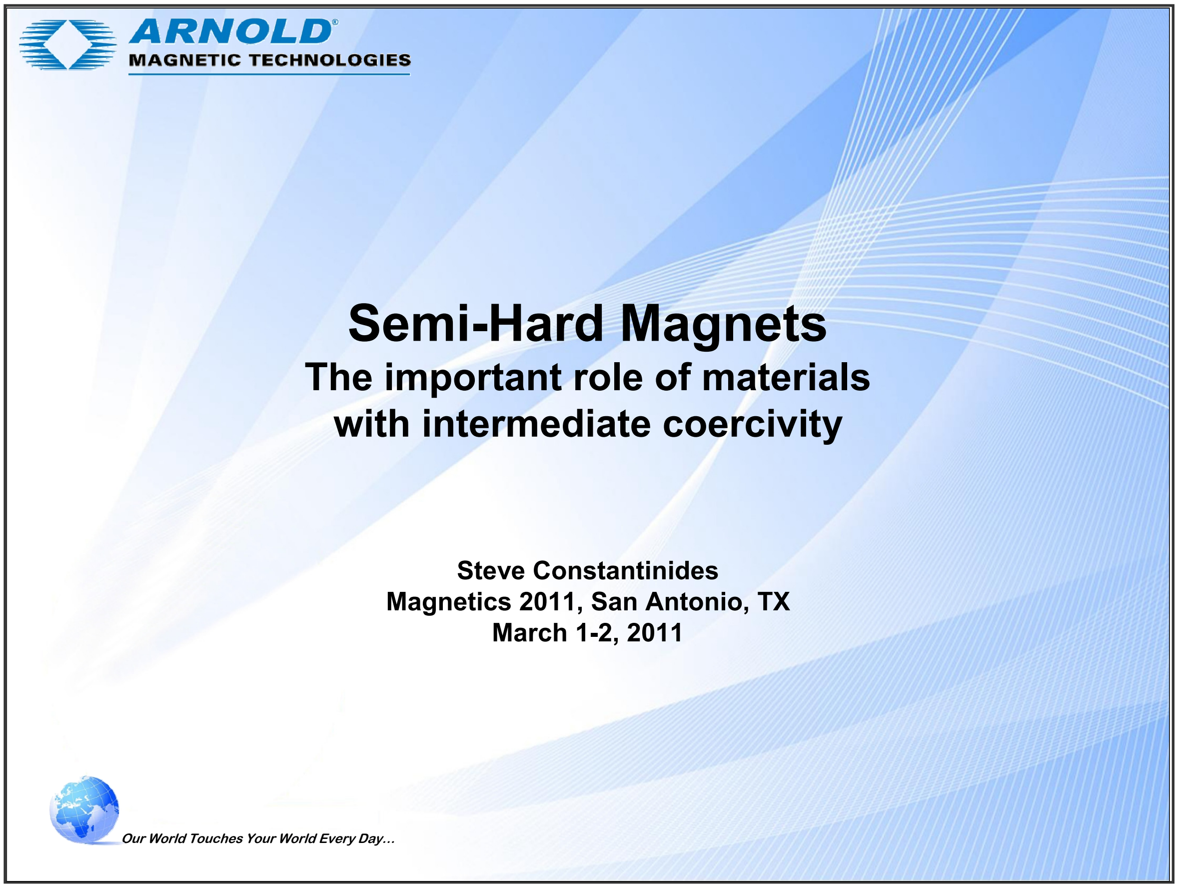
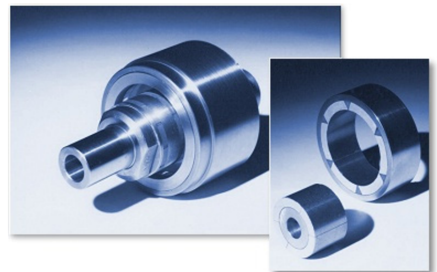


- Much of the focus of industry is on high coercivity permanent magnets and very low coercivity soft magnetic steels.
- A less glamorous, but no less important set of materials provide modest coercivity for applications such as brakes and hysteresis coupled drives.
- Many semi-hard materials are also malleable and therefore capable of being formed and of being machined with standard metal-working tools.
- These malleable alloys can also be extruded into wire, rods and stamped into other forms.

