- Magnetic materials range from soft (not retaining its own magnetic field) to hard (retaining a field in the absence of external forces).
- Cobalt, as one of the three naturally ferromagnetic elements, has played a crucial role in the development of magnetic materials
- And remains, today, essential to some of the highest performing materials – both soft and hard.

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Agenda

- Quick review of basics
- Soft magnetic materials
- Semi-Hard magnetic materials
- Permanent Magnets
- Price Issues
- New Material R&D

- Let's begin with a brief explanation of what is meant by soft, semi-hard and hard when speaking of magnetic characteristics.

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Key Characteristics of Magnetic Materials

Symbol	Name	Units CGS, SI	What it means
M_s, J_s	Saturation Magnetization	Gauss, Tesla	Maximum induced magnetic contribution from the magnet
B_r	Residual Induction	Gauss, Tesla	Net external field remaining due to the magnet after externally applied fields have been removed
$(BH)_{max}$	Maximum Energy Product	MGOe, kJ/m^3	Maximum product of B and H along the Normal curve
H_{cB}	(Normal) Coercivity		Value of H on the hysteresis loop where B = 0
H_{cJ}	Intrinsic Coercivity		Value of H on the hysteresis loop where B-H = 0
μ_{init}	Initial Permeability	(none)	Slope of the hysteresis loop as H is raised from 0 to a small positive value
μ_{max}	Maximum Permeability	(none)	Maximum slope of a line drawn from the origin and tangent to the (Normal) hysteresis curve in the first quadrant
ρ	Resistivity	μOhm•cm	Resistance to flow of electric current; inverse of conductivity

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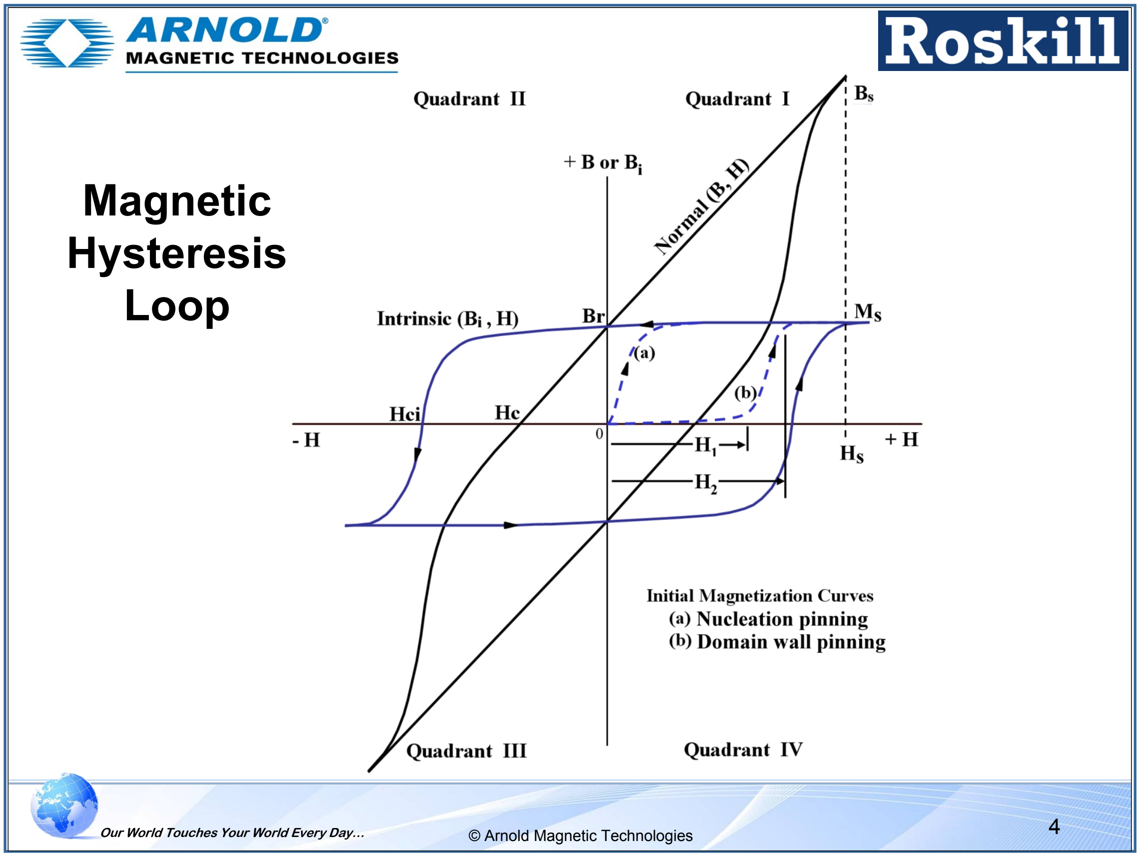
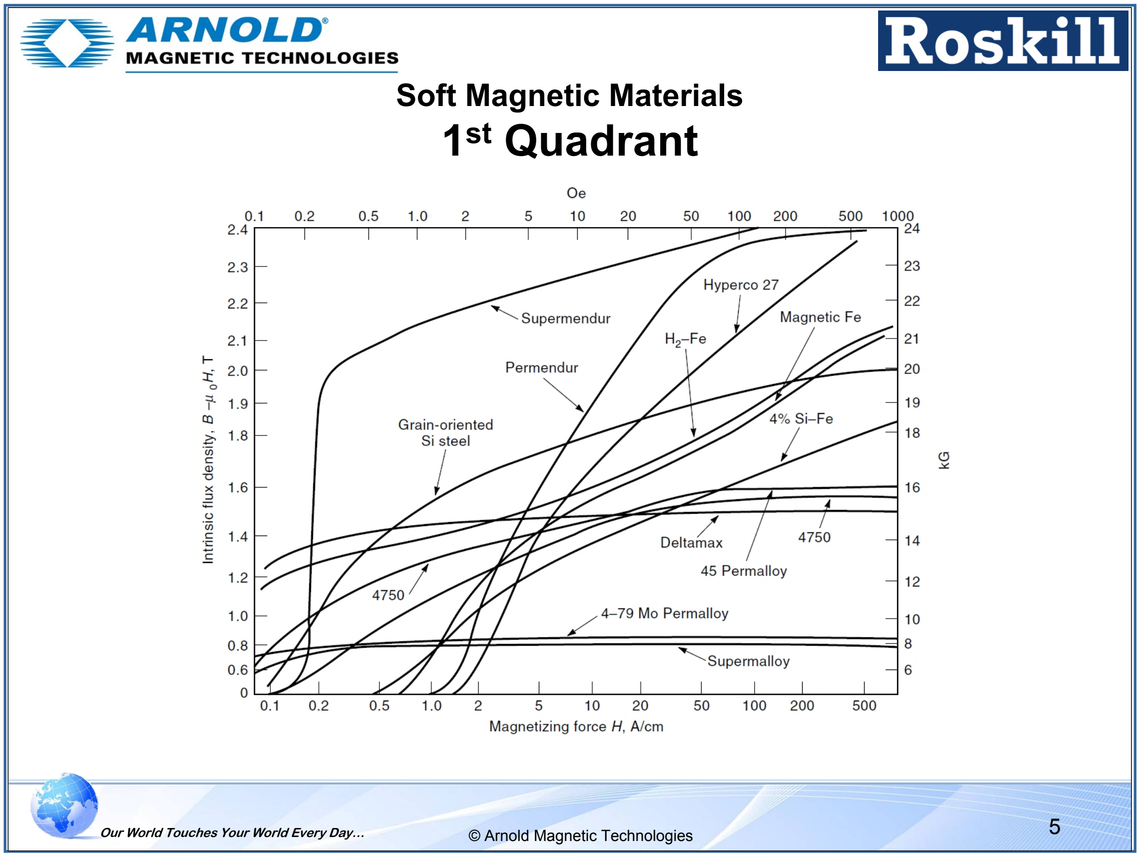
- These are most of the important characteristics that magnetic materials exhibit.
- To specify and use the materials we need to measure them and understand how they affect the devices in which they are used.
- All but a few of the these are derived from the material's hysteresis loop.
- The hysteresis loop is a graph showing the relationship between the strength of a magnetic field which is applied to a magnetic material plotted versus the resultant (induced) field in the material.



