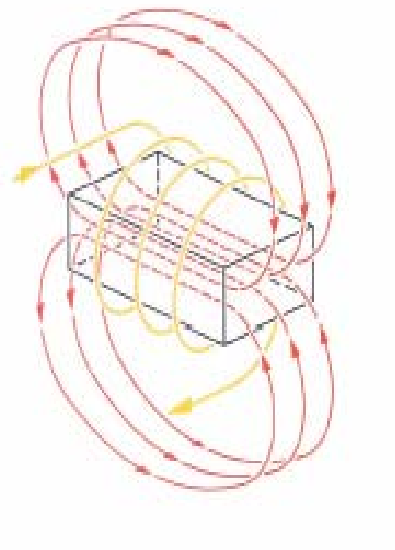
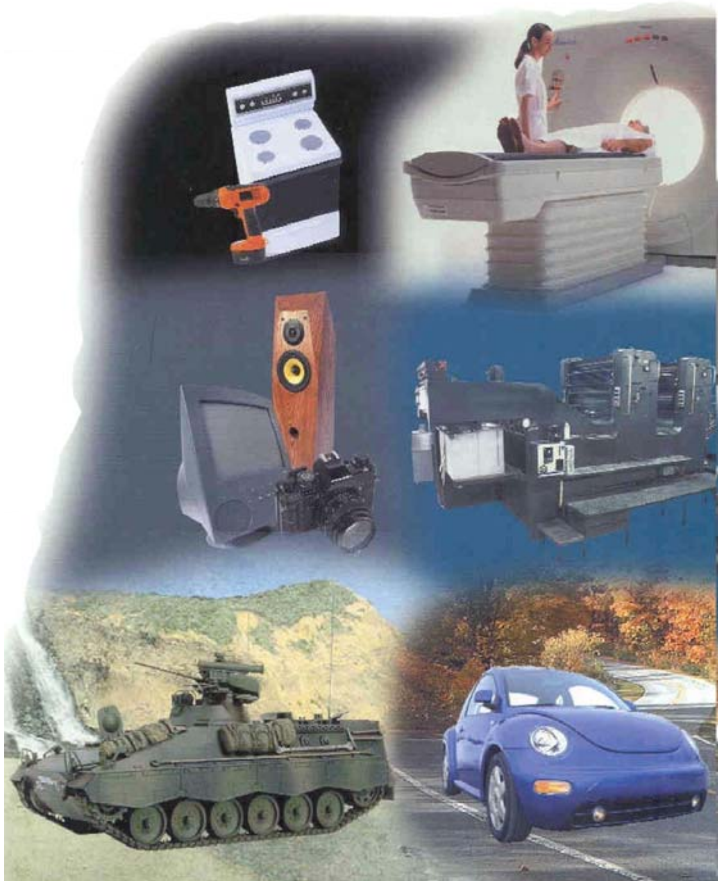
Fundamentals of Permanent Magnets