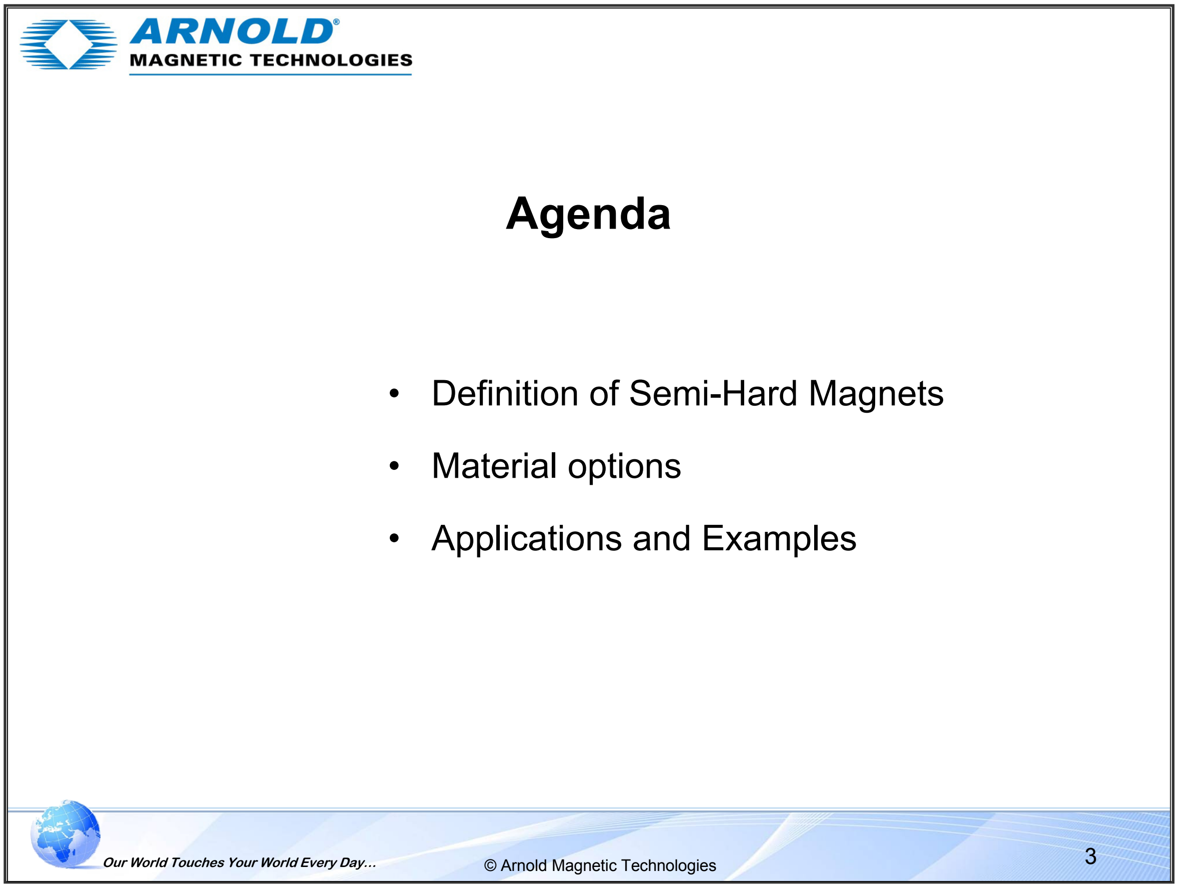
ARNOLD®
MAGNETIC TECHNOLOGIES

Arnold Today

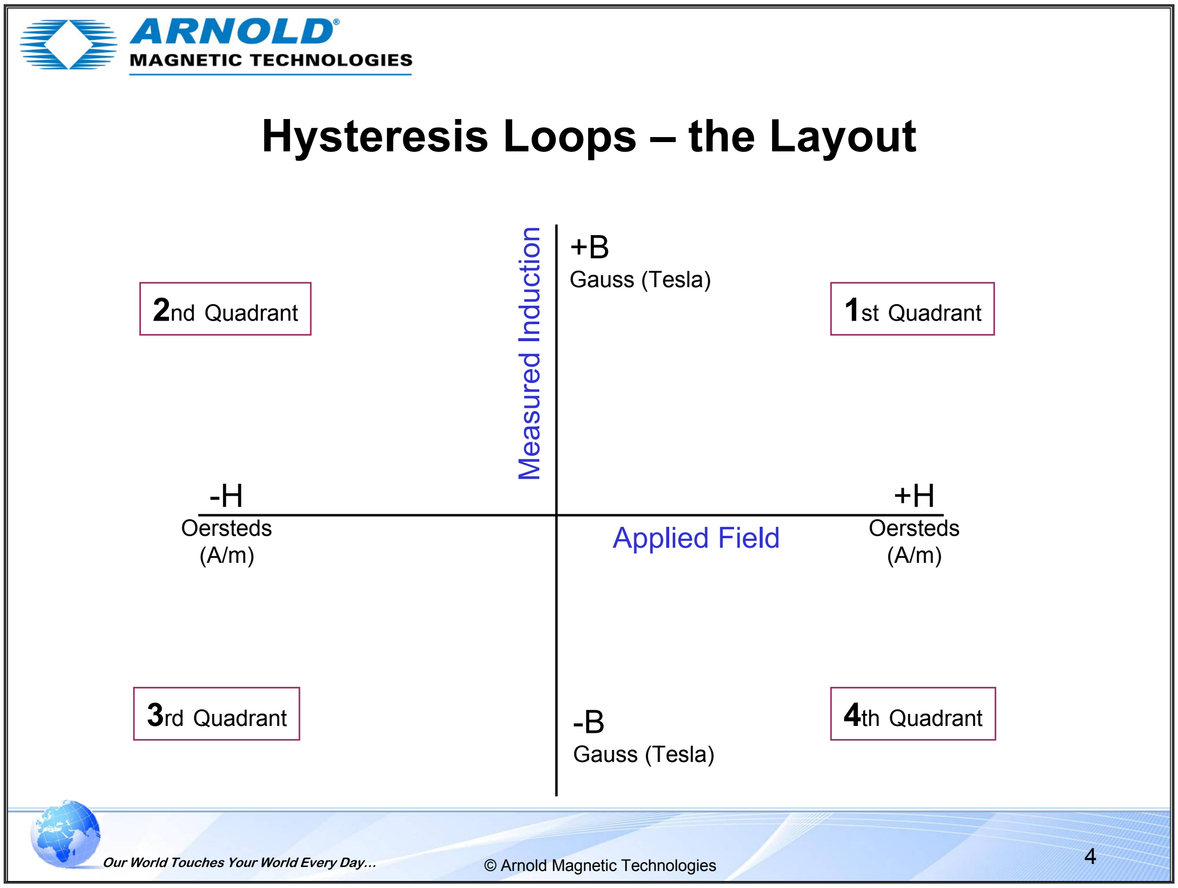
- Magnet Production, Vertically Integrated
  - SmCo (Lupfig, Switzerland, Rochester, NY)
  - Alnico (Marengo, IL)
  - Ferrite (Bonded) (Marietta, OH; Norfolk, NE)
  - Injection Molded (Bonded) (Shenzhen, China)
- Fabricate Magnets
  - Slice, grind, EDM
- Assemblies / Value Added Production
  - Precision assembly
    - Complex magnet and assembled shapes
    - Magnetized / unmagnetized assembly
    - High temperature and specialized adhesives
  - Rotor Balancing
  - Encapsulation / sleeving
- Precision Machining Centers
  - Magnets and components



- A quick introduction to Arnold Magnetic Technologies...



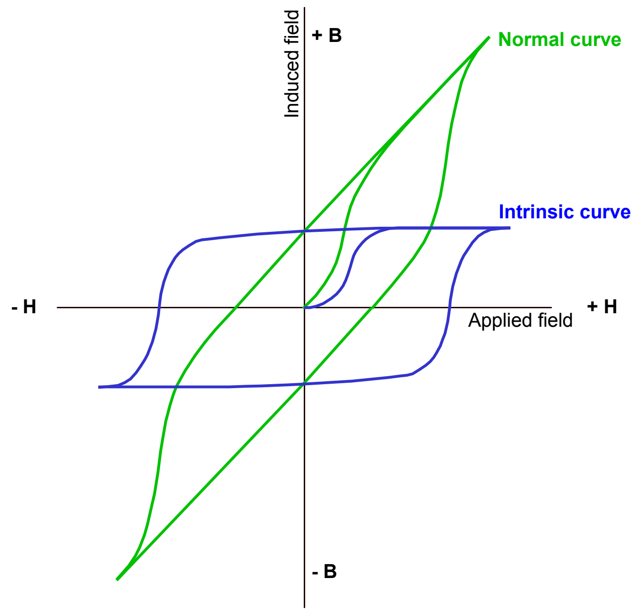
- We'll compare properties for a number of these materials and examine some of the more common uses.



- To quantify magnetic characteristics, we apply an external field (H) and measure the effect on the material (B).
- The results are plotted on an X-Y (or B-H) chart as shown here where the horizontal axis represents the magnitude of the applied field and the vertical axis is the magnitude of the induced (measured) field.

ARNOLD
MAGNETIC TECHNOLOGIES

Hysteresis Loops – Normal and Intrinsic



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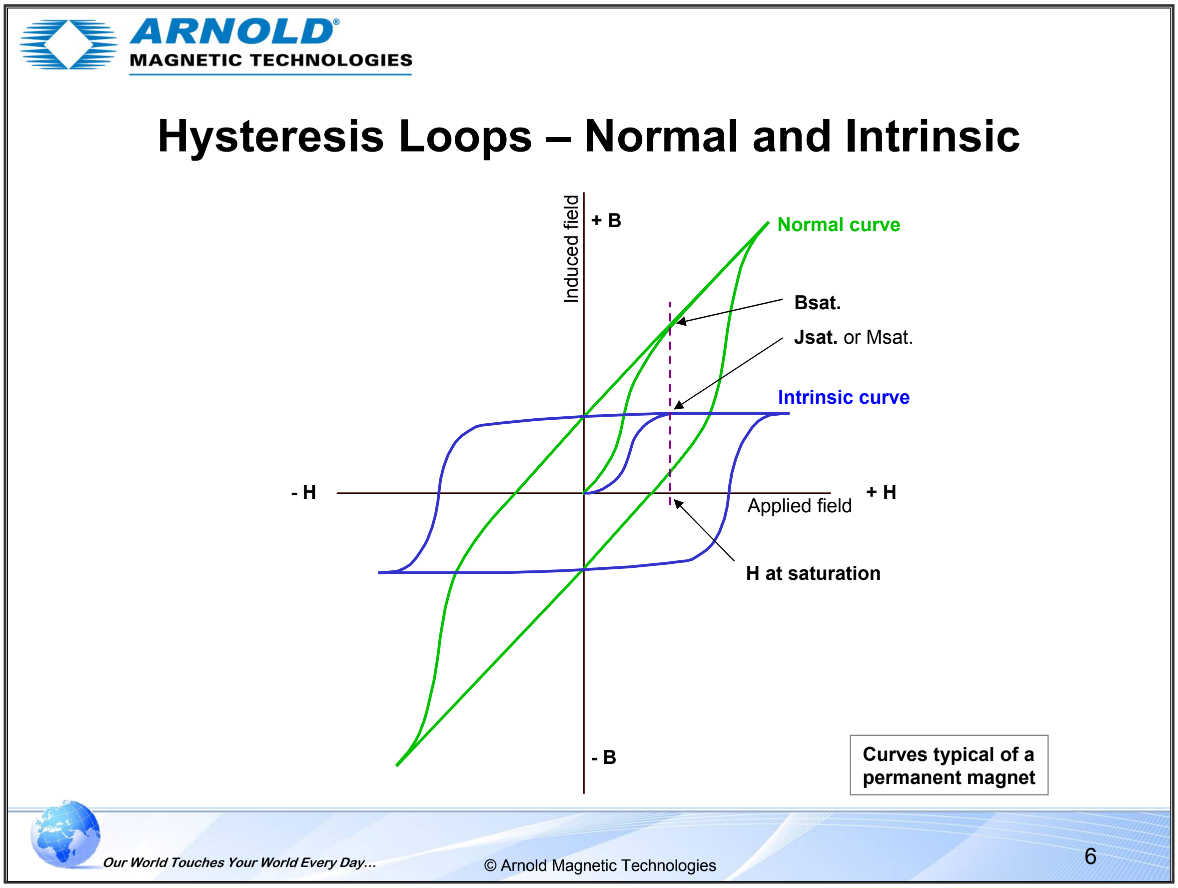
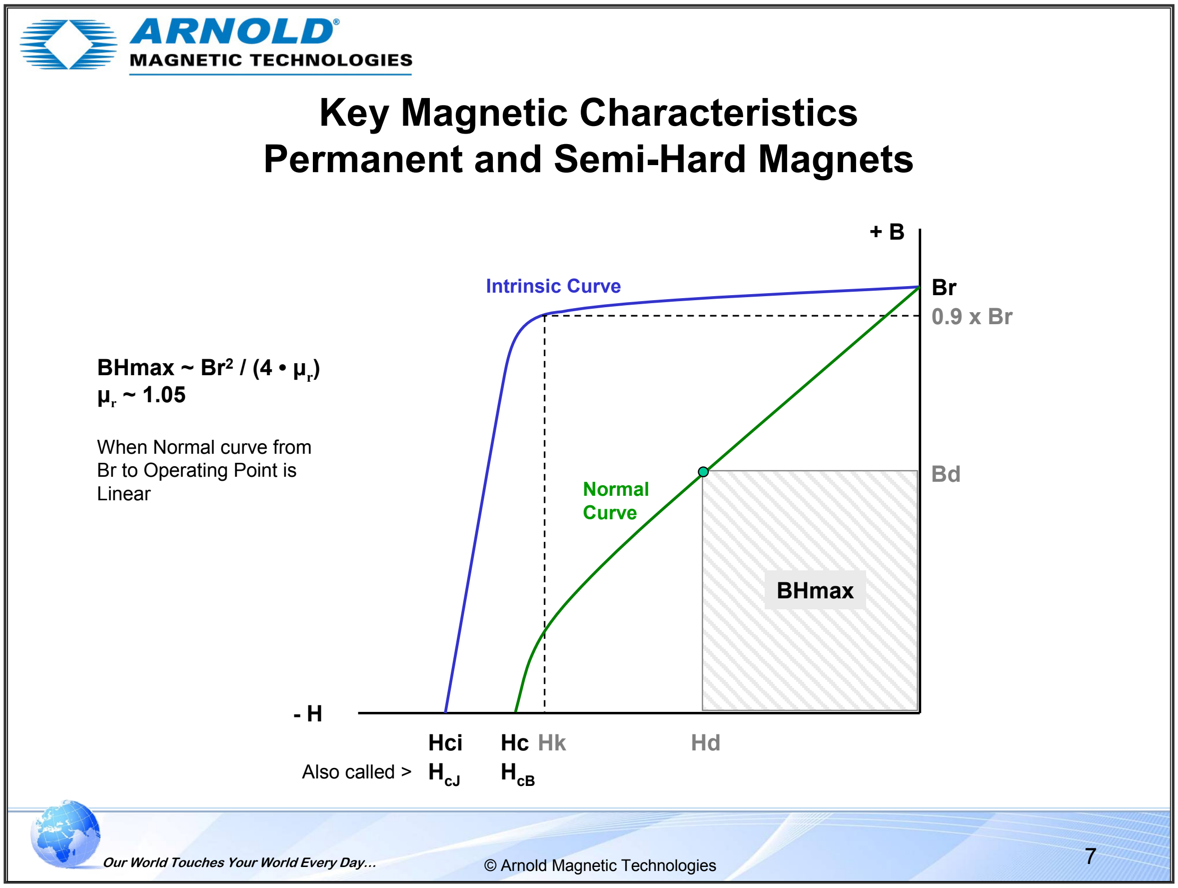
- There is no practical way to directly determine the induced field, so the measured, Normal Curve represents a combination of the applied field and the effect of the magnetic material.
- The magnitude of the applied field can be separately measured.
- The Intrinsic Curve is calculated by subtracting the applied field from the Normal Curve data and it represents just the magnet material – the intrinsic magnetic properties of the material.
- If we begin the measurement with completely unmagnetized material, both the Normal and the Intrinsic curves start at the origin.