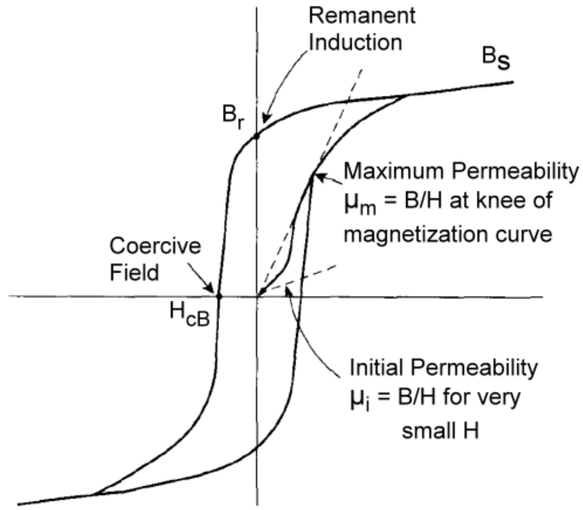
- The H axis is the applied field; the B axis is the induced field.
- The applied field is included in the measurement of the induced field – it is not possible to separate them at the measurement.
- However, it is possible to separately measure the applied field and subtract it from the combined field.
- So we have two curves: a black curve representing the combined applied and induced fields and a blue curve produced by subtracting the applied field and just showing the induced field.
- The combined curve is called the “Normal” curve; the induced-field-only curve is called the Intrinsic curve.
- The curve is plotted in both positive and negative values of H and B thus producing all four quadrants.



- Soft magnetic materials use information gleaned from the 1st quadrant such as initial and maximum permeabilities and magnetic saturation.

Soft Magnetic Materials

All Quadrants



- Soft magnetic materials also use information from all four quadrants.
- Typical uses for soft materials are transformers, motor laminations and inductors.
- In all these cases, the magnetic material is induced to carry a magnetic field (flux) in varying polarity: first north one way and south the other then changing to a new magnetic orientation.
- This changing polarity is represented by the material operating at different points around the hysteresis loop.
- The external energy required to “drive” the material through the loop is proportional to the area within the loop.
- The area is largely controlled by the value of HcB, so smaller HcB is beneficial to achieving lower energy loss in devices.
- Permeability describes how easily the material can be magnetized.
- The saturation magnetization tells us the maximum magnetic strength.

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Soft Magnetic Materials
Compositions and Properties

Material	Composition (%), Fe bal.							B_s	H_{cB}	μ_{init}	μ_{max}	Resist.
	Co	Cr	Ni	Mo	V	Cu	Other	G	Oe			μ-ohm•cm
Soft Magnetic Materials												
Low carbon steel (M-19)								19,000	0.2-0.5	300	10,000	47
Iron-Silicon (Si-Fe)							3 - 6	19,700	0.6	350	50,000	50
Deltamax			50					16,000	0.04-0.16	500	100,000	45
Alloy 4750			48					15,500	0.02-0.10	7,000	100,000	45
Mu Metal		2	77			5		7,500	0.01-0.03	20,000	~100,000	60
Supermalloy			79	5				7,800	~0.005	60,000	800,000	65
Perminvar (7-70)	7		70					12,500	0.6	850	4,000	16
Kovar	17		29					12,000			3,000	49
Perminvar (45-25)	25		45					15,500	1.2	400	2,000	19
Hiperco 27	27	0.6	0.6					24,200	1.0	650	10,000	
Hiperco 35	35	0.5						24,200	1.0	650	10,000	20
2V-Permendur	49				2			24,000	2.0	800	4,900	26
Supermendur	49				2			24,000	0.2		92,500	
Hiperco 50A	49				2			24,000	< 1		15,000	40
Permendur	50							24,500	2.0	800	5,000	7
Metglas 2705M	79		3.5	3.8			9.2	7,700	0.4		600,000	136
Metglas 2714A	85		3				8	5,700			1,000,000	142

- This is a listing of most of the commercial soft magnetic materials showing generic chemistry and typical properties.
- Most of these alloys contain iron with either or both cobalt and nickel.
- The highest Bs materials contain cobalt in combination with iron.
- All but a few are crystalline. The two non-crystalline materials shown are Metglas which is processed to remain essentially amorphous – without long range crystalline structure.
- While the saturation magnetization is much lower, the maximum permeability is exceptionally high.
- This means there is little resistance in the material to exhibiting an induced field.

