency Market Research	$21.86B
• Market Research Reports	$14.53B
• Walt T. Benecki LLC (Global PM Industry 3rd Ed.)	$21.54B
• Magnets and Magnetic Materials LLC	$13.77B

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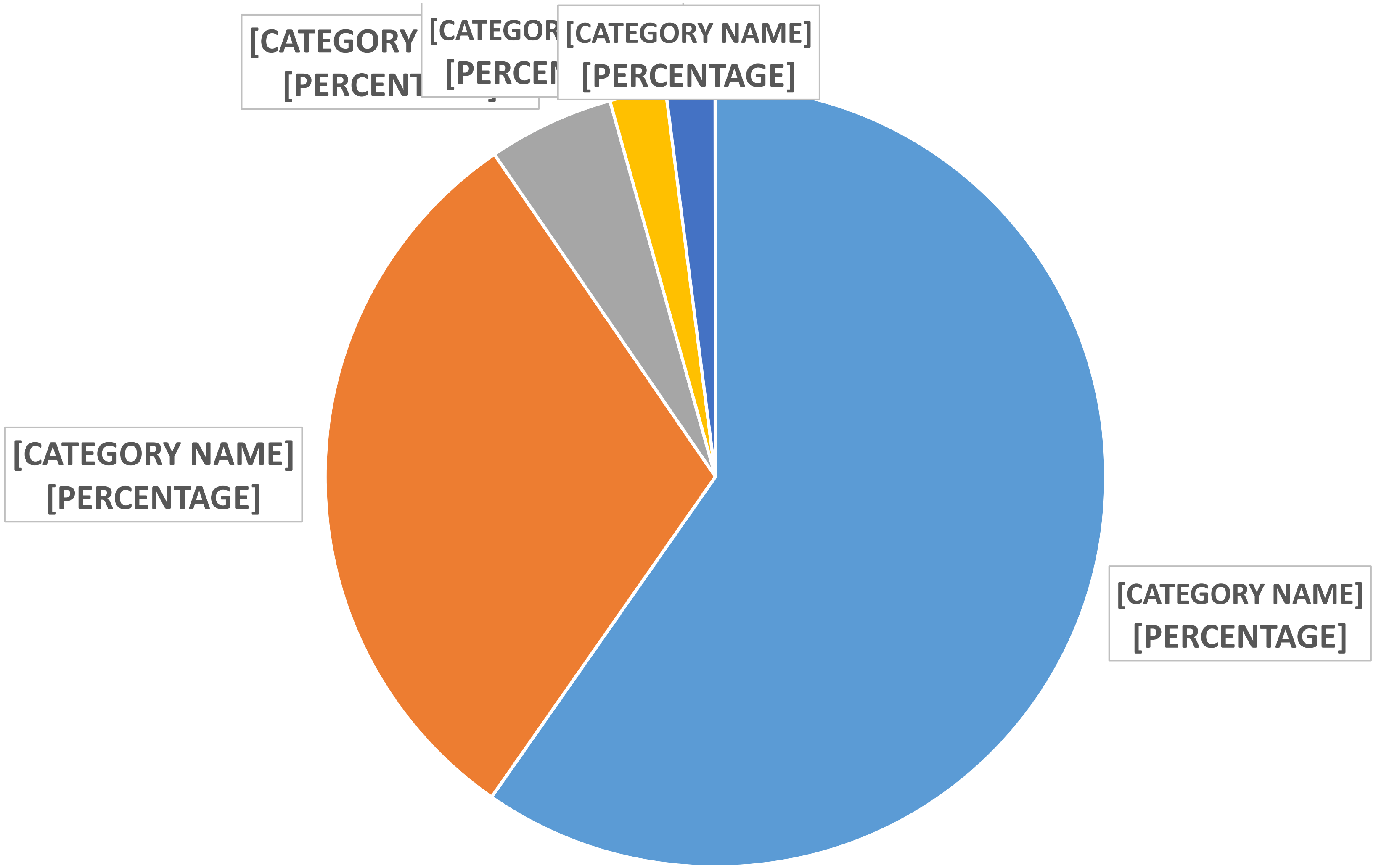
Permanent Magnet Market – My Guess