Robert Wolf
Data Decisions / Alliance LLC



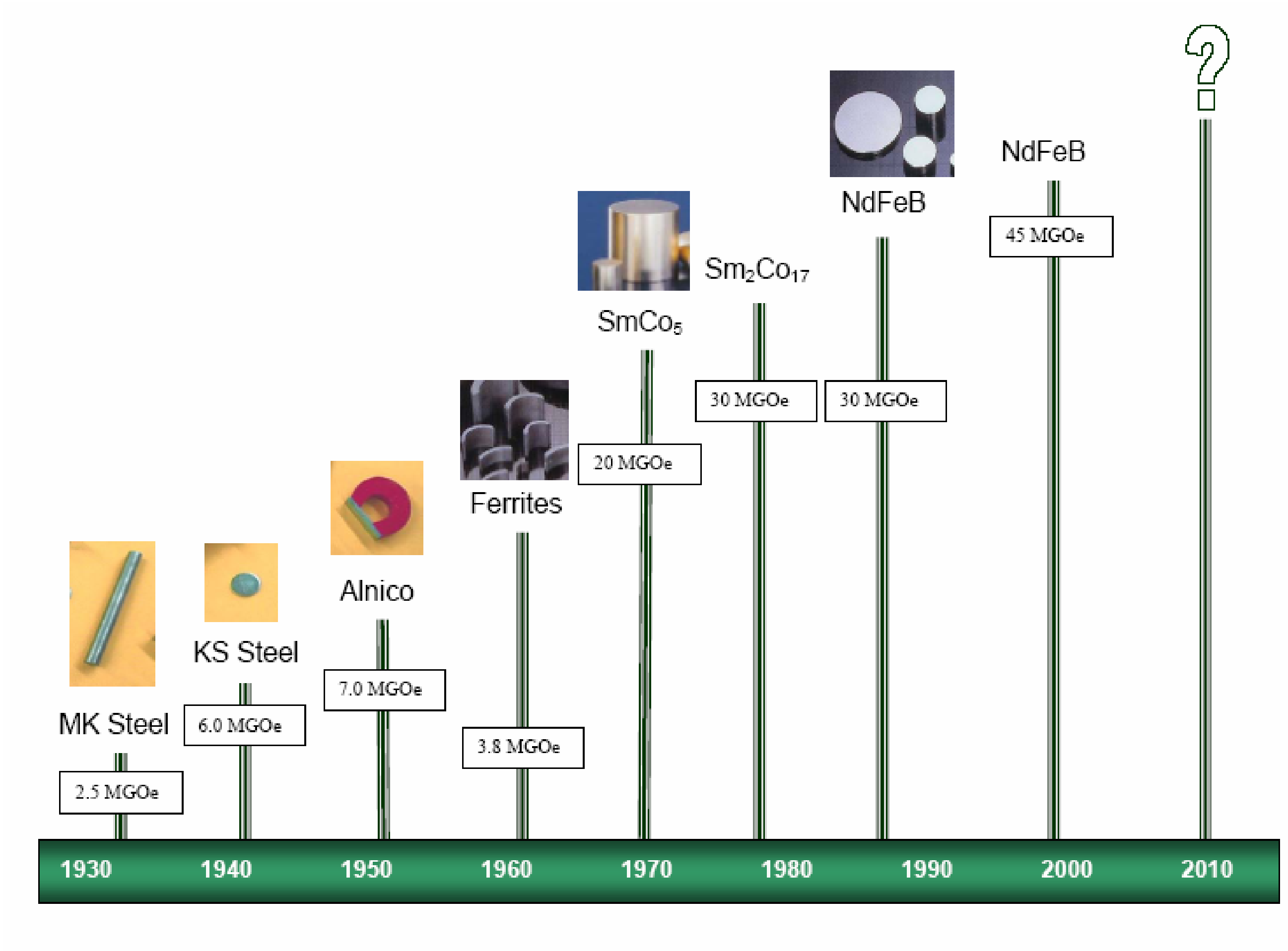
Magnet Markets

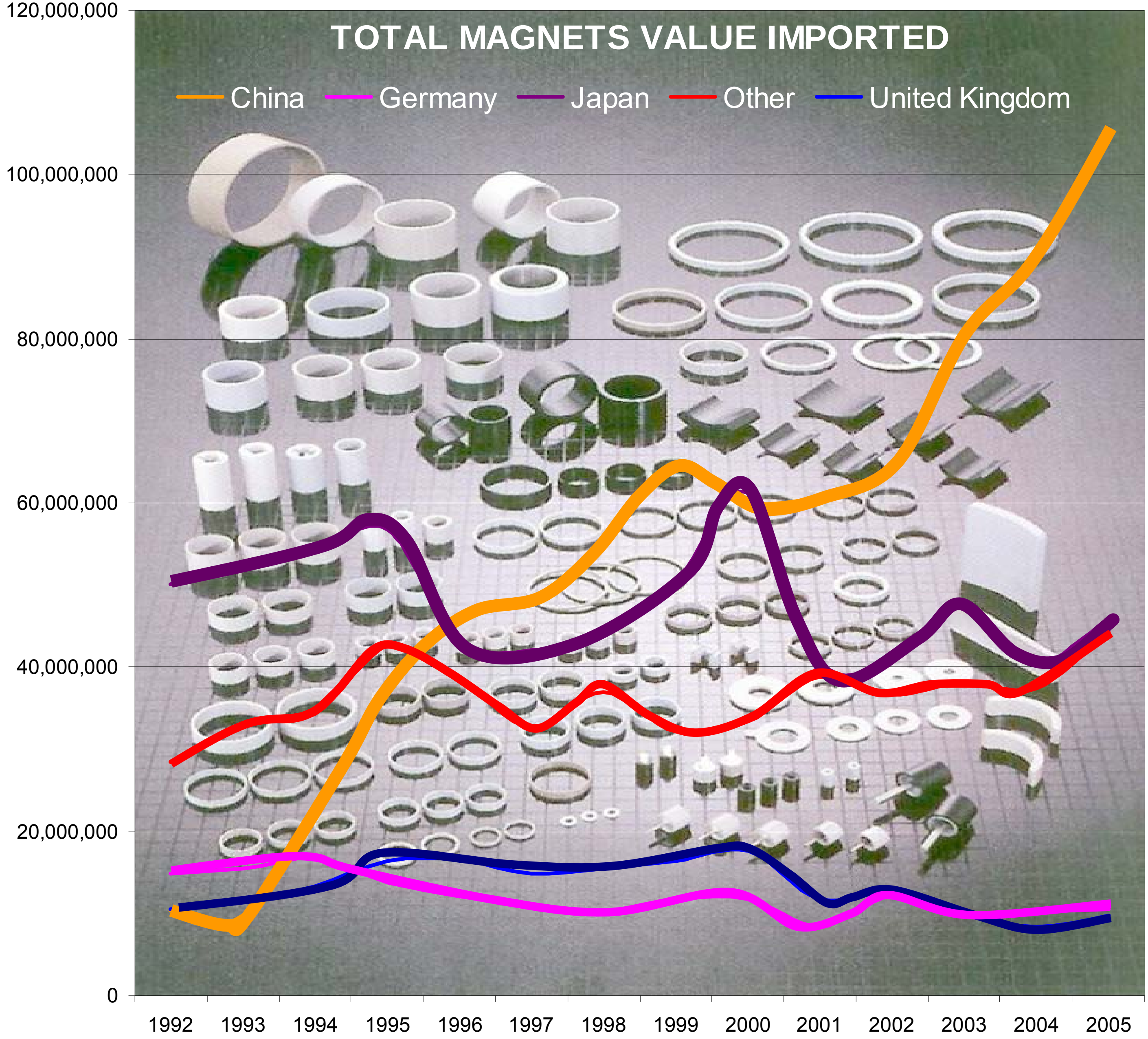
- Automotive
- Consumer Electronics
- Appliances
- Medical
- Military / Aerospace
- Office Automation