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Semi-Hard Magnetic Materials - Chronology

Material	Main Ingredients	Year First Reported	Br Gauss	Hc Oersteds
Carbon Steel	Fe, C	c.1600	9,000	50
Tungsten Steel	Fe, W, Mn, C	c.1855	10,500	70
Chrome Steels	Fe, Cr, Mn, C	c.1870	9,500	65
Cobalt Steels	Fe, Co, W, Cr, C	1916	9,600	230
Remalloy	Fe, Mo, Co	1931	10,000	230
Alnico 3	Fe, Al, Ni	1931	6,800	490
Alnico 2	Fe, Al, Ni, Co, Cu	1934	7,300	560
Cunife	Fe, Cu, Ni	1937	5,700	590
Cunico	Cu, Ni, Co	1938	5,300	450
Vicalloy 1	Fe, Co, V (10%)	1940	8,800	300
Vicalloy 2	Fe, Co, V (14%)	1940	10,000	450
MT Magnet	Fe, Al, C	1947	5,000	200
FeCrCo	Fe, Cr, Co	1977	11,000	250
Indalloy	Fe, Co, Mo	1980	9,000	240

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- In the search for materials that would behave as a permanent magnet, many weakly permanent materials were identified.
- Rather than dismiss them as useless, ways were found to utilize these materials unique properties.
- These semi-hard materials function well in devices such as compass, hysteresis-coupled drives, and braking systems.
- We see the same ferromagnetic elements (iron and cobalt) in these alloys, but with modifying elements that create the semi-hard behavior.
- Typical of these elements are the refractory elements titanium, vanadium, molybdenum and chrome.

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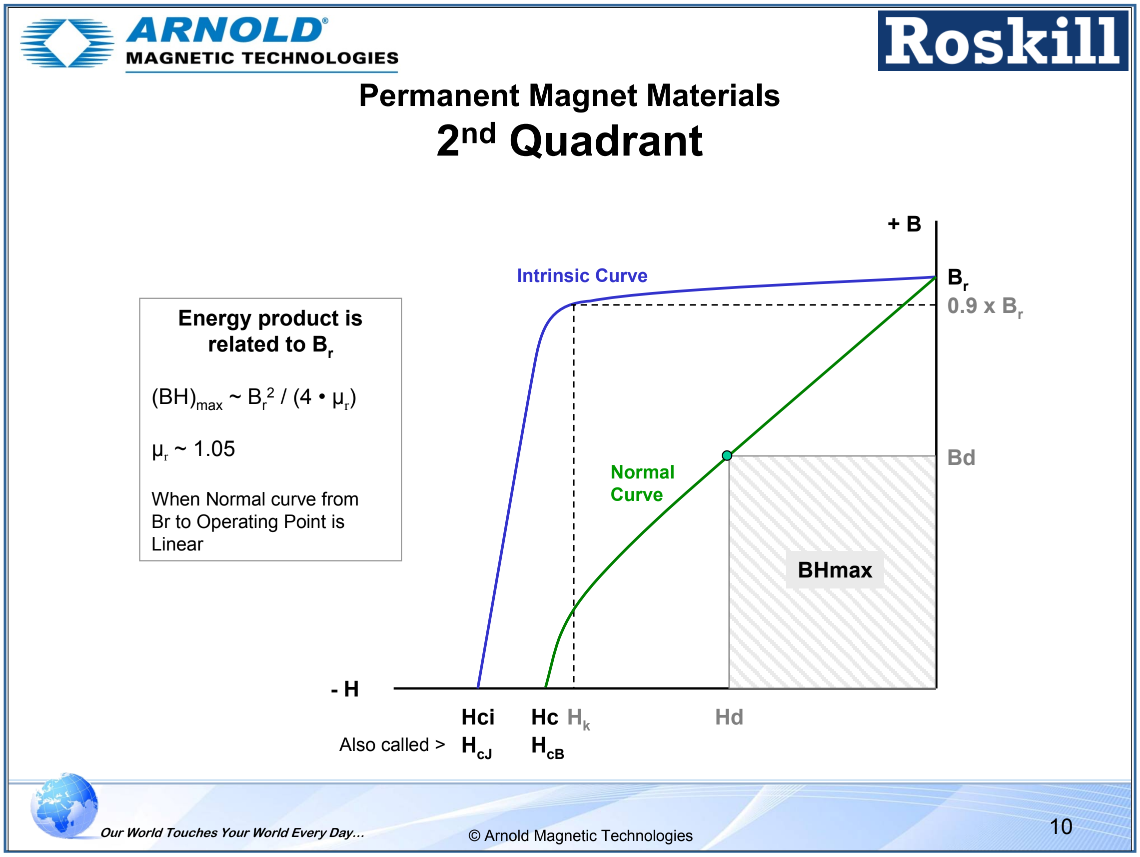
Semi-Hard Magnetic Materials Composition and Properties

	Material	Composition (%), Fe bal.							B_s	B_r	H_{cB}	BHmax	Resist.
		Co	Cr	Ni	Mo	Nb	V	W	G	kG	Oe	MGOe	μ-ohm•cm
Semi-Hard Mat'ls	3% Cobalt-Steel	3	9		1.5					7	130	0.4	
	Remalloy (Comol)	12			17					11	250	1.1	
	Iron-Chrome-Cobalt	12	33						12,000		50 - 300		69
	17% Cobalt-Steel	17	2.5					8		10	170	0.7	
	35%, ~KS Steel	35	6					4		10	250	1.0	
	Remendur	49					3			10		1.0	
	Vicalloy I	52					10			9	300	1.0	
	Vicalloy II	52					13			10.0	510	1.2	
	Nibcolloy	85				3				10.0	510	3.5	

- Several of the most commonly used semi-hard materials are shown here sorted from low to high cobalt content.
- A unique characteristic of these materials is that many are malleable (deformable at room temperature).
- Additionally, the magnetic properties can be adjusted by changing thermal processing conditions.
- For that reason, magnetic values shown here are typical, not absolute.