- The point at which increasing the applied field results in no additional contribution by the magnet material is called saturation.
- When referenced to the Normal curve, it is the B-saturation point. On the Intrinsic curve it is called either J-saturation or M-saturation.
- The value of H is the same for both curves.
- The curves shown here represent a “straight line” permanent magnet material such as ferrite, neo or SmCo.
- The term “straight line’ derives from the straightness of the Normal curve in the second quadrant.
- We also refer to straight line materials as “square loop” when referring to the intrinsic curve.



- With permanent magnets we deal most often with just the second quadrant.
- These are the key figures of merit for permanent magnet materials.
- The maximum energy product can be estimated as shown here from just the Br.
- Conversely, the Br can be estimated when the maximum energy product is known.

ARNOLD® MAGNETIC TECHNOLOGIES

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 treatec	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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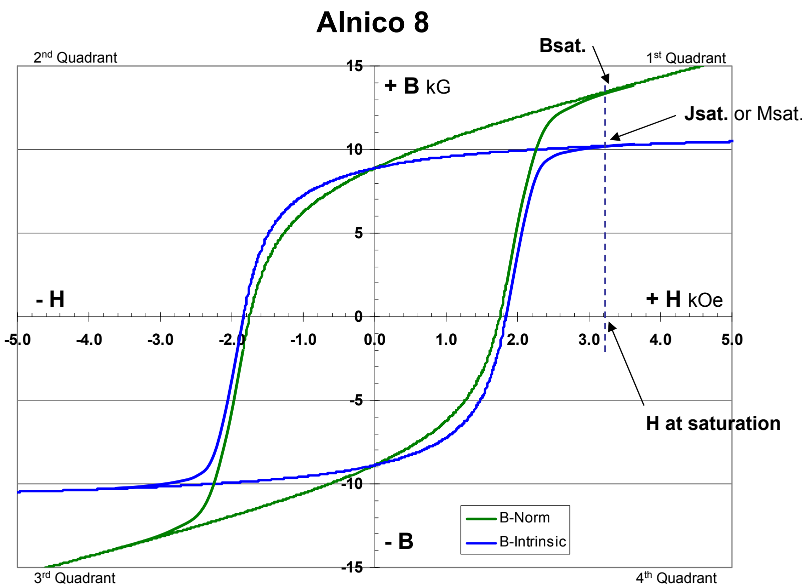
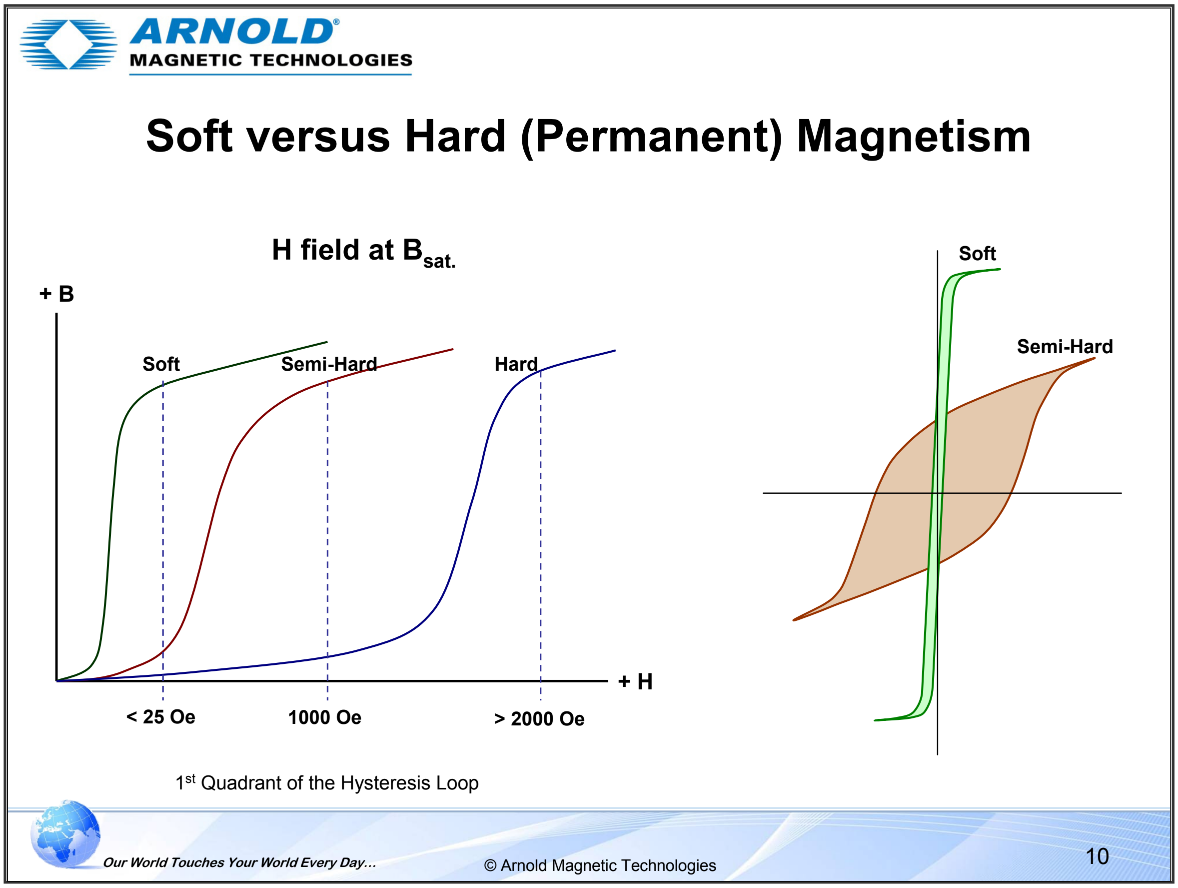
- During the 1900's great strides were made in the development of improved permanent magnets as shown in this table.
- Increased values of both maximum energy product and Hci, resistance to demagnetization, were made culminating with neo magnets (RE2TM14B).
- Two sets of data are shown for neo magnets with the second set representing improvements in both energy product and intrinsic coercivity over the earlier material.
- There has been a trade-off between energy product and coercivity. Sometimes one is desired over the other and many grades are available within the ranges shown.