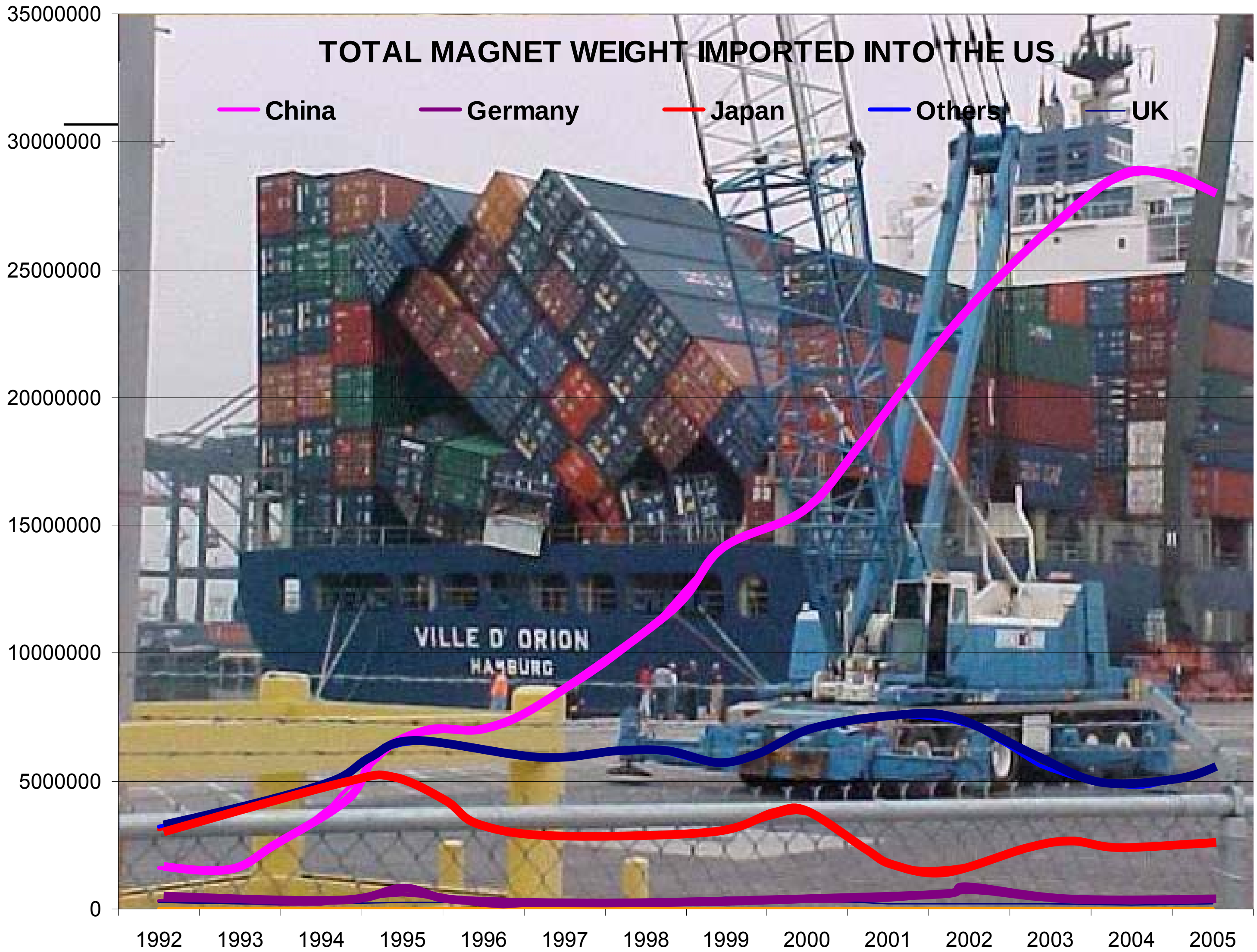
Magnet Applications

History of Magnetic Materials

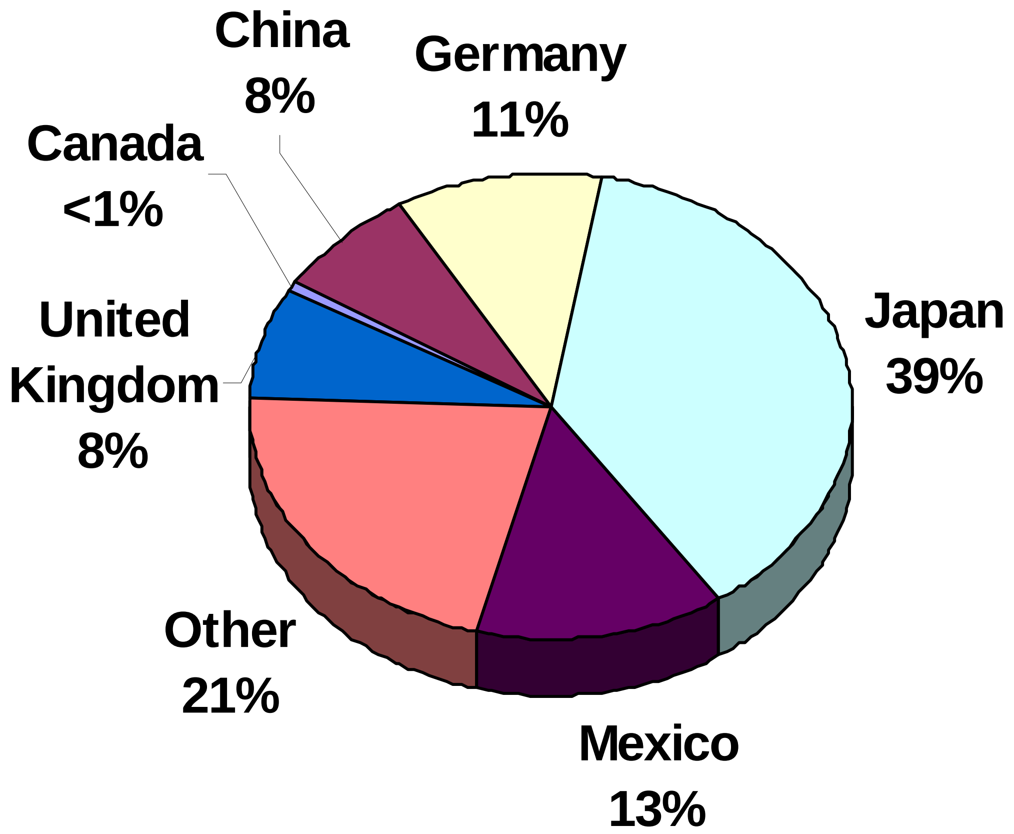




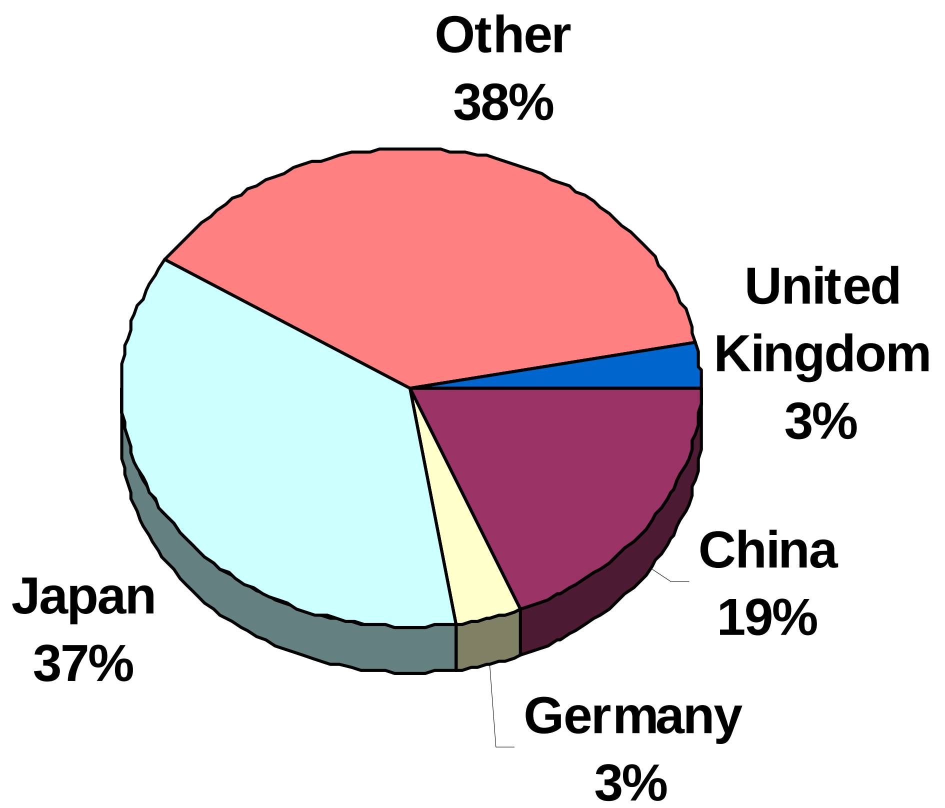
TOTAL MAGNETS VALUE IMPORTED
China
Germany
Japan
Other
United Kingdom
120,000,000
100,000,000
80,000,000
60,000,000
40,000,000
20,000,000
0
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005


TOTAL MAGNET WEIGHT IMPORTED INTO THE US
China
Germany
Japan
Others
UK
35000000
30000000
25000000
20000000
15000000
10000000
5000000
0
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
VILLE D' ORION
HAMBURG