- The key figures of merit for permanent magnet materials are indicated on this chart of the second quadrant.
- Unlike soft and semi-hard materials that utilize the Normal curve only, permanent magnets are characterized by both the Normal and the Intrinsic curves.
- With permanent magnets we deal most often with just the second quadrant.
- The maximum energy product can be estimated as shown here from the Br.
- Conversely, the Br can be estimated when the maximum energy product is known.
- As shown here, this material would be considered a straight line (Normal curve) or square loop (Intrinsic curve) material.
- That is, the Normal curve is straight from Br to past the maximum energy operating point.
- The Intrinsic curve exhibits a sharp corner as it drops in B toward the H axis.
- Hk is a calculated value and, like Hci, is indicative of a magnet's resistance to demagnetization.
- Hk/Hci is considered the squareness coefficient. A number approaching 1 is considered excellent.

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Permanent Magnet Development Timeline

- Permanent Magnets have been developed to achieve
  - Higher Br and Energy Product (BHmax)
  - Greater resistance to demagnetization (Hci)
- Most are still in production
  - Exceptions
    - ***Lodex*** *was discontinued due to use of hazardous materials in production and in the product*
    - ***Cunife*** *has been replaced by FeCrCo*
    - ***PtCo*** *is a specialty item made in very limited quantities due to it's high material cost*

Material	First Reported	BH(max)	Hci
Remalloy	1931	1.1	230
Alnico	1931	1.4	490
PtCo	1936	7.5	4,300
Cunife	1937	1.8	590
Cunico	1938	1.0	450
Alnico, field treat d	1938	5.5	640
Vicalloy	1940	3.0	450
Alnico, DG	1948	6.5	680
Ferrite, isotropic	1952	1.0	1,800
Ferrite, anisotropic	1954	3.6	2,200
Lodex®	1955	3.5	940
Alnico 9	1956	9.2	1,500
$RECo_5$	1966	16.0	20,000
$RECo_5$	1970	19.0	25,000
$RE_2(Co,Fe,Zr,Cu)_1$	1976	32.0	25,000
$RE_2TM_{14}B$	1984	26.0	**25,000**
		35.0	11,000
$RE_2TM_{14}B$	2010	30.0	**35,000**
		52.0	11,000

Table based on information in *Advances in Permanent Magnetism* by Rollin J. Parker, p.331-332

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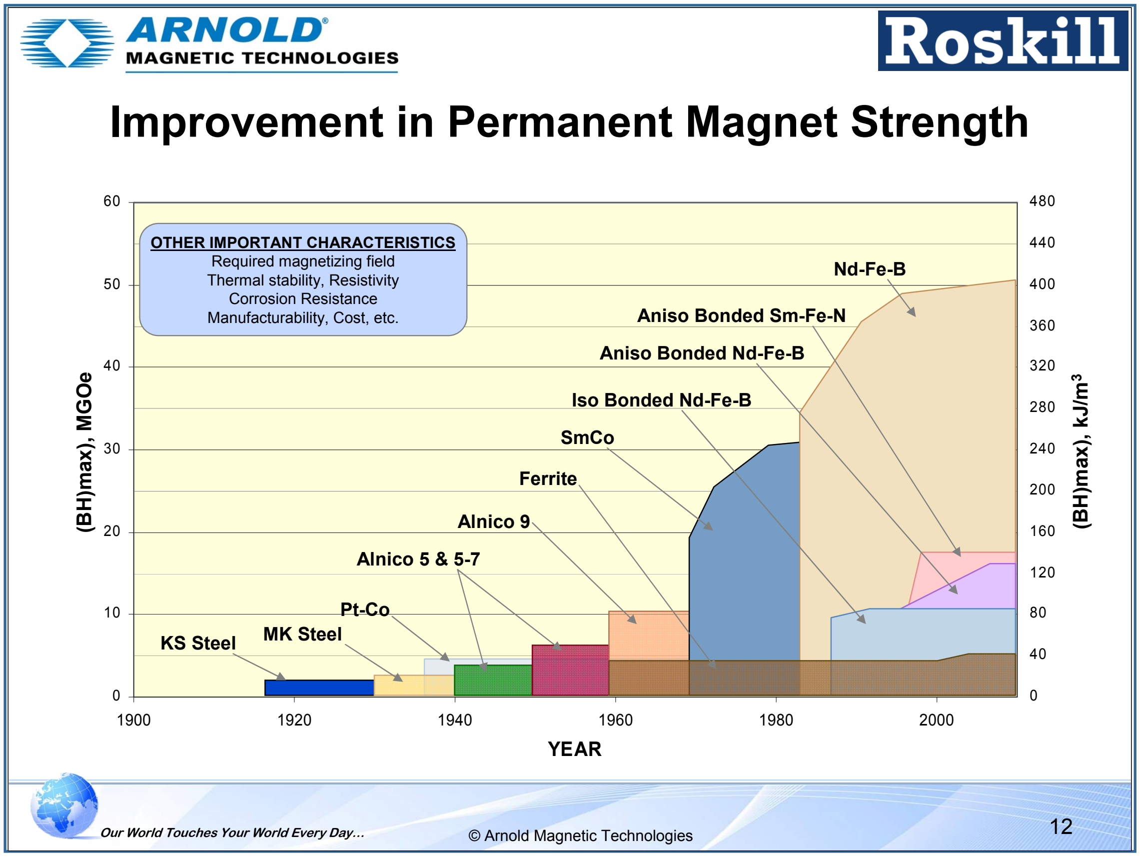
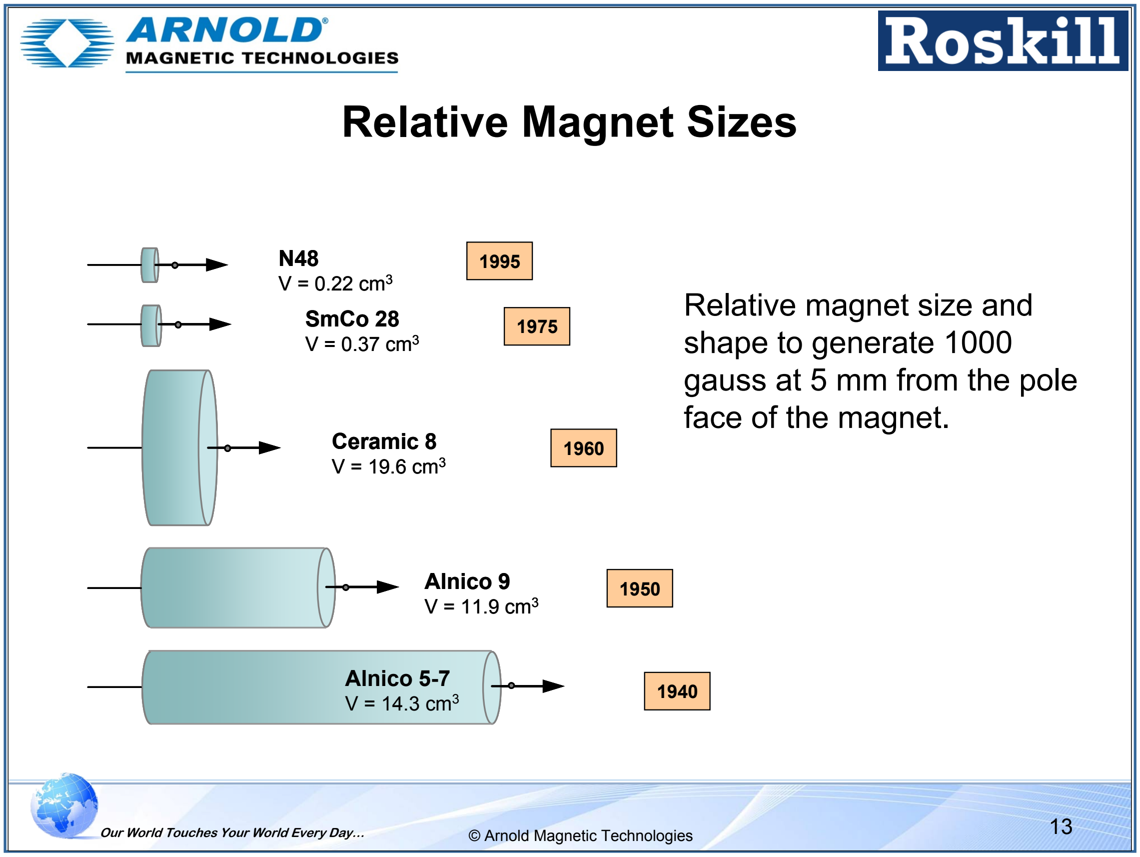
- During the 1900's great strides were made in the development of improved permanent magnets as shown in this table.
- Increased values of both maximum energy product (BHmax) and Hci, resistance to demagnetization, were made culminating with neo magnets ($RE_2TM_{14}B$).