ARNOLD
MAGNETIC TECHNOLOGIES

Non-Square Loop Material

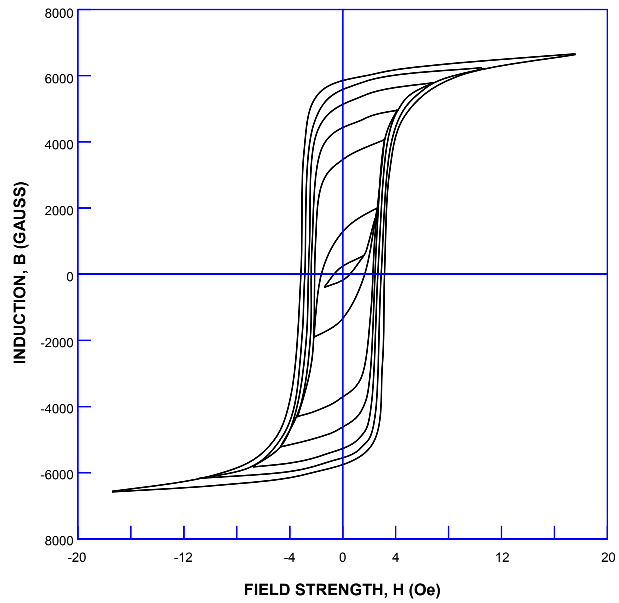


- Many of the early permanent magnets and all of the semi-hard materials are not straight line (therefore also not square loop).
- The curves here represent actual measurements of an alnico 8 sample.
- Clearly visible is the closeness of Hci to Hc. For this reason both soft and semi-hard materials continue to use only the Normal curve to represent material properties.

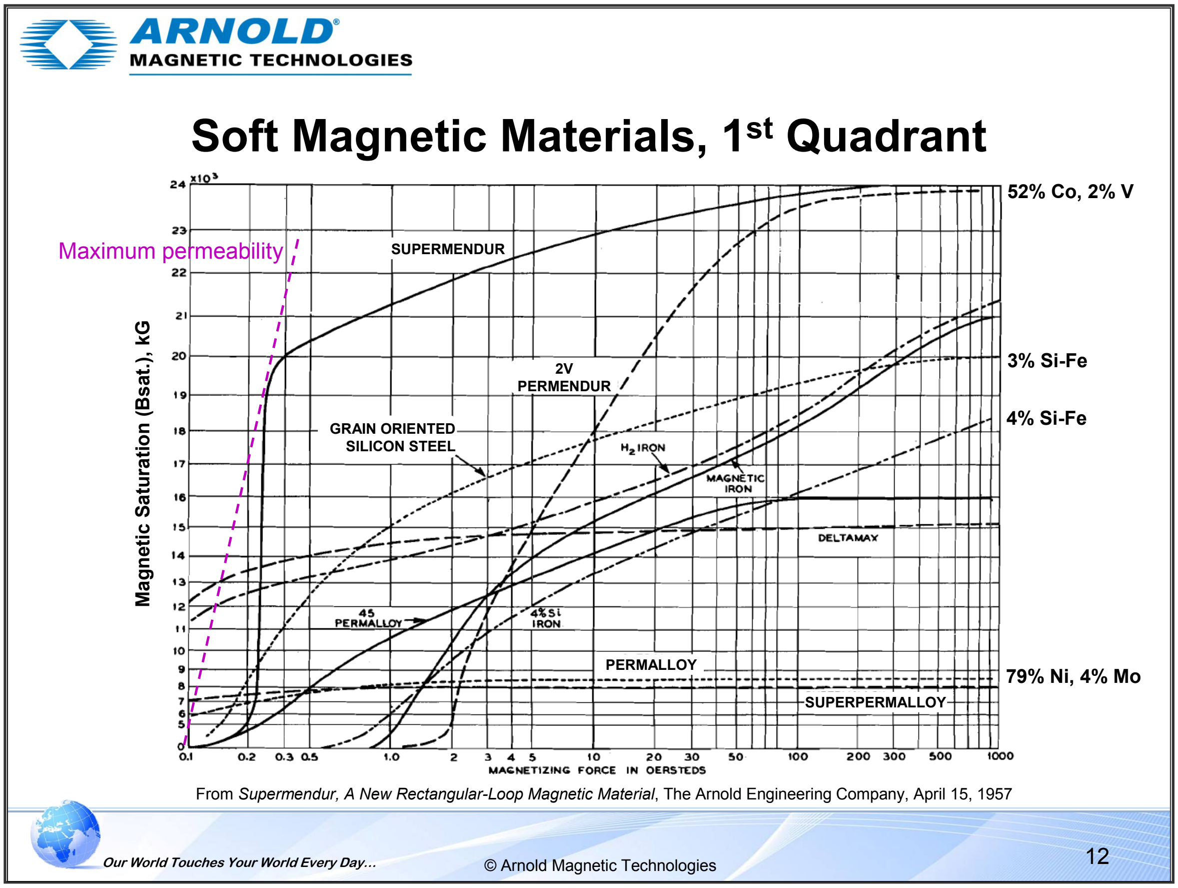


- If, instead of the second quadrant we focus on the first quadrant of the hysteresis loop, we can see a difference in the ease of magnetizing materials.
- Soft materials are relatively easy, requiring a small +H, while hard materials are difficult to magnetize and require a large +H.
- As shown in the right figure, the hysteresis loops representing soft and permanent magnets are also different.
- The energy taken to move a magnetic material around the hysteresis loop is proportional to the area within the loop.
- So we see that soft materials are relatively easy (take little energy) to move around the loop, semi-hard materials require quite a bit more energy and good permanent magnets require a lot of energy.

Minor Hysteresis Loops



- If the magnetic material is not driven to saturation, it will “operate” on a minor loop.
- This illustration shows a number of loops representing something less than saturation.
- Implied is that minor loops require less energy for moving the magnet around them.
- This is the basis of operation for many hysteresis devices.



- Another difference between soft and semi-hard or hard magnets is that with soft magnets we also are concerned with how low a field is required for saturation – how quickly the material moves up the hysteresis loop. This value is called maximum permeability.
- An example is shown by the dashed purple line. A high slope indicates a high value of maximum permeability. The line is drawn from the origin to the “knee” of the curve – in this case for Supermendur.
- A second figure of merit is the field required to casue the material to reach saturation.
- Supermendur, a material with very high maximum permeability, does not saturate until the applied field reaches ~1,000 oersteds.
- Some soft materials such as Permalloy are saturated by an applied field of less than 5 oersteds.
- In review: soft magnetic materials are evaluated by: Hcb, area within the hysteresis loop, maximum permeability, magnetic saturation and field required for saturation.
- Semi-hard and hard magnets are evaluated by: Br, maximum energy product, and Hci (resistance to demagnetization).
- Additionally, semi-hard magnets are evaluated based on the area within the hysteresis loop.

Definition and Examples

	Hc	Hci	H at Bsat	Bsat. (~Msat.)[A]
Soft	< 25	< 25	< 700	X
Semi-Hard	25 to 700	25 to 700	700 to 2000	
Permanent	> 700	> 700	> 2000	

	Material	Hc	Hci	H at Bsat	Bsat. (~Msat.)[A]
Soft	**Supermalloy**	0.003		2	7,800
	Deltamax	0.08		10	16,000
	Si-Fe	0.6		500	19,500
Semi-Hard	**FeCrCo**[B]	50-300		700	9,000 - 12,000
	Remalloy	250		1,000	15,200
	Vicalloy	250		1,000	14,500
	Cunife	500		1,500	8,400
	Cunico	700		1,500	8,800
Permanent	**Alnico 5-7**	740	750	2,000	13,500
	Alnico 8	1,600	1,800	4,500	10,500
	Ferrite (Ceramic 8	3,000	3,500	6,000	4,500
	SmCo 1:5 (R20)	8,700	30,000	30,000	10,000
	SmCo 2:17 (R26)	9,900	25,000	45,000	11,500
	NdFeB (N38SH)	12,000	20,000	35,000	14,000

[A] Soft and Semi-Hard materials generally use Bsat.; PM materials use Msat.
[B] FeCrCo can be heat treated to yield many combinations of Hc and Bsat.