1992 Import Magnet Dollars to US

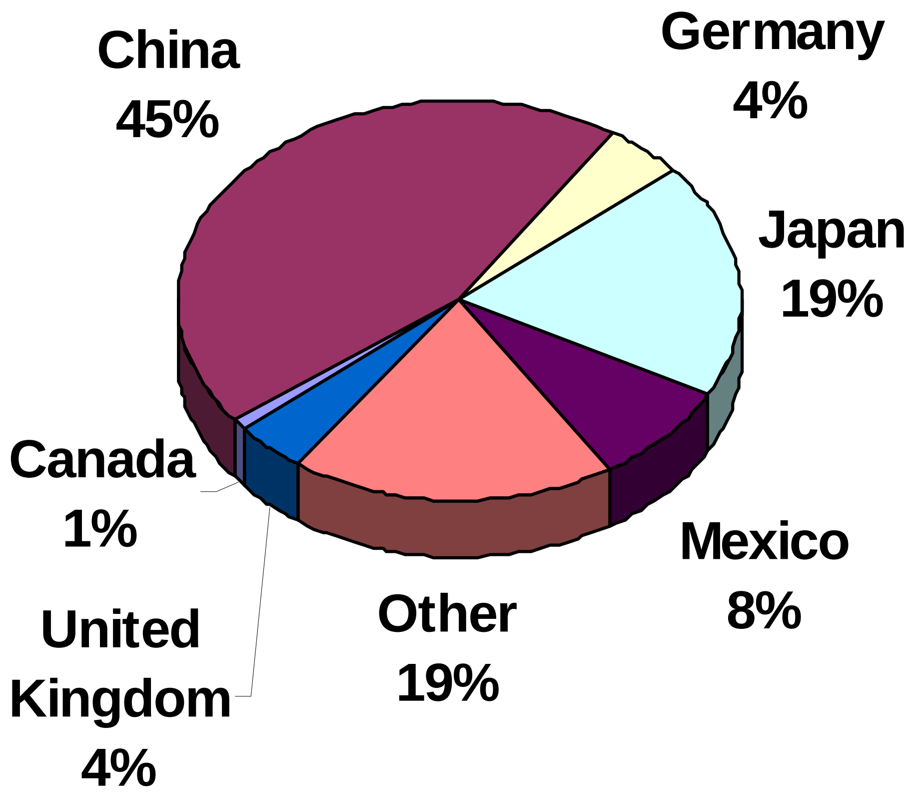


1992 Import Magnet Weight to the US

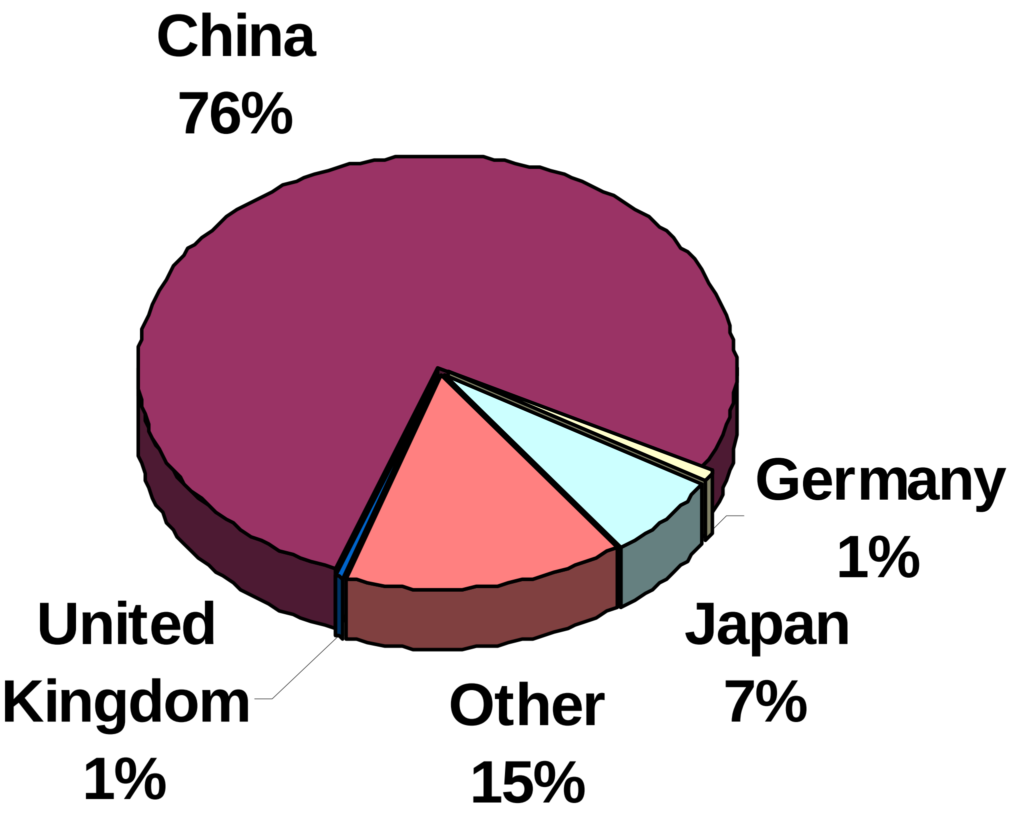


*Mexico and Canada do not report weights

2005 Import Magnet Dollars to the US



2005 Import Magnet Weight to the US



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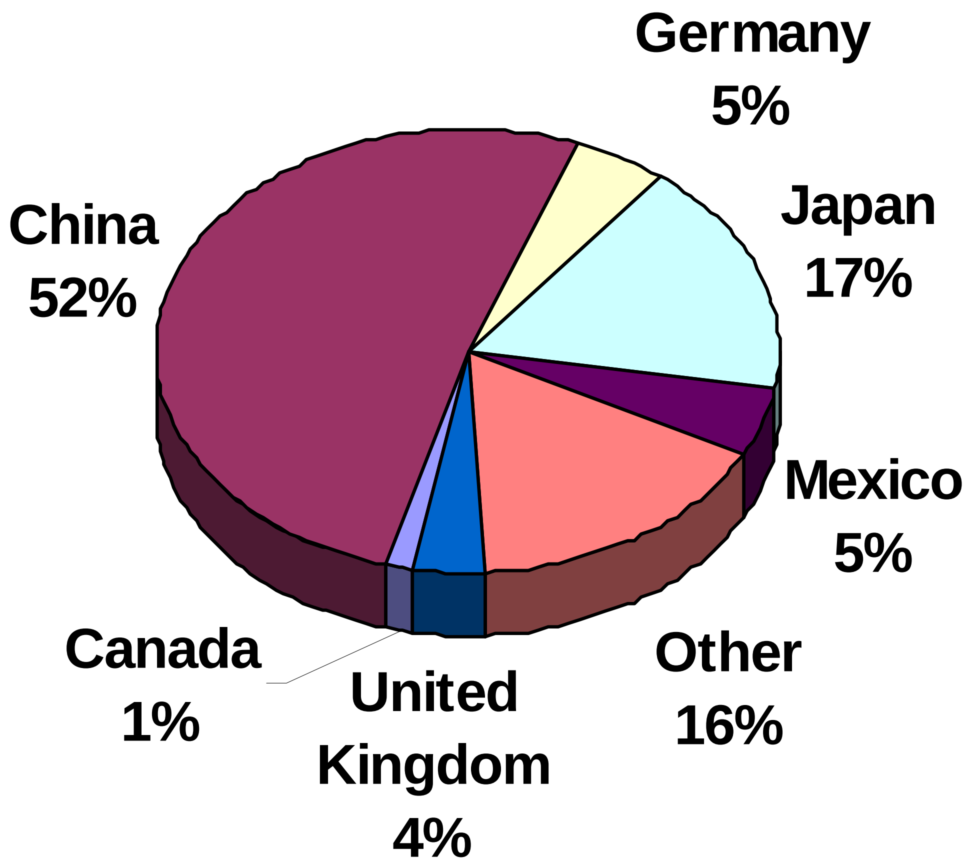
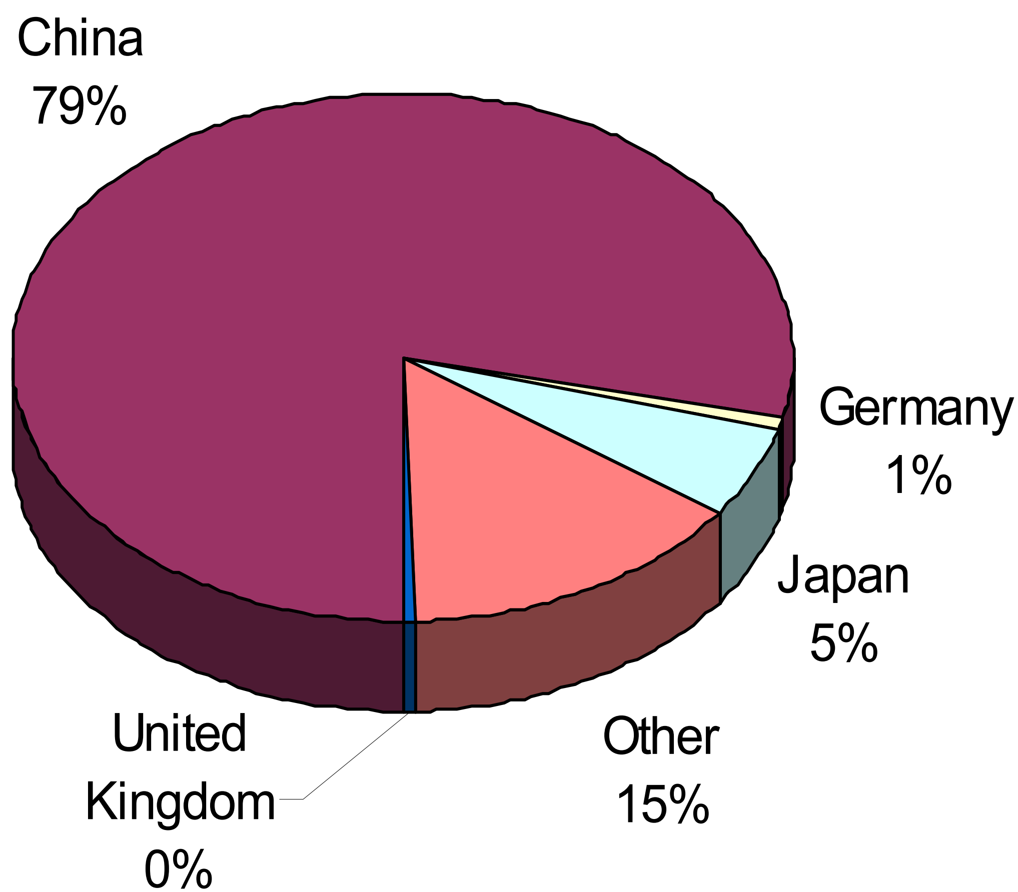
2006 Import Magnet Dollars to the US



2006 Import Magnet Weight to the US



*Mexico and Canada do not report weights

Magnetostatic Equations

a. Gauss Law $\int \vec{B} \bullet \vec{dA} = 0$

b. Ampere's Law $\int \vec{H} \bullet \vec{dl} = \int \vec{J} \bullet \vec{n} ds$