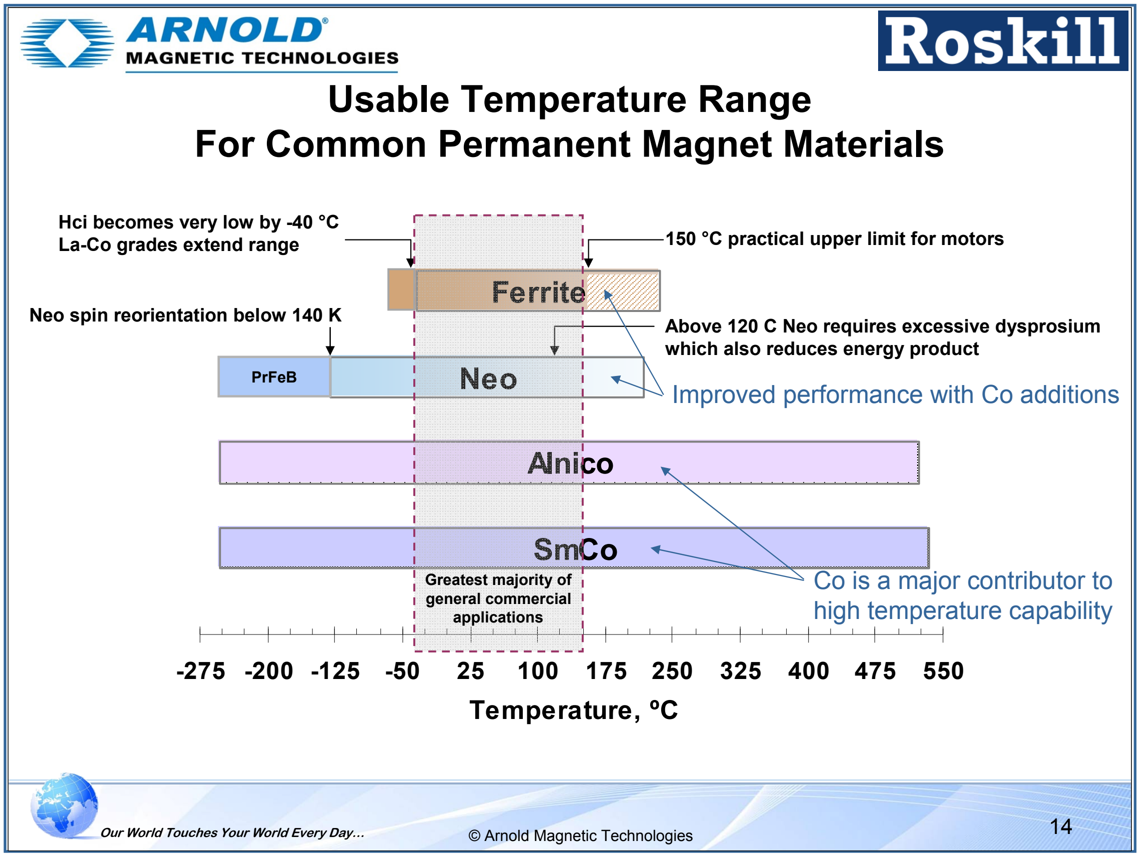
- Maximum energy product is one of the most important characteristics of a permanent magnet and many authors have drawn charts similar to this showing the increase in energy product over the course of the 20th century.
- Interestingly, ferrite magnets, although considerably weaker than the rare earth magnets SmCo and NdFeB, are so much lower in cost that they still contribute over 85% of all permanent magnets made each year.



- The improvements in energy product that have facilitated modern applications can be pictorially demonstrated.

  (This is a recalculation of a chart first published by Vacuumschmelze about 20 years ago).