- For convenience we speak of these three categories and have assigned arbitrary values to distinguish one from the next. But there is no hard rule regarding the differentiation in category - there is a continuum of materials from very soft to very hard.
- This slide shows some examples of materials from low to high coercivity – from very soft to very hard.
- In some materials, such as FeCrCo, properties can be varied by adjusting the final heat treatment time, temperature and quench rate.

ARNOLD® MAGNETIC TECHNOLOGIES

Semi-Hard Magnetic Alloys Comprehensive List - 1

Carbon Steels

Cobalt Steels

Iron-Chrome-Cobalt

Alnico's

TABLE 3. PROPERTIES OF SOME COMMERCIAL TYPES OF PERMANENT MAGNET MATERIALS

References to original reports have been given by Chegwidden [48C1], Oliver and Hadfield [48O1], Scott [48S5], Ruder [46R3], and others.

Name	Composition*	H_c	B_r	$(BH)_m \times 10^{-6}$	Preparation	Heat Treatment‡	Mechanical Properties**	Density (g/cm^3)
Carbon Steel	0.9 C, 1 Mn	50	10 000	0.2		Q800		7.8
Tungsten Steel	0.7 C, 0.3 Mn, 5 W	70	10 300	.3		Q850		8.1
Tungsten Steel†	0.4 C, 6W	65	10 500	.3		AQ750, Q800		8.1
Chrome Steel	0.6 C, 1 Cr	45	9 000	.2		Q800		7.8
Chrome Steel	0.9 C, 0.3 Mn, 3.5 Cr	65	9 700	.3		Q830		7.7
Chrome Steel†	1.05 C, 6 Cr	70	9 800	.3		AQ750, Q840		7.75
3 Co Steel	1.0 C, 3 Co, 4 Cr, 0.4 Mo	80	10 000	.4		Q860		7.8
3 Co Steel†	1.05 C, 3 Co, 9 Cr, 1.5 Mo	130	7 200	.35	Hot roll, machine, punch	FC780, AQ1000	Hard, strong	7.7
6 Co Steel†	1.05 C, 6 Co, 9 Cr, 1.5 Mo	145	7 500	.45		FC780, AQ1000		7.75
9 Co Steel†	1.05 C, 9 Co, 9 Cr, 1.5 Mo	160	7 800	.5		AQ1150, FC780, AQ1000		7.8
15 Co Steel†	1.05 C, 15 Co, 9 Cr, 1.5 Mo	180	8 200	.6		AQ1150, FC780, AQ1000		7.9
17 Co Steel	0.75 C, 17 Co, 2.5 Cr, 8 W	150	9 500	.65		Q930		8.35
35 Co Steel†	0.85 C, 35 Co, 6 Cr, 4 W	250	9 500	1.0		AQ1150, FC780, Q950		8.15
36 Co Steel	0.7 C, 36 Co, 4 Cr, 5 W	240	9 500	1.0		Q930		8.2
Alnit† (MK)	25 Ni, 13 Al, 4 Cu	500	6 000	1.3				7.0
Oerstit 120	27 Ni, 12.5 Al	500	5 700	1.1				
Alnico†	13 Co, 18 Ni, 10 Al, 6 Cu	510	7 000	1.6		Q1200, B600		7.45
Alnico 1	5 Co, 20 Ni, 12 Al	440	7 200	1.4		Q1200, B700		6.9
Alnico 2	12.5 Co, 17 Ni, 10 Al, 6 Cu	540	7 200	1.6		Q1200, B600		7.1
Alnico 4	5 Co, 28 Ni, 12 Al	700	5 500	1.3		Q1200, B650		7.0
Alnico 5 (Ticonal)	24 Co, 14 Ni, 8 Al, 3 Cu	575	12 500	5.0		AF1300, B600		7.3
Alnico 5 (DG)	24 Co, 14 Ni, 8 Al, 3 Cu	640	13 100	5.5	Cast and ground	AF1300, B600	Hard, brittle	7.3
Alcomax 1†	25 Co, 11 Ni, 7 Al, 3 Cu, 1.5 Ti	475	12 000	3.5		AF1300, B600		7.3
Alcomax 2†	25 Co, 11 Ni, 8 Al, 6 Cu	570	12 400	4.3		AF1300, B600		7.55
Alcomax 3†	25 Co, 13 Ni, 8 Al, 3 Cu, 0.7 Nb	650	13 200	5.0		AF1300, B600		7.35
Alcomax 4†	25 Co, 13 Ni, 8 Al, 3 Cu, 2.7 Nb	760	11 800	4.7		AF1300, B600		7.35
Alnico 6	24 Co, 15 Ni, 8 Al, 3 Cu, 1.25 Ti	730	10 700	3.8		AF1300, B600		7.4

Ferromagnetism, Bozorth, Appendix 4, p.872-3

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- This list from Bozorth is summarized by the material families identified in blue text.
- There are many compositions and they are known by many brand names.

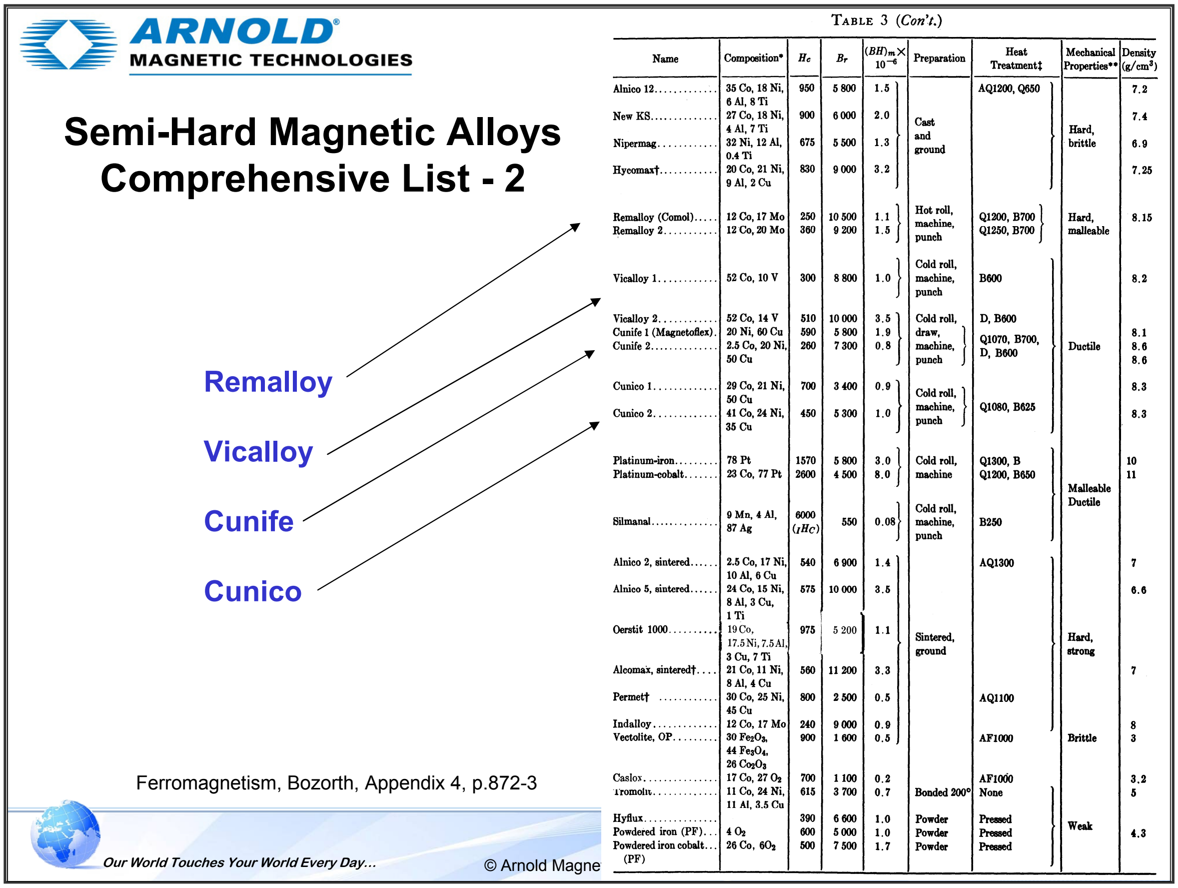


TABLE 3 (*Con't.*)