Material	Weight (000's kg)	Value ($ Millions)
NdFeB	137,500	10,300
Ferrite	750,000	5,300
Bonded NdFeB	10,000	900
SmCo	4,000	400
Alnico	6,000	350
	Total	Approximately $17 B

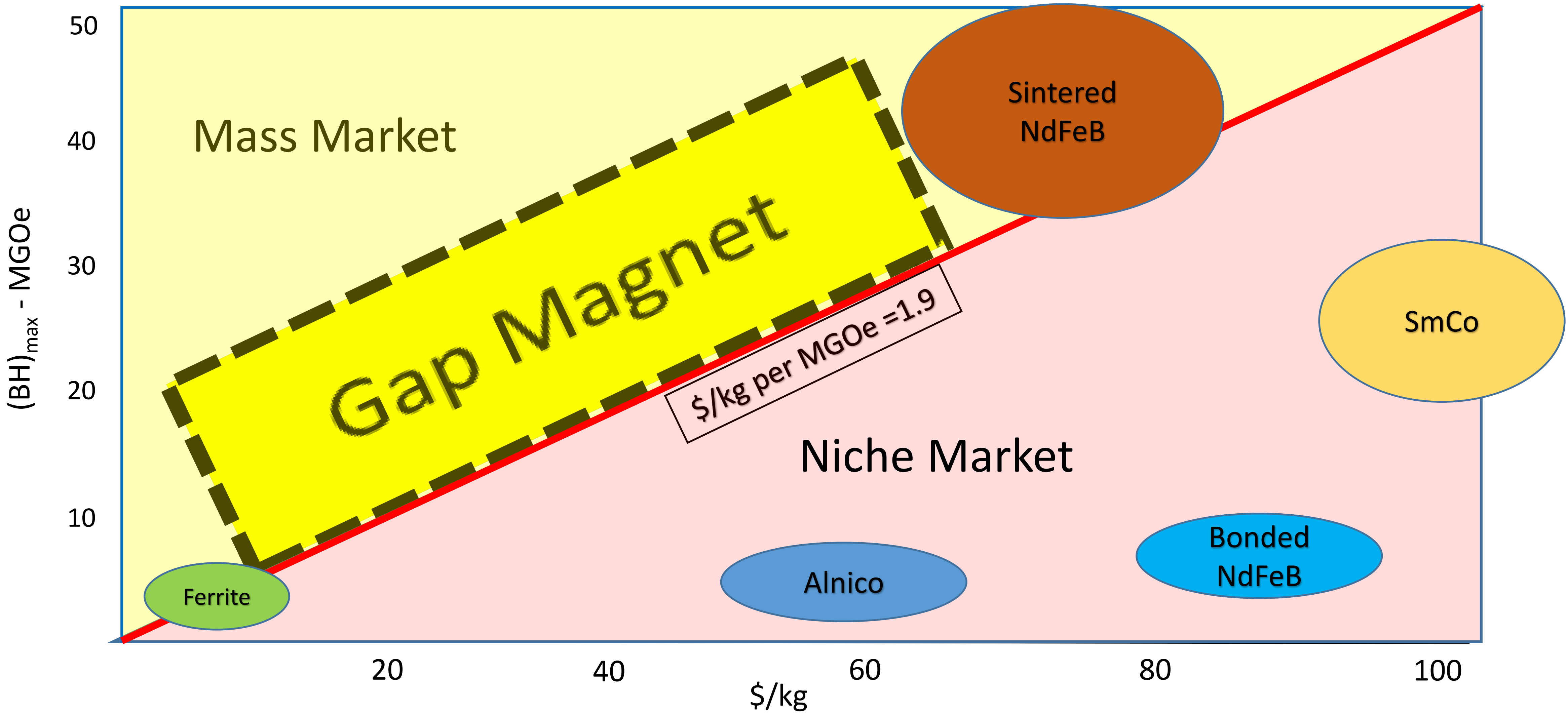
Market ($) Dominated By NdFeB And Ferrite – Why?



Is There An Optimum Price-Performance Metric?