- The "V" under each product name is the magnet volume. For example, an N48 magnet with a V of 0.22 cubic centimeters provides the same magnetic field strength near the pole as a ceramic magnet that is 89 times larger.
- Wherever small size and low weight are preferred, rare earth magnets are necessary.
- System size depends also on the steel flux path. A weaker magnet must be larger and so requires a larger structure which requires more steel.



- Another key characteristic in selecting the best magnet is the temperature range of the application.
- We note here that both Neo and ferrite magnets have a more limited useful temperature range.
- The addition of cobalt to the chemistry expands the usable range.
- Both alnico and SmCo magnets can be used from ~4 Kelvin to about 550 °C.

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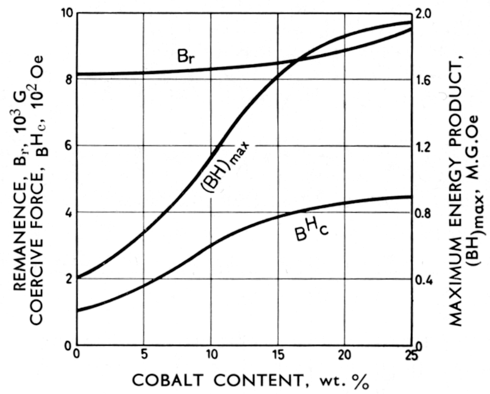
Importance of Cobalt

NdFeB

AlNiCo



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- Co added to Neo (NdFeB) magnets raises the Curie temperature and reduces the rate of change in magnetic output as a function of temperature.
- Cobalt also improves performance of alnico magnets – all three characteristics showing improvement with cobalt additions.

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Compositions and Properties of Commercial Permanent Magnets

	Material	Composition (%), Fe bal.								B_r	H_{cB}	H_{cJ}	BHmax	Resist.
		Co	Ni	Nb	Ti	Al	Cu	RE	Other	kG	Oe	Oe	MGOe	μ-ohm•cm
Permanent Magnet Materials	Alnico 1	5	21			12	3			7.1				65
	Alnico 2	13	19			10	3			7.2	560		1.6	65
	Alnico 4	5	27			12				5.5	720		1.4	65
	Alnico 5	24	14			8	3			12.5	640		5.5	47
	Alnico 5-7	24	14			8	3			13.5	740		7.5	47
	Alnico 8	35	15		5	7	4			9.3	1,550		6.0	50
	Alnico 9	35	15		5	7	4			11.2	1,375		10.5	50
	Cunife I		20				60			5.8	590		1.9	18
	Cunife II	2.5	20				50			7.3	260		0.8	18
	Cunico I	29	21				50			3.4	700		0.9	20
	Cunico II	41	24				35			5.3	450		1.0	20
	Cobalt-Platinum	23							77	4.5	2,600		8.0	30
	SmCo5	65						35		8 - 10.3	7.8 - 10.0	> 25,000	16 - 25	55
	Sm2Co17	50					6	25	3	10 - 12	9.6 - 11.4	> 15,000	24 - 33	90
	NdFeB (Sintered)	0 - 3		0 - 0.5				32	2	10.8 - 14.8	10.3 - 14.2	> 11,000	28 - 52	180
	NdFeB (Bonded)	0 - 15		0 - 1.5				30	2	4.8 - 8.7		> 8,000	5 - 15	
	LaCo-Ferrites	1								4.6	4,300	> 4,500	4.5 - 5.4	> 10^4