Name	Composition*	H_c	B_r	$(BH)_m \times 10^{-6}$	Preparation	Heat Treatment‡	Mechanical Properties**	Density (g/cm³)
Alnico 12	35 Co, 18 Ni, 6 Al, 8 Ti	950	5 800	1.5	Cast and ground	AQ1200, Q650	Hard, brittle	7.2
New KS	27 Co, 18 Ni, 4 Al, 7 Ti	900	6 000	2.0				7.4
Nipermag	32 Ni, 12 Al, 0.4 Ti	675	5 500	1.3				6.9
Hycomax†	20 Co, 21 Ni, 9 Al, 2 Cu	830	9 000	3.2				7.25
Remalloy (Comol)	12 Co, 17 Mo	250	10 500	1.1	Hot roll, machine, punch	Q1200, B700	Hard, malleable	8.15
Remalloy 2	12 Co, 20 Mo	360	9 200	1.5		Q1250, B700		
Vicalloy 1	52 Co, 10 V	300	8 800	1.0	Cold roll, machine, punch	B600	Ductile	8.2
Vicalloy 2	52 Co, 14 V	510	10 000	3.5	Cold roll,	D, B600		
Cunife 1 (Magnetoflex)	20 Ni, 60 Cu	590	5 800	1.9	draw, machine, punch	Q1070, B700, D, B600		8.1
Cunife 2	2.5 Co, 20 Ni, 50 Cu	260	7 300	0.8				8.6 8.6
Cunico 1	29 Co, 21 Ni, 50 Cu	700	3 400	0.9	Cold roll, machine, punch	Q1080, B625		8.3
Cunico 2	41 Co, 24 Ni, 35 Cu	450	5 300	1.0				8.3
Platinum-iron	78 Pt	1570	5 800	3.0	Cold roll, machine	Q1300, B	Malleable Ductile	10
Platinum-cobalt	23 Co, 77 Pt	2600	4 500	8.0		Q1200, B650		11
Silmanal	9 Mn, 4 Al, 87 Ag	6000 ($_IH_C$)	550	0.08	Cold roll, machine, punch	B250		
Alnico 2, sintered	2.5 Co, 17 Ni, 10 Al, 6 Cu	540	6 900	1.4	Sintered, ground	AQ1300	Hard, strong	7
Alnico 5, sintered	24 Co, 15 Ni, 8 Al, 3 Cu, 1 Ti	575	10 000	3.5				6.6
Oerstit 1000	19 Co, 17.5 Ni, 7.5 Al, 3 Cu, 7 Ti	975	5 200	1.1				
Alcomax, sintered†	21 Co, 11 Ni, 8 Al, 4 Cu	560	11 200	3.3				7
Permet†	30 Co, 25 Ni, 45 Cu	800	2 500	0.5		AQ1100		
Indalloy	12 Co, 17 Mo	240	9 000	0.9				8
Vectolite, OP	30 Fe_2O_3, 44 Fe_3O_4, 26 Co_2O_3	900	1 600	0.5		AF1000	Brittle	3
Caslox	17 Co, 27 O_2	700	1 100	0.2		AF1000		3.2
Tromolit	11 Co, 24 Ni, 11 Al, 3.5 Cu	615	3 700	0.7	Bonded 200°	None	Weak	5
Hyflux		390	6 600	1.0	Powder	Pressed		
Powdered iron (PF)	4 O_2	600	5 000	1.0	Powder	Pressed		4.3
Powdered iron cobalt (PF)	26 Co, 6O_2	500	7 500	1.7	Powder	Pressed		

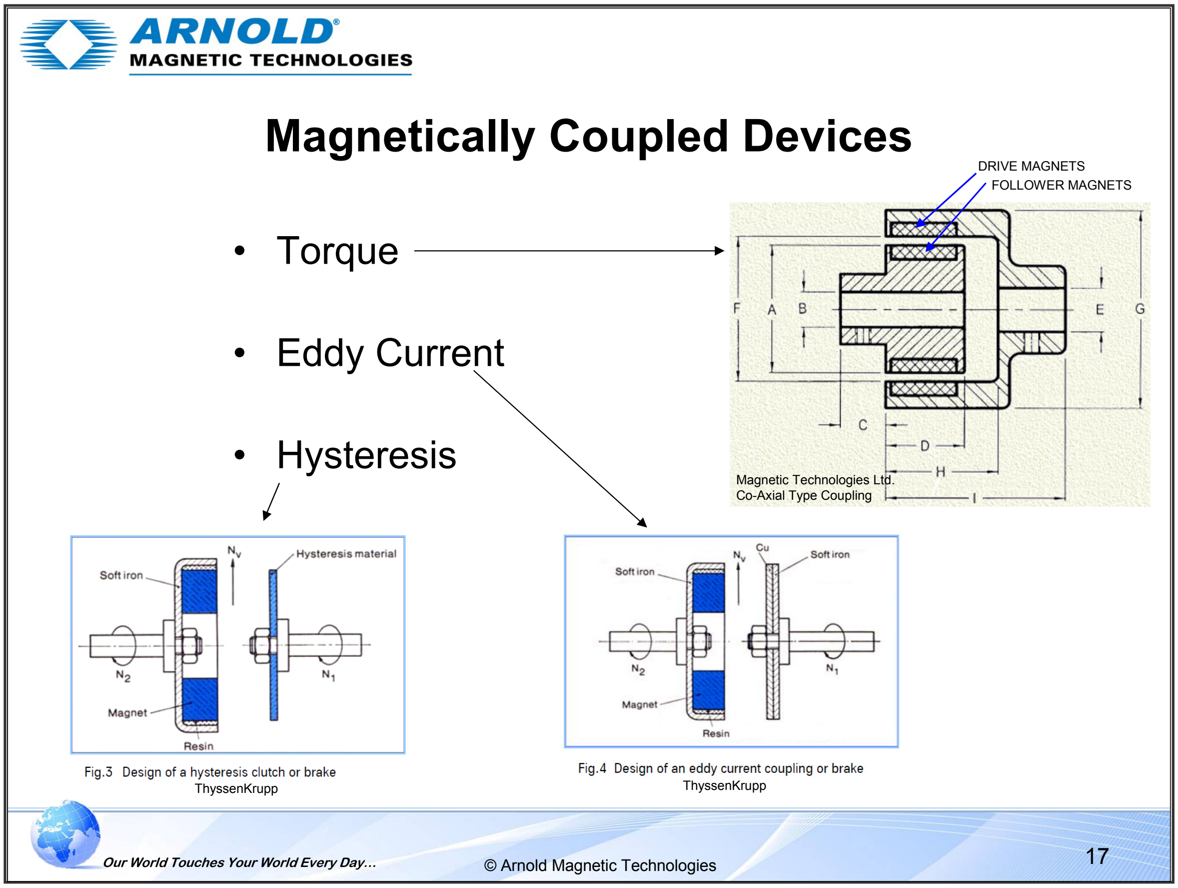
- The list shows many materials that might fall in either the semi-hard or permanent magnet category – Sometimes the only difference is in how they are being utilized – are they driven around the hysteresis loop or remain magnetized in one orientation?

ARNOLD®
MAGNETIC TECHNOLOGIES

Uses for Semi-Hard Magnets

- Magnetically Coupled Devices
  - Brakes
  - Clutches
  - Tensioners
- Biasing Element in Magnetic EAS
  - (Electronic Article Surveillance) "Anti-Theft Tags"
- Relay Magnets
- Magnetic Tooling Holders
- Magnetic Chucks
- Flip Signs
- Sensor Magnets
- Magnetic Stirrer Bars
- Level Sensors

- The largest volume usage for semi-hard materials is in the first category: Magnetically Coupled Devices.
- Let's take a closer look at these and then show a few other example applications.

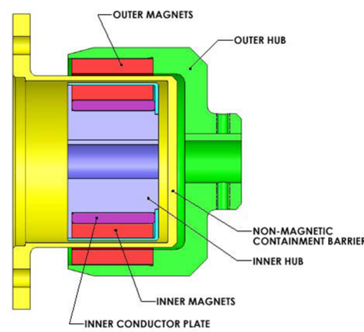


- Magnetically coupled devices fall into three categories. As we discuss these, remember that the permanent magnet might also substituted for by an electromagnet. In general:
  - ➢ Torque coupled devices use sets of magnets interacting with each other.
  - ➢ Eddy current devices utilize permanent (or electro-) magnets interacting with a conductor (frequently a copper disc).
  - ➢ Hysteresis coupled devices use a permanent or electro-magnet to interact with a magnetic material – a “hysteresis material”.

ARNOLD MAGNETIC TECHNOLOGIES

Torque Coupled Devices

- Device uses two sets of adjacent magnets "locked" to each other so that when the first set moves, the second set follows
- Utilize Permanent Magnets
- Magnets require high resistance to demagnetization due to high demag fields when the torque coupling is "broken" and magnet like poles are opposite each other
- Are often used in pumps to avoid rotating seals
- Used to pump chemically hazardous, flammable, or hot materials
- Sizes range from fractional HP to tens of HP



RIMTEC MSV TYPE MAGNETIC COUPLING

Torque Coupled	Drive Component	Follower
Material	Permanent Magnets	Permanent Magnets
Characteristics	High Coercivity	High Coercivity
Function	Magnetic Attraction	

- Torque coupling can be rotational or linear.