c. Lorentz Equation $\vec{F} = q\left(\vec{E} + \overrightarrow{vxB}\right)$

d. Maxwell's Equations

$$1)\nabla \bullet \vec{B} = 0$$

$$2)\nabla x \vec{E} = -\frac{d\vec{B}}{dt}$$

$$3)\nabla x \vec{H} = \vec{J} + \frac{d\vec{D}}{dt}$$

$$4)\nabla \bullet \vec{D} = \rho$$

e. Magnetic Energy $W = \frac{1}{2}\int \vec{H} \bullet \vec{B} dv$

f. General basic design equations

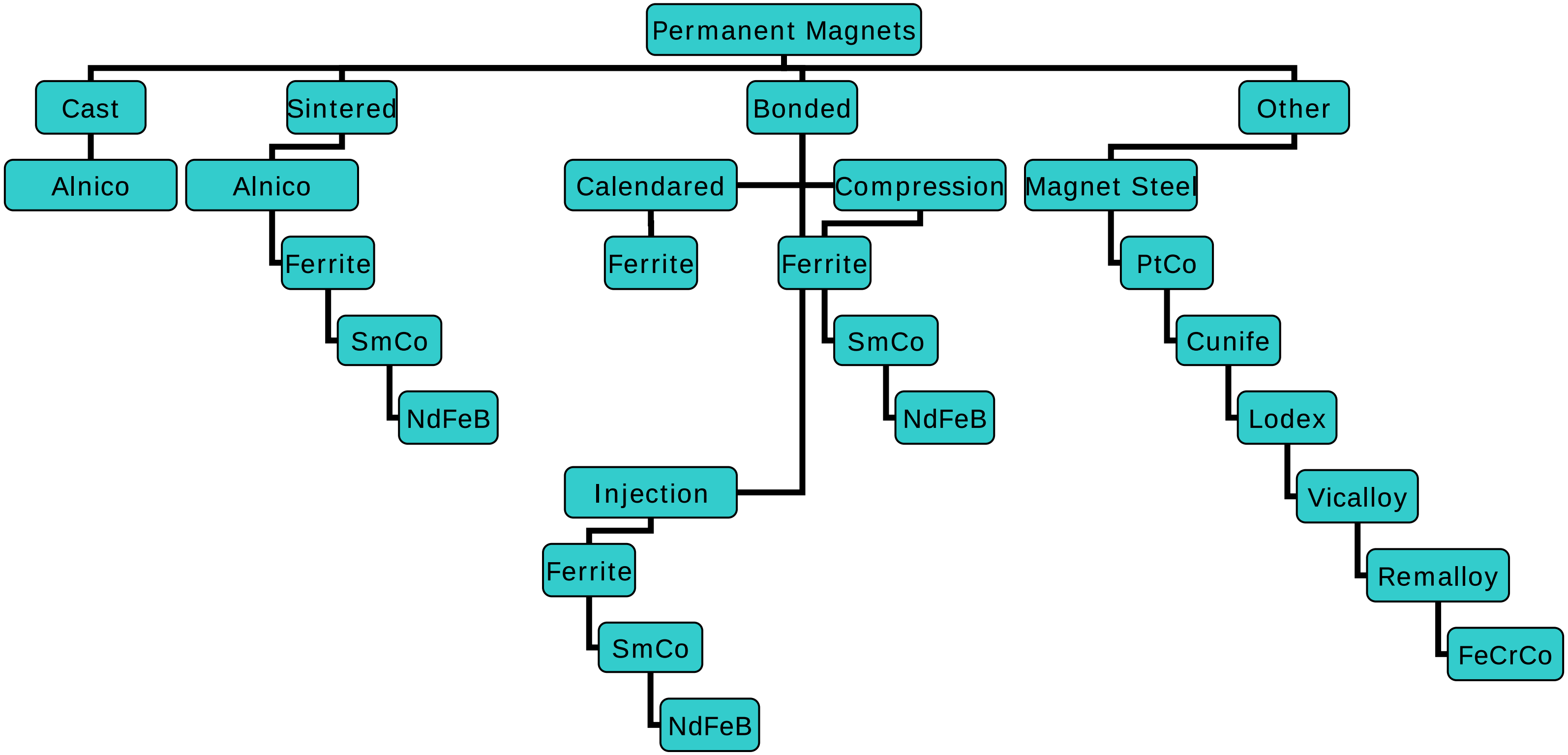
Some Applications Based on Laws

- **Coulombs Law**
- 1- Compass
- 2- Torque Devices
- 3- Force (Holding/Repulsion) Devices
- **Faradays Law**
- 1- Alternators
- 2- Generators
- 3- Microphones
- 4- Eddy Current Devices

Some Applications Based on Laws

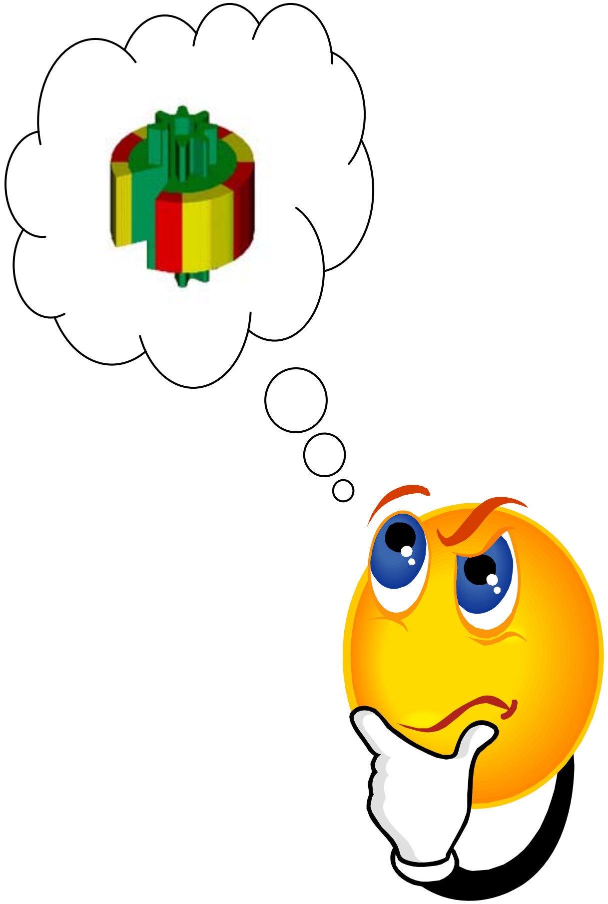
- **Lorentz Force Law**
- 1- Loudspeakers
- 2- Motors
- 3- Meters & Instruments
- **Lorentz Force on Electrons**
- 1- Traveling Wave Tubes
- 2- Magnetic Resonance Imaging
- 3- Spectrometers
- 4- Magnetrons

The Magnet Family



Issues When Designing for a Magnet

- Items to consider when specifying a permanent magnet in an application



The material to be used

- Alnico
- Ferrite
- Samarium Cobalt
- Neodymium Iron Boron
- Cunife
- Iron Chrome Cobalt

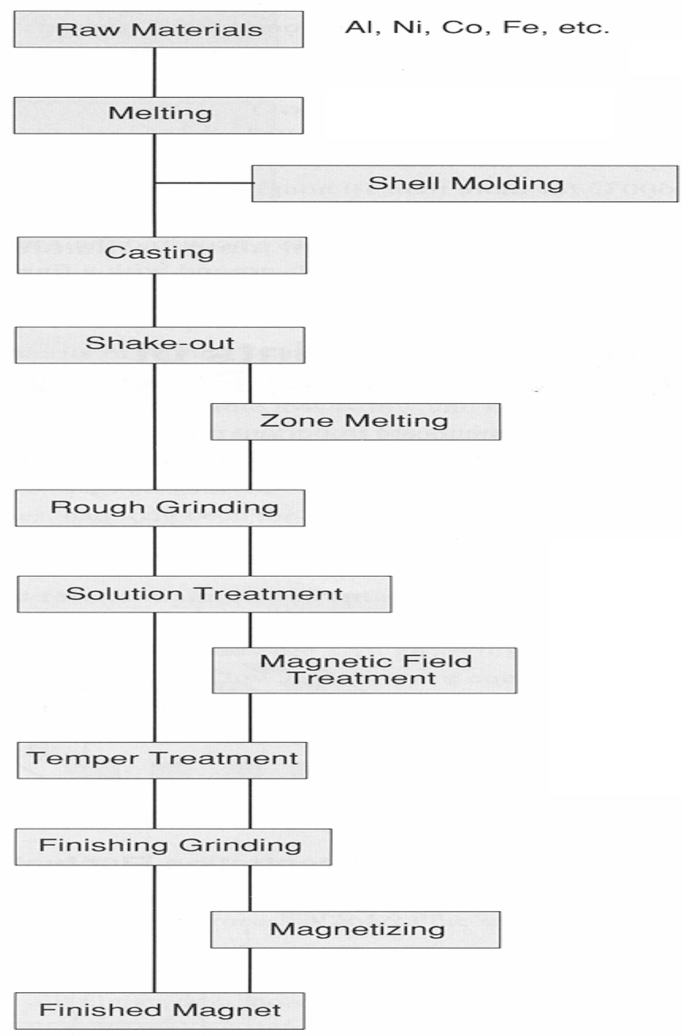
Magnet Characteristics

Materials	Typical Shapes	Pro	Con
Cast Alnico AlNiCo	Rods, Bars, U shape and other cast type	High Br High working T Good T coef.	Very Low Hc High cost High L/D Requires Cast
Sintered Alnico AlNiCo	Powder pressed to shape	Complex shapes High Br, T	Requires Tool High cost Low market
Ceramic/Ferrite $SrFe_2O_3$	Blocks, Rings, Arcs, Discs	Most flux for $ High usage Low corrosion	Low Br Requires tool Simple shapes
Samarium Cobalt SmCo	Blocks, Rings, Discs Arcs, Segments	No corrosion Very low T coef Stable, No tool	Very expensive Simple shapes High Co content
Neodymium NdFeB	Blocks, Rings, Discs Arcs, Segments	Highest magnetic properties No tooling	Corrodes Low working T Difficult to Mag
Bonded Grades All materials	Difficult geometries Can be insert molded or over-molded	Complex shapes Various resins	High tooling Low magnetics High volumes

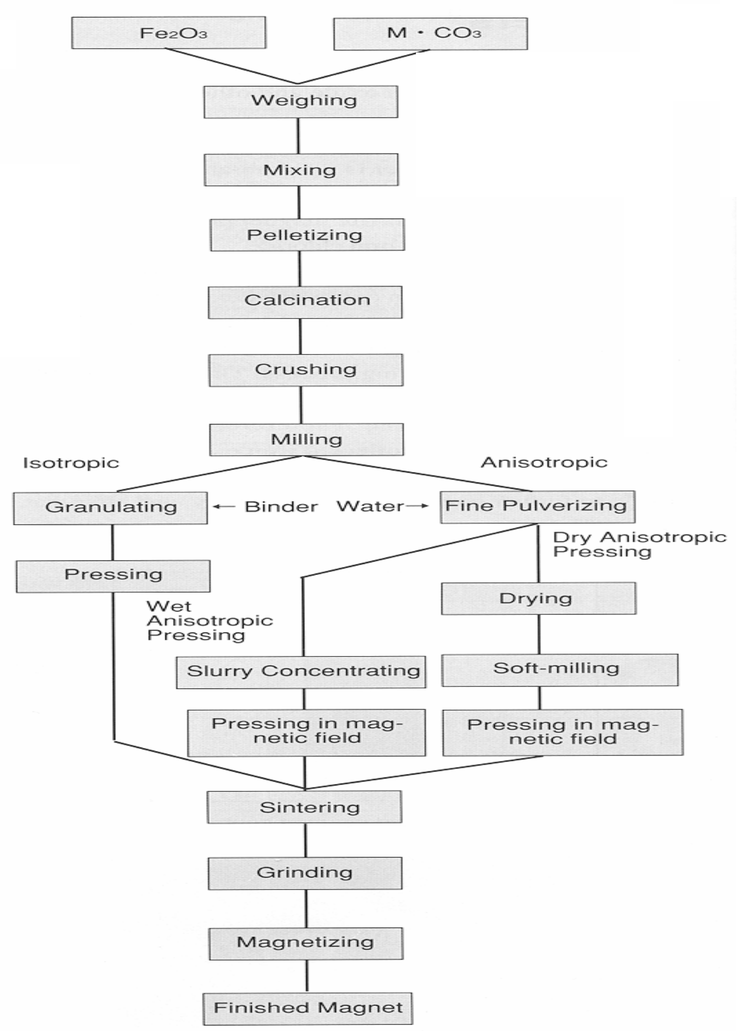
The method of manufacture

- Cast
- Sintered
- Bonded
  - Calendared
  - Injection molded
  - Compression molded
  - Extruded