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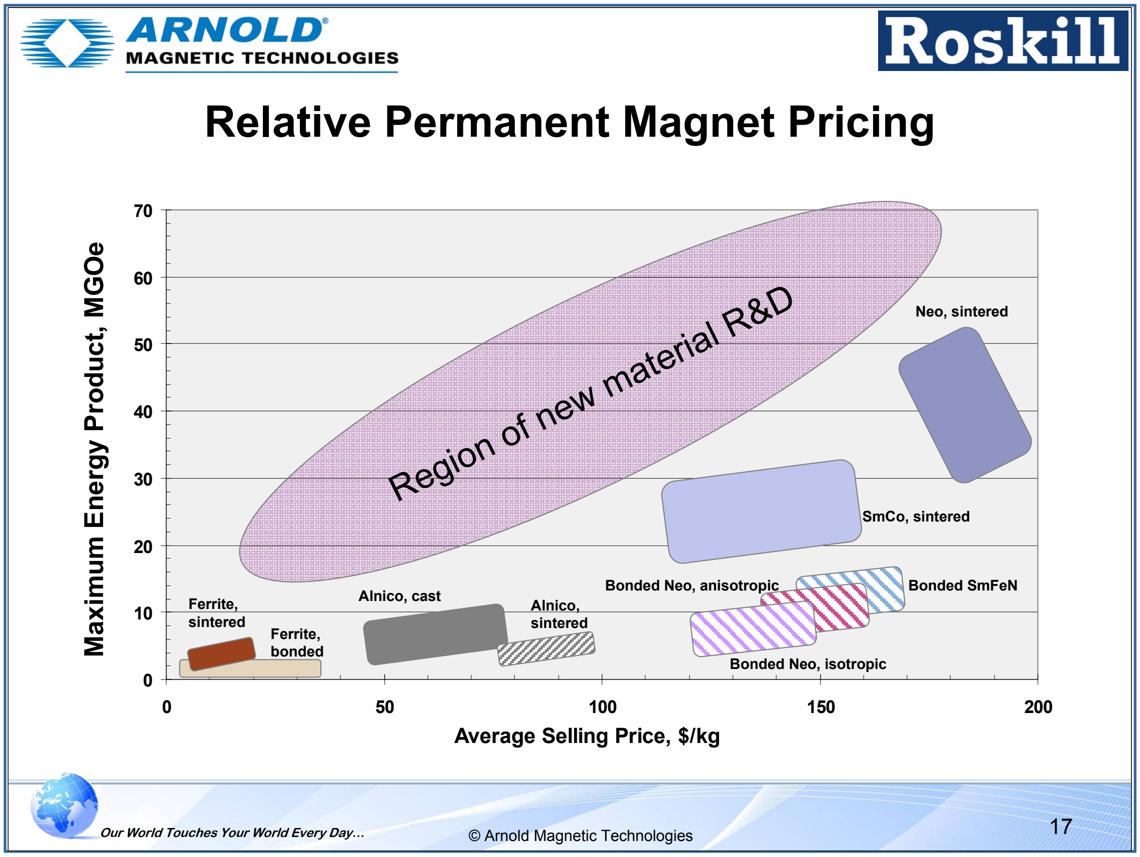
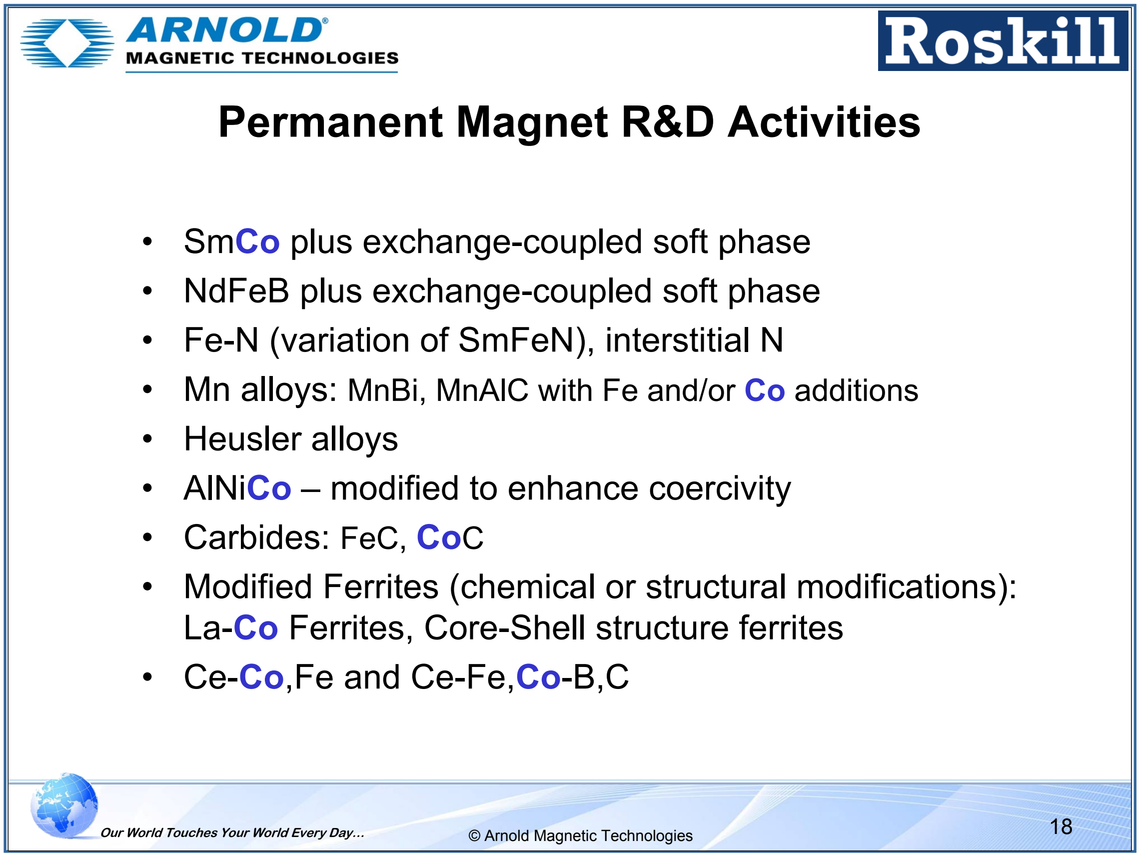
- This table shows most of the commercially available permanent magnets.
- All of these except cunife and cunico are still supplied into the marketplace.



- In addition to magnetic properties, material price is important to secure commercial success.
- These prices are applicable to the North American market.
- Prices for some of the materials, such as rare earths, change rapidly.
- Furthermore, selling price is a function of the size and shape of the magnet.
- This chart should be considered only approximate and directionally indicative.
- An obvious conclusion is that material development is toward higher performance and lower prices.
- For example a higher energy product ferrite at low cost would be a market winner as would a rare earth magnet with substantially reduced cost.
- The optimal material is toward the upper left of the chart.



- Though many of these materials have been previously researched, our current analytic capabilities are superior to what existed even two or three decades ago.
- We also now have techniques to form these materials with a refined structure at micro- and nano-scales.
- Research is focused on materials that exhibit ferromagnetic properties either naturally or when combined with alloying elements.
- It's not surprising to see cobalt considered in many of these experimental alloys.

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Soft Magnetic Materials

Increasing recognition of need for R&D

- Research into soft magnetic materials declined after the invention of amorphous and nano-crystalline alloys in the 1980's
- Development of textured dysprosium metal for use at cryogenic temperatures
- Cobalt-iron alloys offer the highest saturation magnetization (~2.4 Tesla)
- Efficient electrical machines (EMs) would benefit from a new material with improved
  - Saturation magnetization
  - Higher electrical resistivity
  - Lower coercivity (H_{cB})