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

Niche And Mass Market Materials



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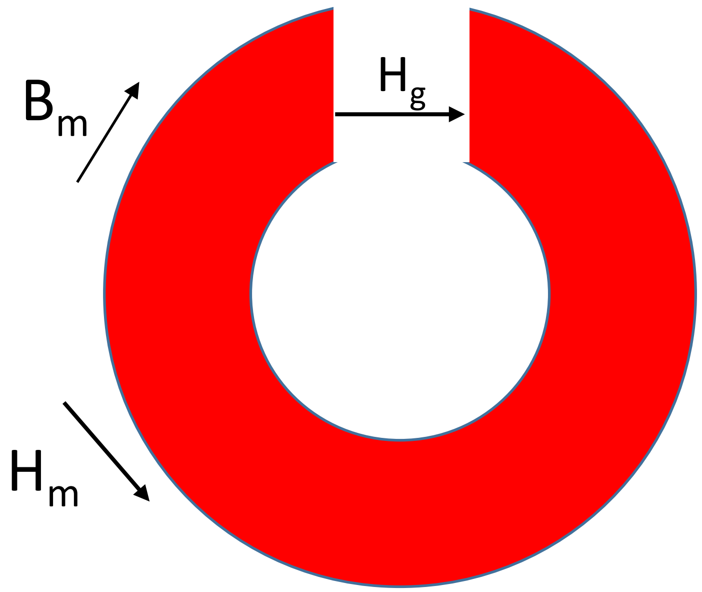
$/kg – What Are The Problems?

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

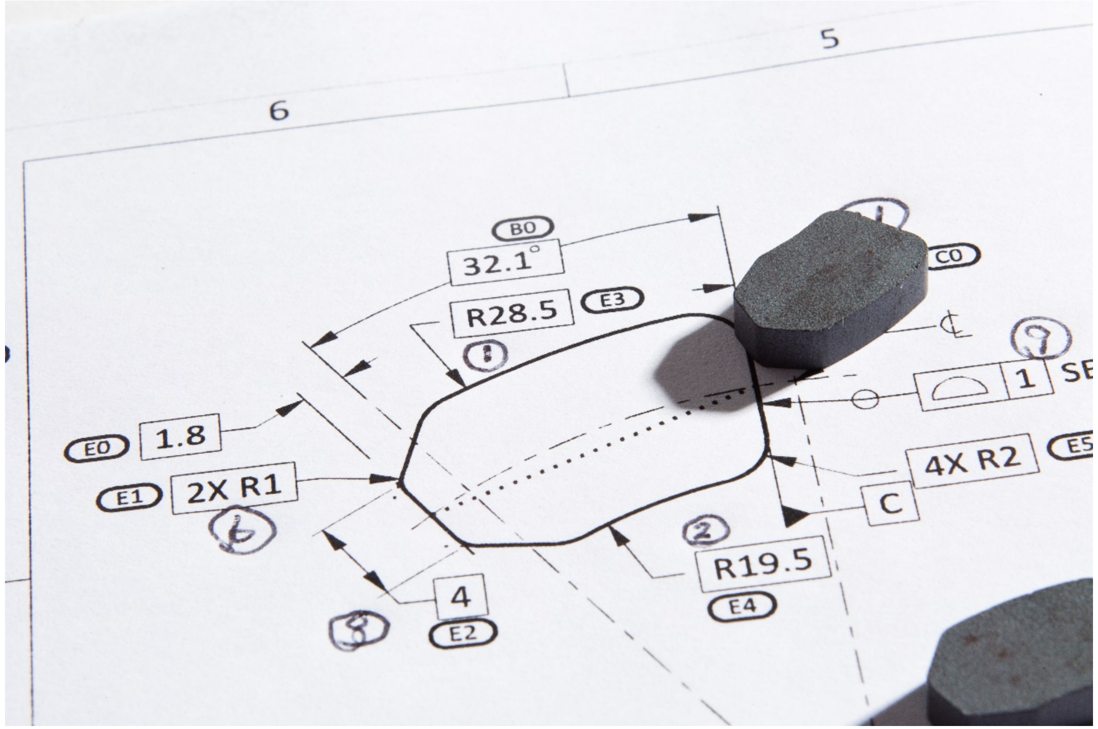
(see Culity and Graham, 2nd Ed)

- From first principles the field produced in a airgap (H_g) is a function of the volume of magnetic material (V_m).



$/kg – What Are The Problems?

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



$/kg – What Are The Problems?