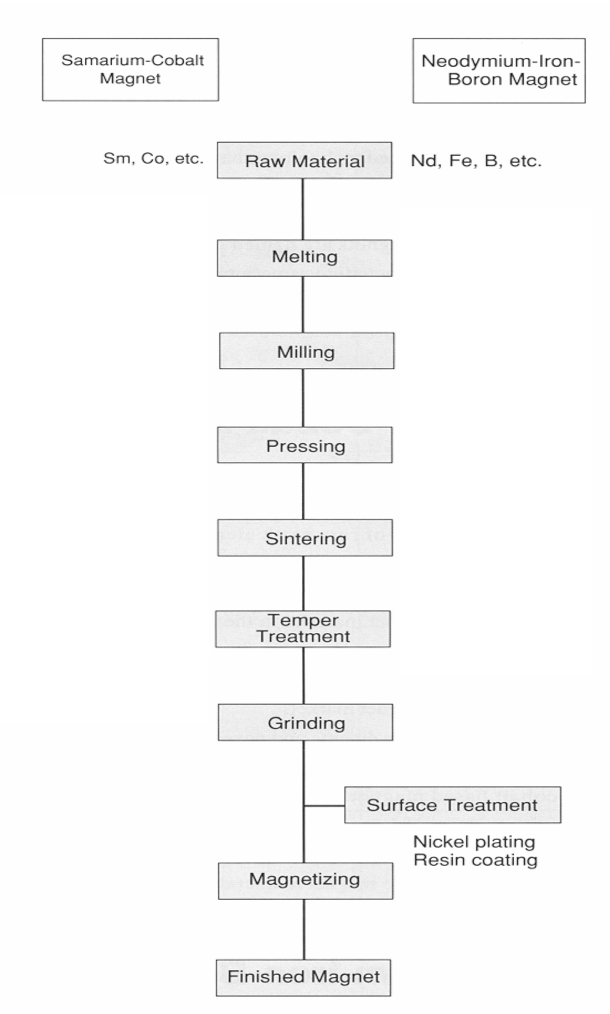
Alnico Manufacturing



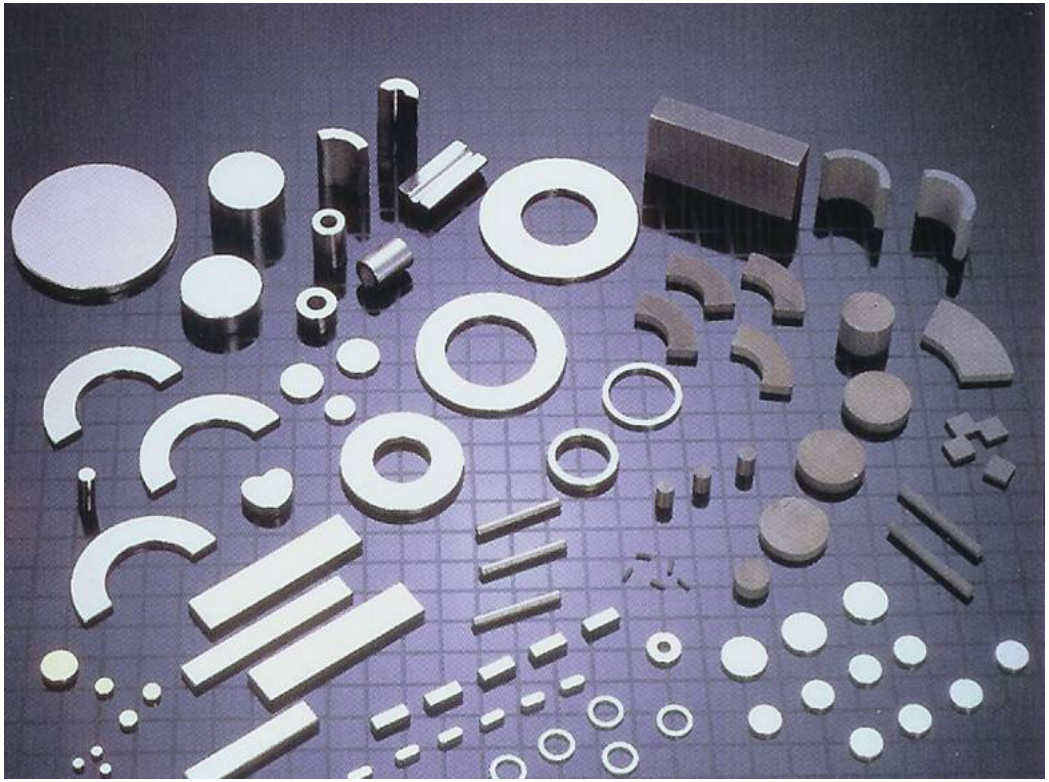
Ceramic Manufacturing



NdFeB & SmCo Manufacturing



Typical Magnet Shapes



Sintered:

Ring
Disc
Arc
Rod
Cylinder
Breadloaf
Segment

Bonded:

It is up to your imagination

Units

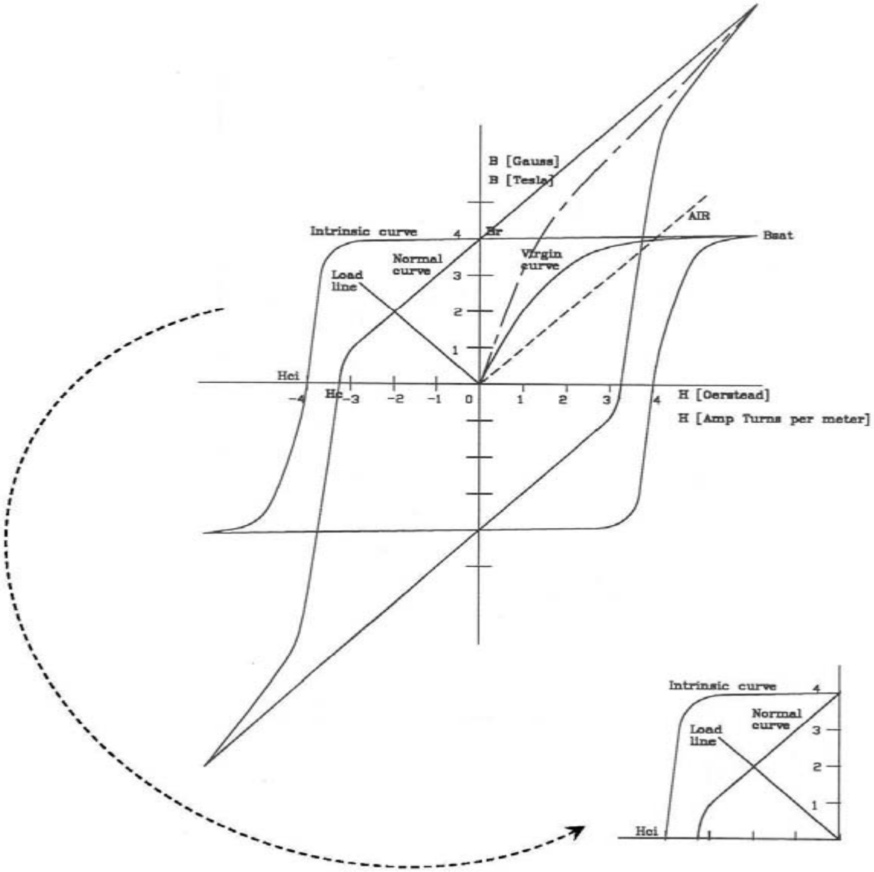
Units of measure for properties, dimensions and tolerances

- British
- Metric
  - 1 MKS
  - 2 CGS
  - 3 SI

Magnetic Properties

- Residual induction - B_r
- Coercive force - H_c
- Intrinsic coercive force - H_{ci}
- Maximum Energy Density – $(BH)_{max}$
- Recoil permeability - μ_{rec}
- H_k Value of H_c at $0.9B_r$
- Magnetic flux Φ