ARNOLD
MAGNETIC TECHNOLOGIES

Eddy Current Coupled Devices

- Movement of a magnet (or arrangement of magnets) adjacent to a conductive material causes eddy currents in the conductive material.
- These eddy currents generate magnetic fields that are in opposition to the fields from the moving permanent magnets.

Magnetic Technologies Ltd. - Eddy Current Clutches

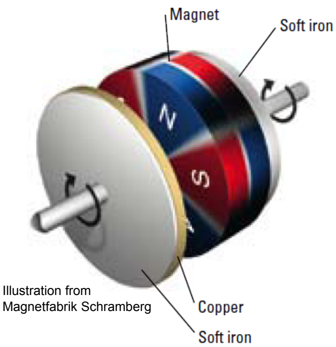


Illustration from Magnetfabrik Schramberg

Eddy Current Coupled	Drive Component	Follower
Material	Permanent Magnets	Conductive Materials
Characteristics	High Energy	High Conductivity
Function	Magnetic Repulsion	

- Eddy current couples can take many forms included rotating cylinders and discs.

ARNOLD®
MAGNETIC TECHNOLOGIES

Hysteresis Coupled Devices

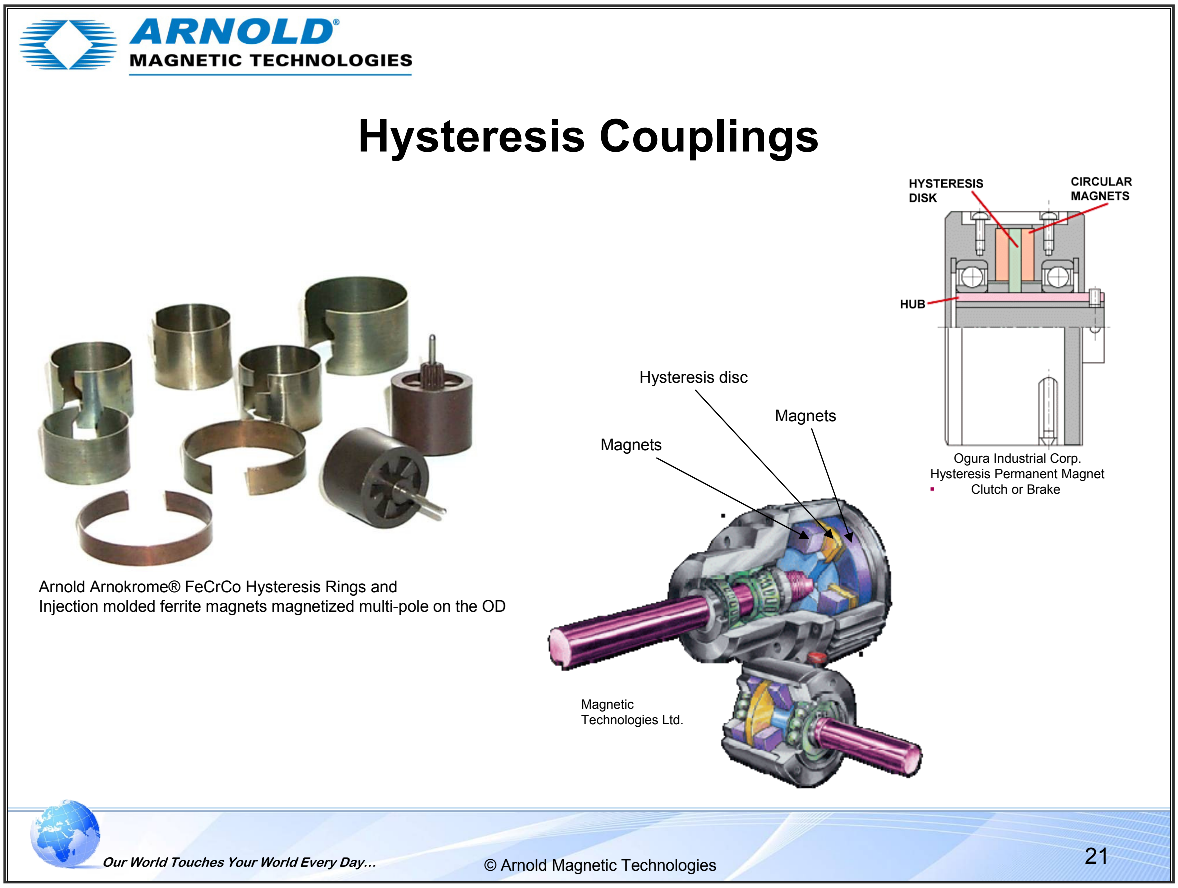
- One part of the device uses a permanent magnet with moderately high Br; A second part uses a semi-hard material.
- As the first part moves, the second part is drawn along.
- However, the second part moves out-of-phase with the first part causing the second part to be driven through its hysteresis loop (usually a minor loop).
- If the second part cannot move, such as at end-of-travel, the magnetic couple functions as a slip clutch

Permanent-Magnet
Hysteresis Clutch/Brake
Ogura Industrial Corp.

Magnetic Hysteresis Headsets
Magnetic Technologies Ltd.

Hysteresis Coupled	Drive Component	Follower
Material	Permanent Magnets	**Semi-Hard Magnets**
Characteristics	High Energy	Easily Magnetizable**
Function	Hysteresis Energy Loss	

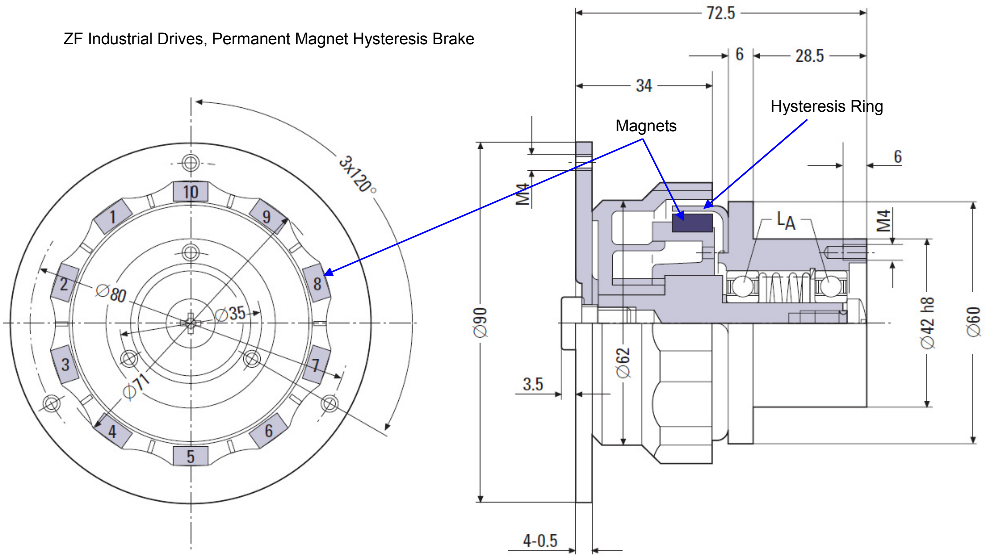
- Hysteresis coupled devices depend upon the interaction of a magnet and a semi-soft magnetic material.
- The proximity of the magnet to the semi-hard, hysteresis material determines the strength of the couple and can be adjusted manually or automatically as part of the device control function.



- Couplings are frequently used to provide slippage at end-of-travel such as for HVAC damper drive components illustrated at the left above. These are a combination of a multi-pole insert-injection molded ferrite magnet coupled to a ring of FeCrCo (Arnold's Arnokrome®).