Material	Density (g/cm3)
NdFeB	7.5
Ferrite	5.0
Bonded NdFeB	5.1
SmCo	8.4
Alnico	7.3

- Different magnet materials have different densities.
- On a volume basis Ferrite has a price performance ratio of approximately 50% better than NdFeB.

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Normalized Price/Performance Based On Weight and Volume (Ferrite is 1.0)

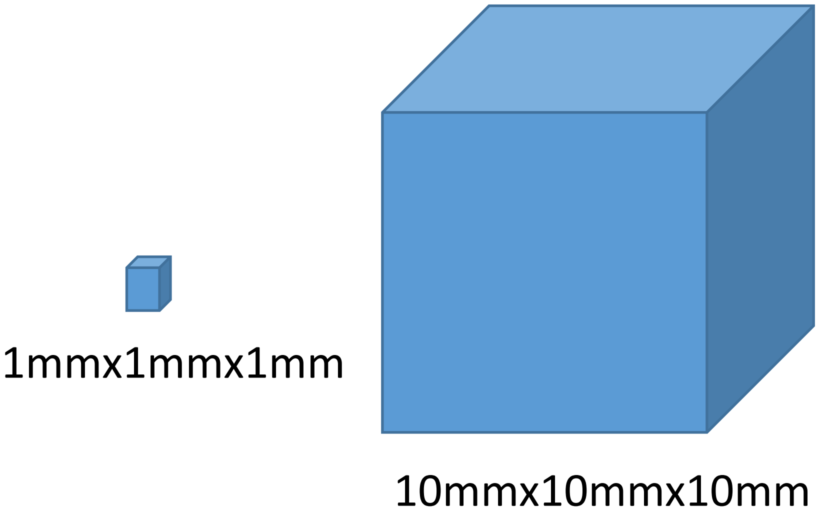
Material	Average $(BH)_{max}$ (MGOe)	Average price ($/kg)	Price/Performance (Unit Weight)	Price/Performance (Unit Volume)
Ferrite	3.8	7.1	1.0	1.0
NdFeB	40	75	1.0	1.5
Bonded NdFeB	8	90	5.9	6.1
SmCo	25	100	2.1	3.5
Alnico	7	58	4.4	6.4

$/kg – What Are The Problems?
Magnets Come In All Shapes And Sizes!

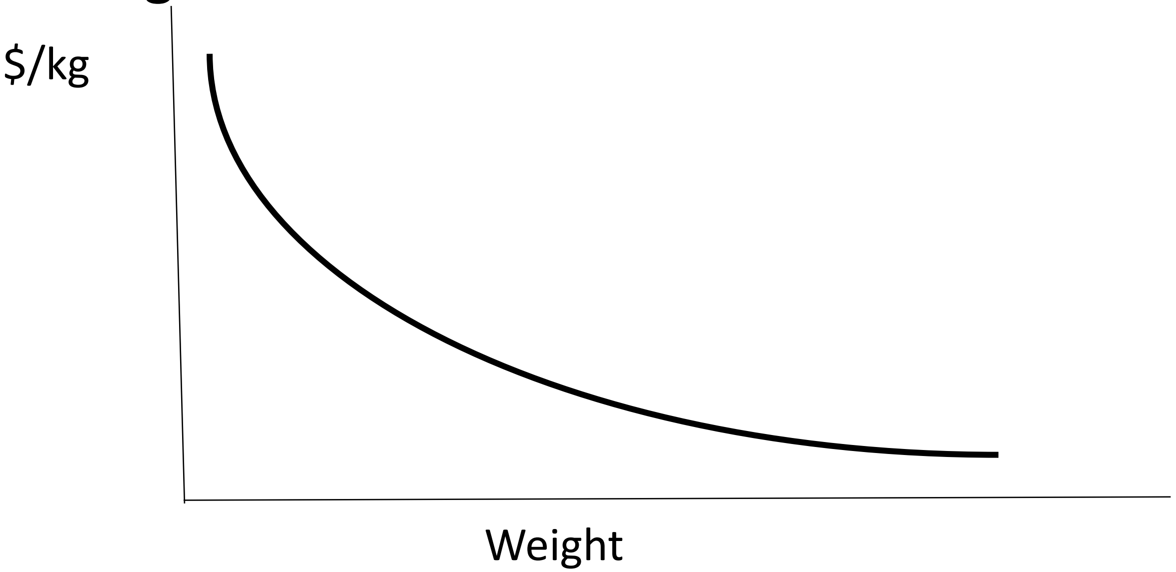
Source: Audemars Microtec

$/kg – What Are The Problems?