Hysteresis and Demagnetization Curves



Magnetic Units Conversions

Designation	CGS	SI	Conversion
H	Oersted (Oe)	A/m	1A/m = 12.57 x 10^3 Oe
B	Gauss (G)	Tesla (T)	1 T = 10,000 G
ϕ	Maxwell (M)	Weber (Wb)	1 Wb = 10^8 M
F	Gilbert	Amp-turn	1 A-t = 1.256 Gilbert
BH	MGOe	Joule/m^3	1 J/m^3 = .1257 x 10^6 GOe

Typical Supplier Data Sheet

Alliance LLC
Magnetic Products for American Industry

www.Allianceorg.com

Inj Molded SmCo BIS-82

		Typical	Minimum
Residual Induction Br	G	6,400	6,800
Coercive Force Hc	Oe	5,320	5,720
Intrinsic Coercive Force Hci	Oe		9,420
Max. Energy Product (BH)max	MGOe	10.3	?
Material Density	g/cm3	4.5	
Max. Operating Temperature	C	150	
Temperature Coefficient for B	-%/C	0.03	
Temperature Coefficient for H	-%/C	0.30	
Required Magnetizing Force	Oe	25,000	
Material Composition	SmCo powder w/ various resins		

Injection Molded Samarium Cobalt magnets are made with SmCo powder compounded with a binder material which is then molded into highly complex shapes or co-injected with other materials to form complete assemblies. Very low magnetic degradation at elevated temperatures.

For more information please call or email Alliance technical support at:

Phone: **219-548-3799** Fax: **219-548-7071** email: **engineering@allianceorg.com**

Alliance LLC
Magnetic Products for American Industry

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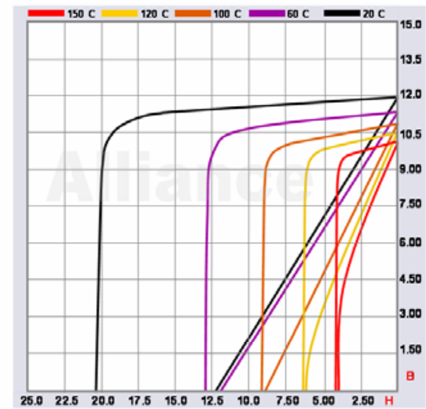
NdFeB N-45M



		Typical	Minimum
Residual Induction Br	G	13,300	13,700
Coercive Force Hc	Oe	10,800	11,200
Intrinsic Coercive Force Hci	Oe		14,000
Max. Energy Product (BH)max	MGOe	43	46
Material Density	Lb/in3	.2673	
Max. Operating Temperature	C	100	
Temperature Coefficient for B	-%/C	0.11	
Temperature Coefficient for H	-%/C	0.60	
Required Magnetizing Force	Oe	60,000	
Material Composition	Nd, B, Fe, Dy, Co		

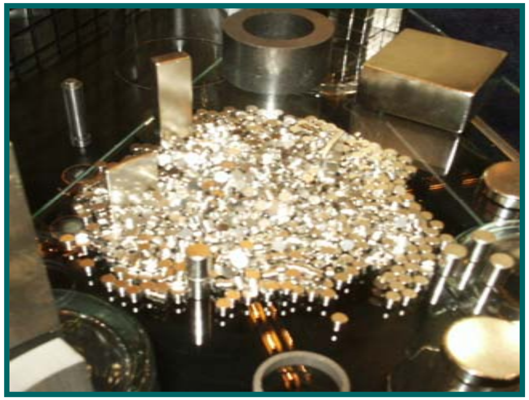
Neodymium Iron Boron magnets, also known as Rare Earths or Neo, have the highest energy product of all permanent magnet materials today. In most cases, no tooling charges exist. Various grades are available, depending on maximum operating temps.

For more information please call or email Alliance technical support at:

Phone: **219-548-3799** Fax: **219-548-7071** email: **engineering@allianceorg.com**

Coating and Plating

- Material
- 1 e-coat
- 2 Epoxy
- 3 Nickel
- 4 Zinc
- 5 Paralene
- Method of coating
- Coating thickness
- Color or luster



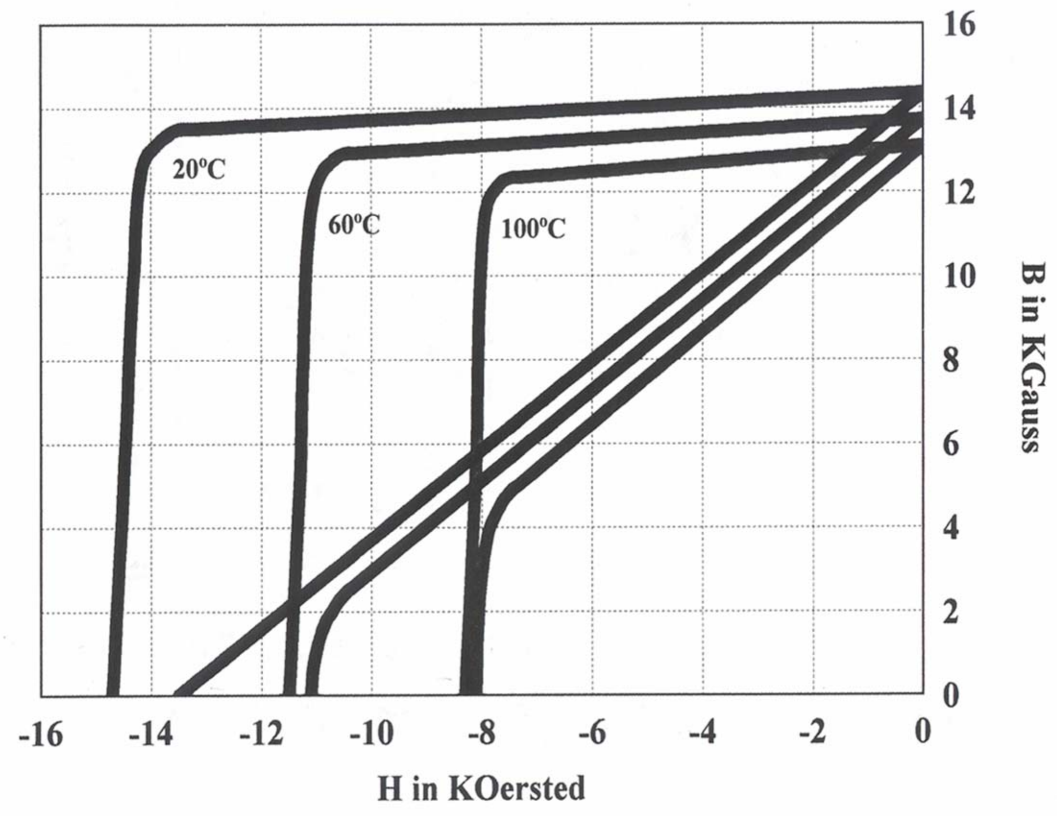
NdFeB Coatings

Properties	Organic: E-Coat	Metallic: Nickel Plating
Application Type	Immersion Electrodeposition Epoxy/Urethane Water Based	Immersion Barrel Electroplate Electroless
Pretreat Process	Alkaline Clean Acid Etch/Passivate	Alkaline Clean Electroclean Acid Etch/Activate
Thickness	15-25 μ (0.6-1.0 mil)	10-50 μ (0.4-2.0 mil)
Uniformity (Flatness/Edges)	Excellent 20% Edge Loss	Good 50% Edge Gain
Durability	Good Pencil 2H-4H	Excellent 300-1000 V_{100}
Temp and Humidity at 85°C and 85% RH	250 Hours	Over 1200 Hours

Thermal Properties

- Reversible temperature coefficient of residual induction – α_{Br}
- Reversible temperature coefficient of coercive force – β_{Hc}
- Reversible temperature coefficient of intrinsic coercive force
- Curie temperature
- Maximum service temperature

Temperature Effects



Physical properties

- Density
- Coefficient of thermal expansion
  1 parallel to the direction of orientation
  2 perpendicular to the direction of orientation
- Thermal conductivity
- Electrical resistivity
- Porosity
- Modulus of elasticity
- Compressive strength
- Tensile strength
- Flexural strength
- Hardness