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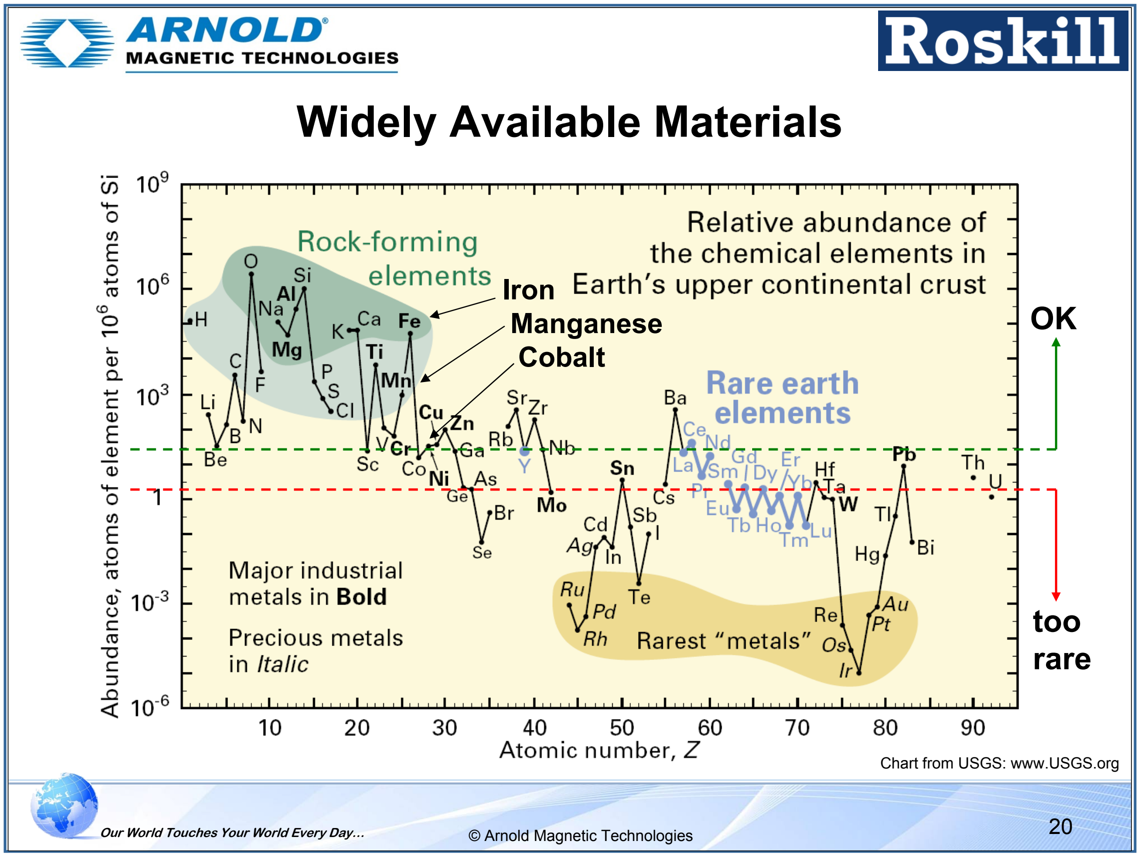
- There has been a great deal of focus on improved permanent magnets from the 1960s right through the present time.
- High prices and shortages of rare earth alloys are driving research into alternate materials.
- Soft magnetic material would also benefit from improvement in performance characteristics that would permit higher efficiency and performance electric machines.



- As a primary ingredient, it's highly recommended to select more common materials such as those above the green dashed line though minor ingredients may be from between the green and red lines.
- But elements from below the dashed red line should be avoided except in the very smallest additions.
- Cobalt lies along the green line.
- Cobalt in magnetic materials currently represents about 7% of all cobalt usage.
- An advantage of cobalt is that there are established sources of supply around the world.
- But it will still be necessary to use cobalt in conjunction with more prevalent elements such as iron and manganese

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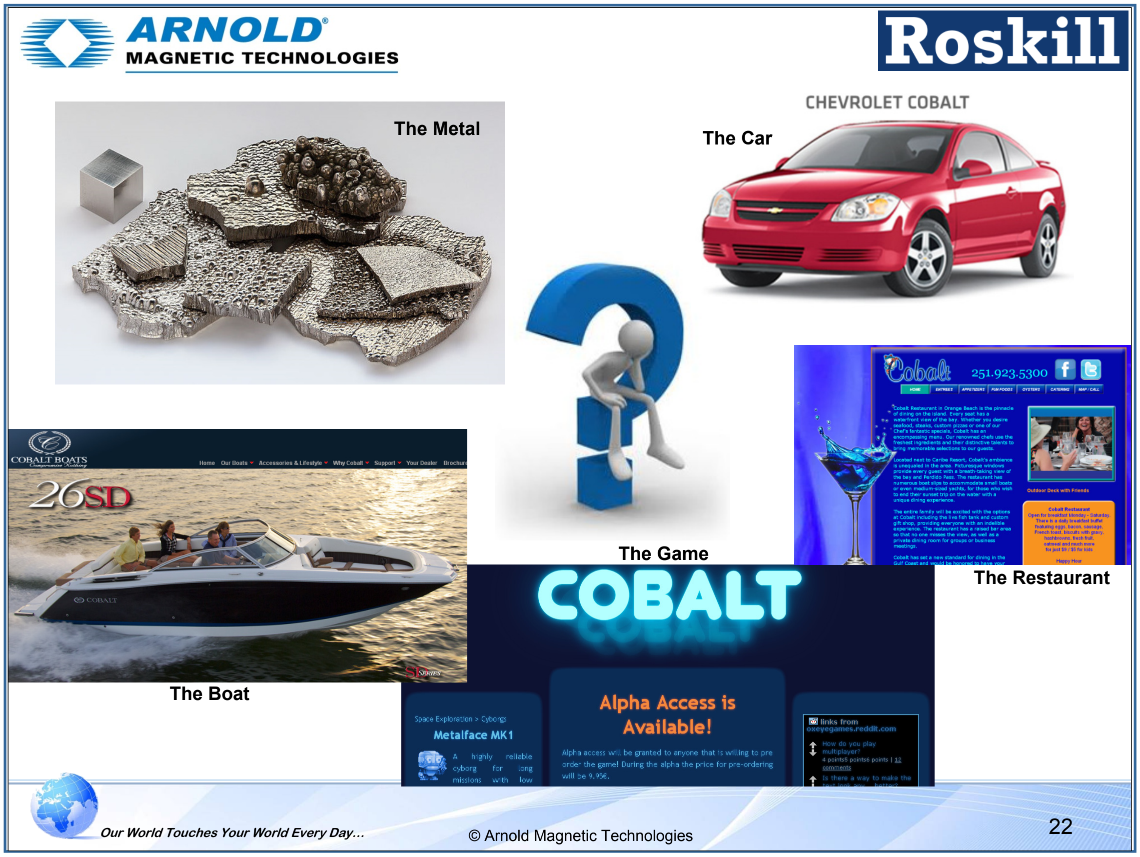
Summary

- Cobalt is an important constituent of soft, semi-hard and permanent magnetic materials
- Cobalt extends the useful temperature range of permanent magnet alloys
- Cobalt improves the permeability of soft alloys
- Cobalt alloys have the highest magnetic saturation
- Many permanent magnet R&D projects include cobalt as a key alloying ingredient
- There is an increasing recognition that improvements in soft magnetic materials would be beneficial



- One final word…
- Cobalt has been so important to our society that we find numerous examples of the word being used, in a positive way, for unrelated products.