- Processing costs and material loss tend to be higher for smaller magnets.
- e.g. magnets that require machining the $/kg is a function of size:

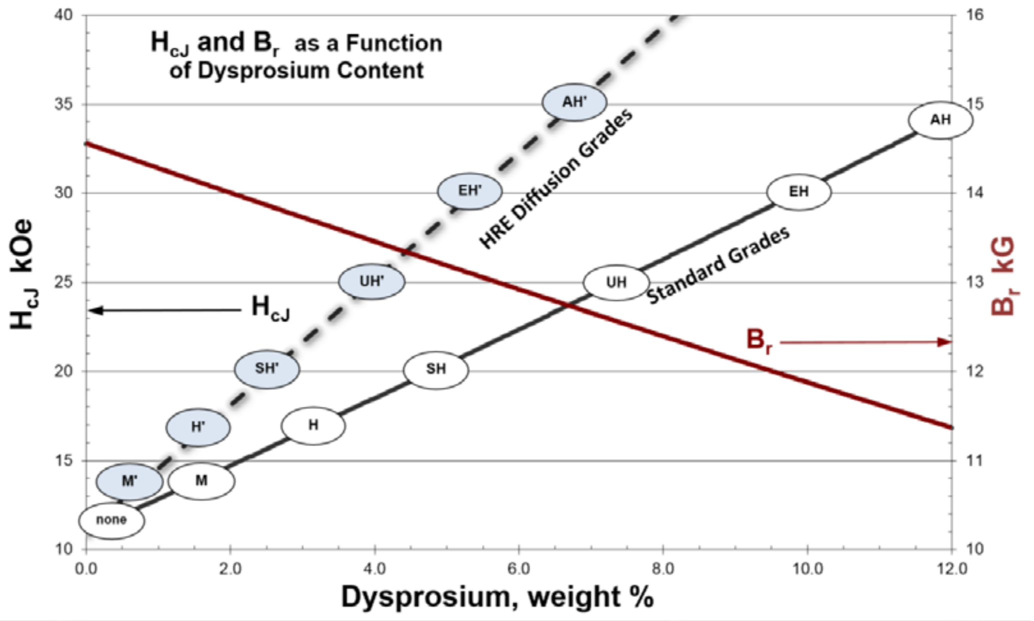


- Assume machining allowance of 0.1 mm.
- Material loss for small block is 73% and 6% for large block.



$/kg – What Are The Problems?

- Average is well just average.
- Wide range of grades (therefore cost) within a material class:
  - Ferrite from dry pressed isotropic < 1 MGOe to LaCo doped at > 5 MGOe.
  - Prices range over an order of magnitude.
  - Over 100 NdFeB grades - Dy drives operating temperature and cost.