Typical Magnet Properties

Typical Magnetic and Physical Properties of Permanent Magnet Materials

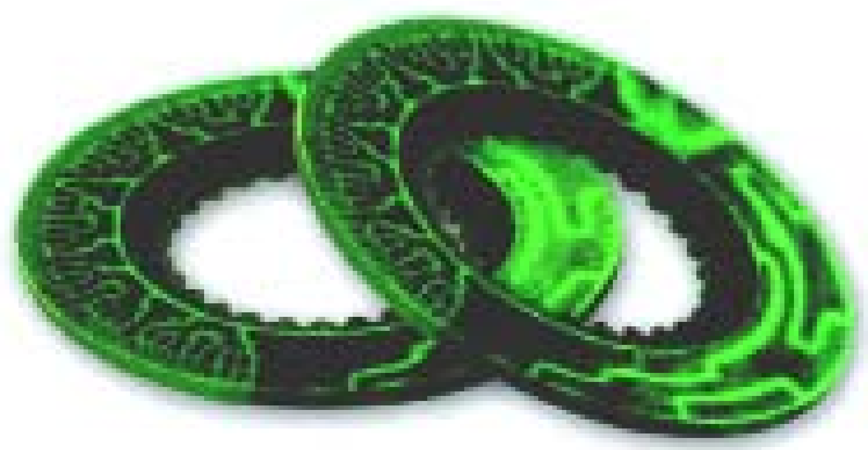
	Units	Cast Alnico	Sintered Alnico	Sintered Ferrite (Ceramic)	Sintered Samarium Cobalt (1:5)	Sintered Samarium Cobalt (2:17)	Sintered NdFeB	Bonded (Injection) NdFeB	Bonded (Compression) NdFeB	Bonded (Injection) Ferrite	Bonded (Compression) SmCo	Bonded (Injection) SmCo
Density	g/cm^3	7.3	6.9 · 7.3	4.8 – 5.0	8.4	8.4	7.5 – 7.8	4.5 · 5.5	5.6 – 6.0	2.6 – 3.6	6.6-7.2	5.7-6.1
Maximum Operating Temperature	°C	550	550	350	250	350	100 – 200	110	100 – 180	100 - 200		
Temperature Coefficient B_r (20 – 100 °C)	%/°C	-0.025	-0.025	-0.18	-0.04	-0.03	-0.11	-0.1	-0.11	-0.2	-0.035	-0.035
Temperature Coefficient H_{ci} (20 – 100 °C)	%/°C	0.01	0.01	0.4	-0.045	-0.18	-0.72	-0.4	-0.39	0.3		
Coefficient Thermal Expansion ⊥DOM	10^{-6}/°C			8	13	12	-1					
Coefficient Thermal Expansion // DOM	10^{-6}/°C	11 - 13	10 – 13	9.0 – 9.5	7	10	5	60 - 80	10 - 30	30 – 50	13	
Bending (Flexural) Strength	MPa			55	120	90 – 150	180 - 270	60 - 80		50 - 100		
Compressive Strength	MPa		300 - 400	700	1000	650	850 - 1050		80 - 120		31	
Young's Modulus	GPa		100 - 200	150	110	150	150 - 160		0.7 – 1.0	4.0 – 5.5	29	30
Tensile Strength	MPa		80 - 300	20 - 50			80	25 - 40	37	30 - 80		29
Curie Temperature	°C	960	750	450	720	800	330 - 350	300 - 470	300 - 470	450		
Thermal Conductivity	W/(m•C)		10 - 200		10	12	9		2			
Vickers Hardness	H_V	450 - 700	300 - 500	480 - 580	550	640	570 - 580				80-120	90-130
Electrical Resistivity	μΩm	0.47 – 0.53	0.4 – 0.7	>10^4	0.5 – 0.6	0.75 – 0.85	1.2 – 1.6	40 - 70	10 - 30	>10^4	>10^4	>10^4
Specific Heat	J/Kg°C		350 - 500		370	390	440		400	25 - 200		

DOM = Direction of Magnetization

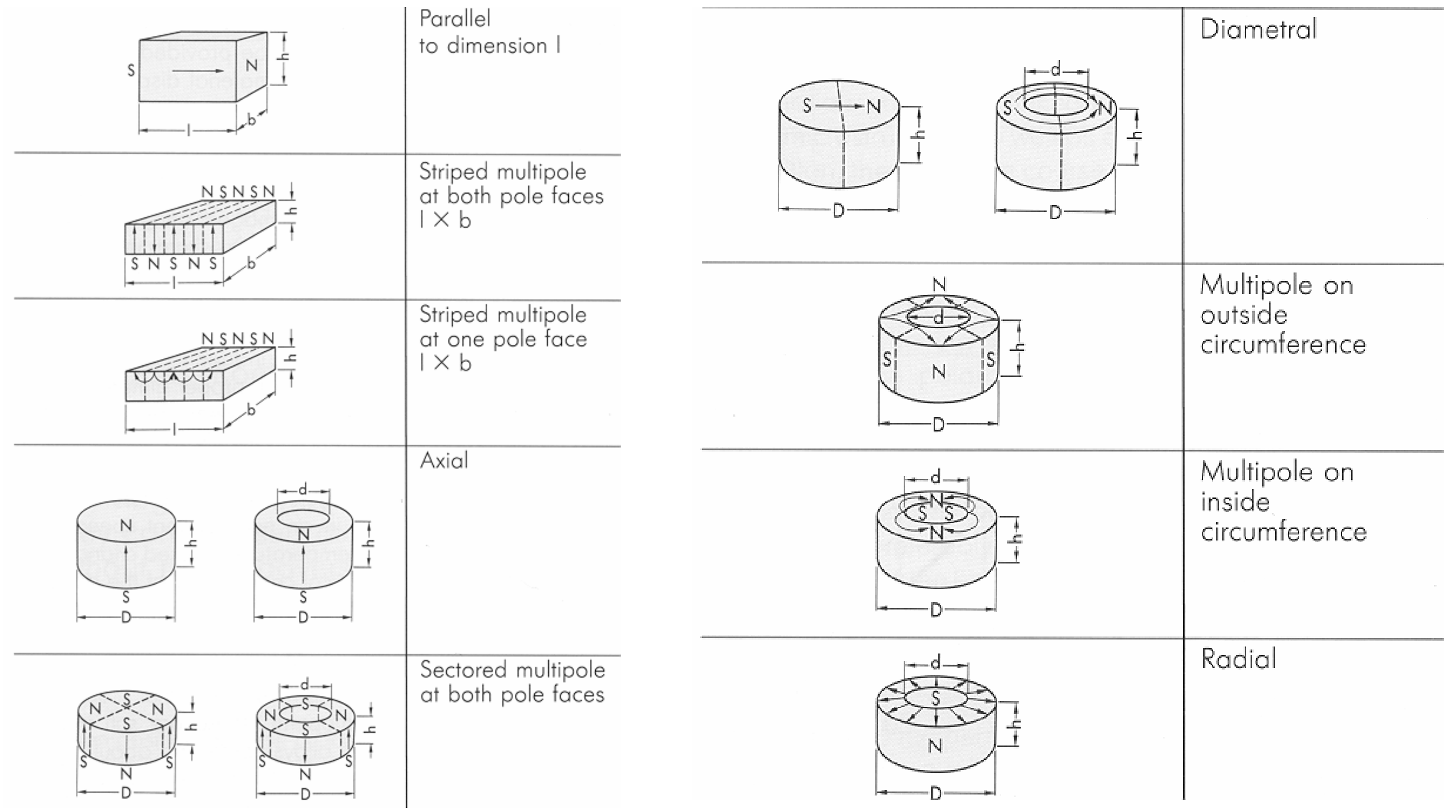
Robert Wolf Alliance LLC 11/30/2006

Magnetization

- Direction of magnetization (orientation)
- Magnetized
- Not magnetized



Magnetization Styles

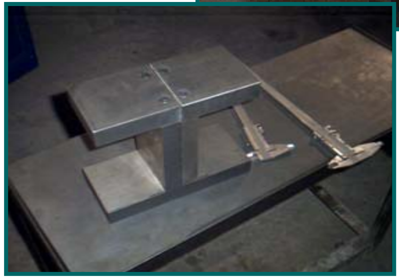


Mechanical Characteristics

- Dimensions (apply before or after coating or plating)
- Parallelism
- Squareness
- Concentricity
- Surface finish
- Chips, cracks, burrs

Test Methods

- Helmholtz coils
- Total flux
- Permeameter
- Functional test fixture
- Drop through (go, no-go) gauges
- Snap gauges



Magnet Environment

- Immersed in a fluid – what type
- Sealed enclosure
- Subject to forces – acceleration, shock etc
- Subject to radiation – what type, level and duration
- Temperature extremes in use
- Demagnetization fields

Special Conditions

- Conform to some older standard like MMPA 0100-XX
- Humidity testing
- Coating cross hatch tests
- Conform to European Union directive 2002/95/EC (RoHS)
- Certificate of Origin
- Material Certifications
- Material Safety Data Sheet (MSDS)

Conclusion

Magnets are everywhere, may as well get to know them