Source: Magnetics and Materials LLC

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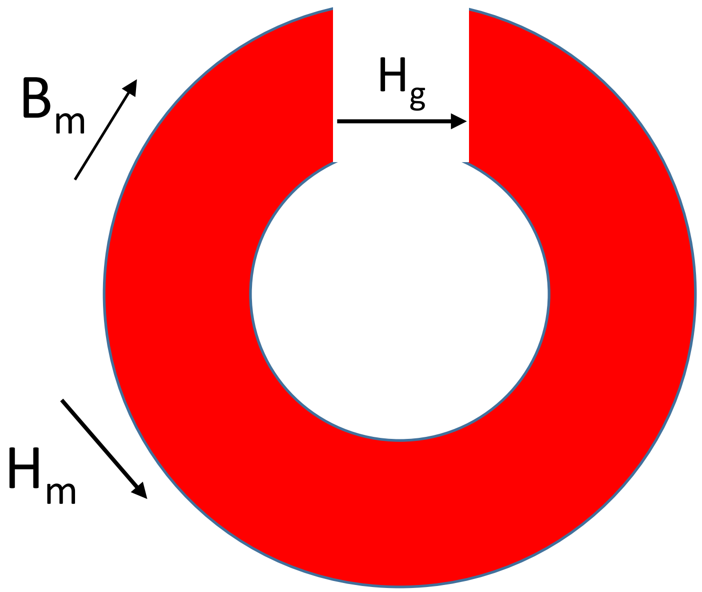
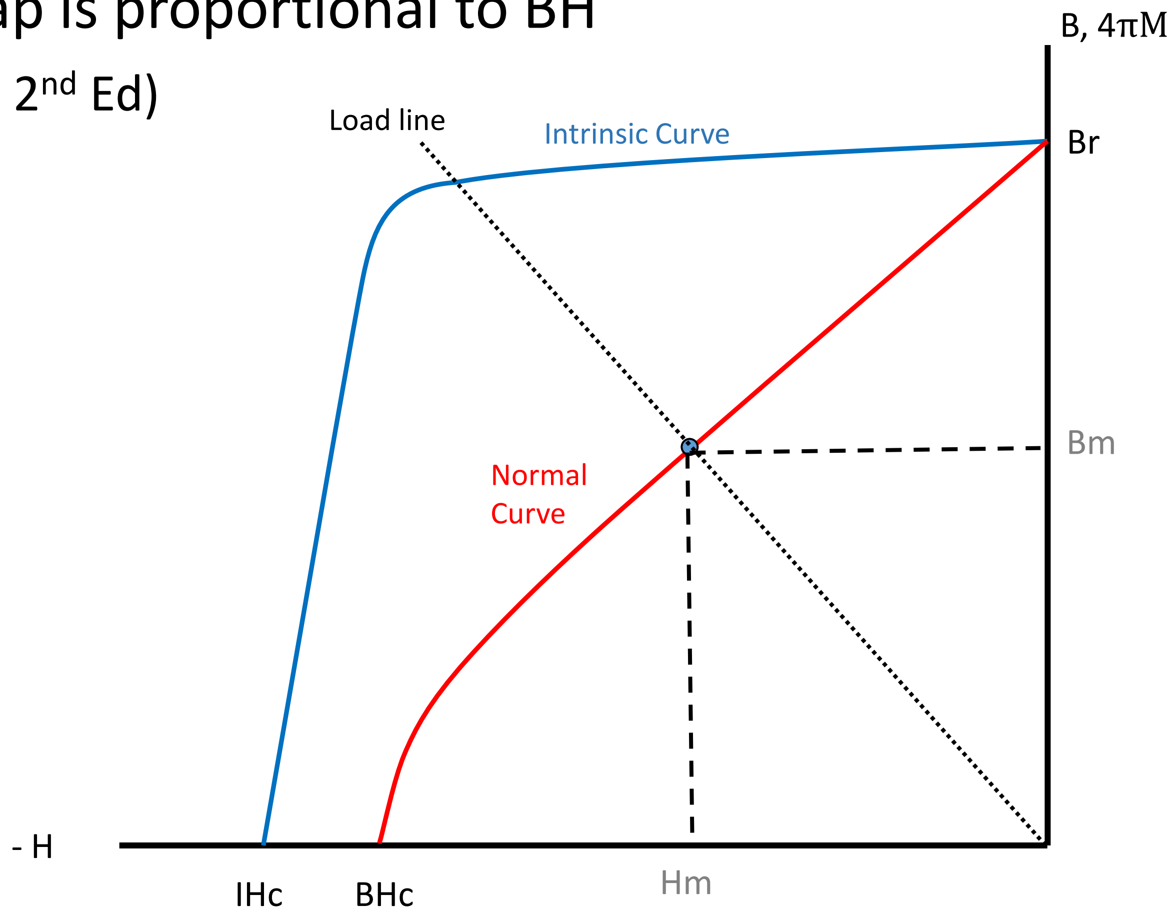
What Is $(BH)_{max}$?

- $H_g^2 = (B_m H_m) V_m / V_g$ – Hence, Vm is minimum when BH is maximum
- $E_g = H_g^2 V_g / 8\pi$ – Energy in airgap is proportional to BH

(see Culity and Graham, 2nd Ed)





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

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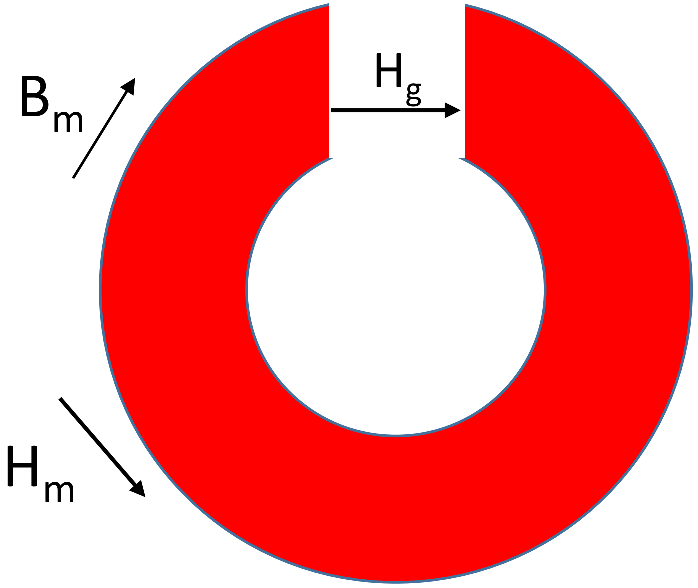

- Hence in order to minimize magnet volume (Vm) the magnet is designed to operate at $(BH)_{max.}$
- It's possible for static applications but not for dynamic applications.
- $(BH)_{max} \longrightarrow B_r^2/4$

Major Functions Of A Magnet

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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

Many Other Important Characteristics

- B_r
- BH_c
- IH_c
- H_k
- Recoil permeability
- Rate of change of B and BH_c with temperature
- Maximum operating temperature
- Ease of magnetizing
- Resistivity
- Mechanical properties
- Machinability
- Shape availability
- Raw material cost and availability
- Corrosion resistance
- Manufacturability and ease of device/sub assembly integration
- Economics of total raw materials and manufacturing process
- Process Control and Quality Assurance

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NdFeB Patent Litigation Update
"Oh what a tangled web we weave…………"

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- Update from Magnetics 2017 presentation and LinkedIn article (https://www.linkedin.com/pulse/ndfeb-magnet-patents-oh-what-tangled-web-we-weave-john-ormerod/
- HML's Federal Court Appeal of PTAB invalidity ruling on IPR's of 6,537,385 and 6,491,765.
- '765 and '385 – Removal of RE-rich particles less than 1 micron from RE alloy magnetic powder.
- April 2017 the court affirmed most of the conclusions that lower courts had previously ruled in the "Hitachi Metals, Ltd. v. Alliance of Rare-Earth Industry" case.
- The Federal Court ordered the PTAB to reconsider whether the 2 claims ('765) requiring some amount of oxygen in the high speed gas in the jet mill are obvious.
- Currently awaiting PTAB ruling (and Supreme Court decision on IPR constitutionality).

NdFeB Patent Litigation Update
"Oh What A Tangled Web We Weave…………"

- On April 24, 2017, three Chinese companies (DMEGC, Zhejiang Innuovo and Zhejiang Dongyang East Magnetic Rare Earth) filed IPR petitions challenging HML's US patents 6,461,565 and 6,527,874.
- '565 – Method of pressing a RE alloy magnetic powder in a controlled environment from 5^{o}C to 30^{o}C and RH from 40% to 65%.
- '874 – RE magnetic alloy containing 0.1 to 1.0 At % Nb.
- On November 5th, 2017 the USPTO initiated IPR proceedings for '565 but denied the petition for '874.
- Discovery phase for the '565 IPR began January 2018.

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Final Thoughts

- When selecting the optimum material the application details and environmental conditions are critical.
- Need to compare cost and performance for specific magnet geometry and grades – averages can be misleading.
- $/kg is misleading when comparing material types.
- Consider all the magnet parameters not just $(BH)_{max}$..
- Mass market “Gap Magnet” opportunity is very large.
- 2018 – 35 years since the commercial introduction of NdFeB magnets.
  - Still litigating the IP rights!
  - Many thousands of hours by very smart researchers have been devoted and millions of $’s invested in the search for the next big thing.

> **“If you really look closely, most overnight successes took a long time”**
>
> **- Steve Jobs**

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Driverless vehicles and AI are the future
More magnetic applications!