Hysteresis Coupling

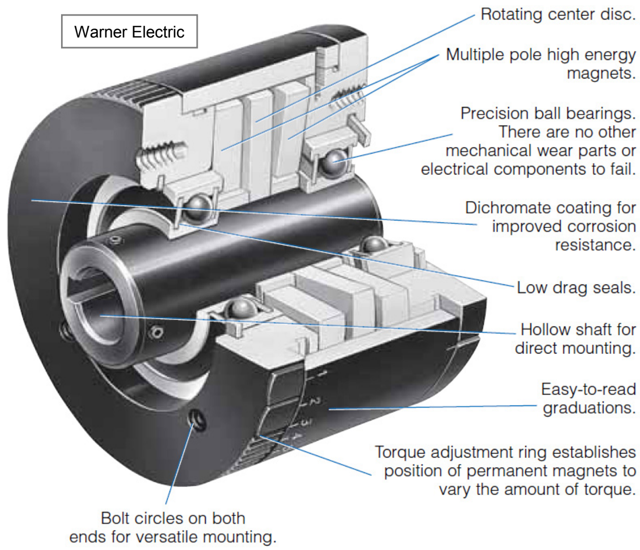
ZF Industrial Drives, Permanent Magnet Hysteresis Brake



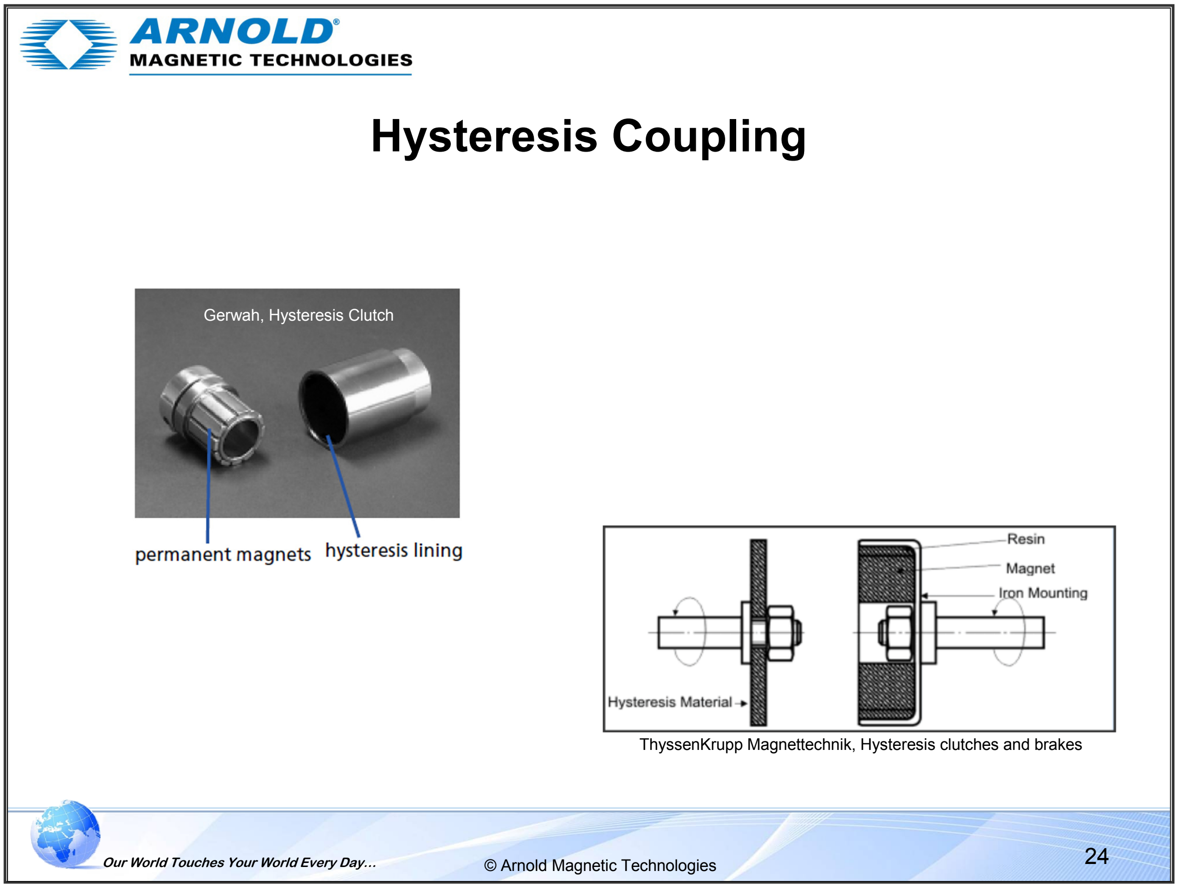
- In this design from ZF Industrial, the hysteresis material is in the form of a cylindrical sleeve around an inner set of “drive” magnets.

ARNOLD® MAGNETIC TECHNOLOGIES

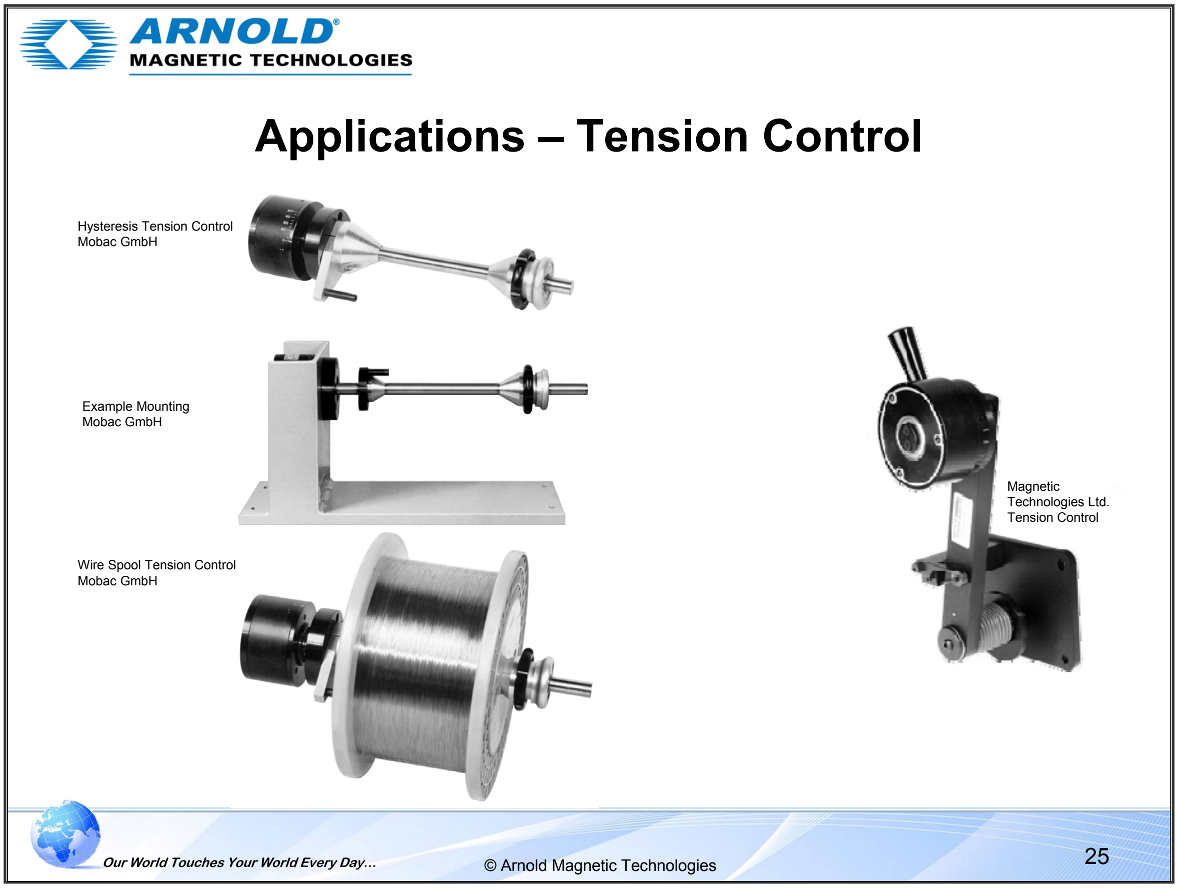
Hysteresis Coupling



- In this Warner Electric design, multi-pole magnets are on either side of a rotating center disc of hysteresis material. By adjusting the poles of one set of permanent magnets relative to the other, the field propagation through the hysteresis disc is altered.



- In the design on the left by Gerwah, a cylindrical sleeve surrounds a smaller cylinder with magnets around the perimeter.
- In the design to the right, the hysteresis material is in the form of a disc.
- In all circumstances, hysteresis coupling is achieved by having the arrangement of permanent magnets force portions of the hysteresis material to cycle through its hysteresis loop or a minor loop.



- Since the cycling takes energy and is adjustable, it is possible to use hysteresis couplings to achieve driving, braking and tension control as in the tensioners illustrated here.

ARNOLD
MAGNETIC TECHNOLOGIES

Magnetic Flip Tabs

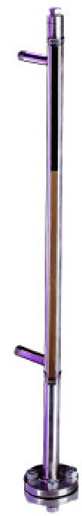
Penberthy Flow and Level Gauges

Gold or yellow on one side and black on the other

Follower Style Indicator

Flag Style Indicator

Mini Magnetic Gage (MMG)



- Another use for semi-hard materials is in signage associated with level indicators and flow meters.
- In these devices by Penberthy, a series of small magnets is "flipped' by the movement of an adjacent stronger permanent magnet.
- With one side dark and the other side a bright color, it is easy to determine at a distance the level or flow situation.

Other Uses for Semi-Hard Magnets

Spring Pin Insertion Tool
www.bmmachine.com

- Many of us are familiar with magnetic screwdriver tips and tool holders. These generally use alnico or another semi-hard material such as FeCrCo. These materials are adequately tough to take the punishment associated with machine tools.
- In the illustration at the left, the holder is used for inserting drive pins. As the pin is magnetically held in place, orientation of the assembly is unimportant – the pin is held in the holder and won't fall out during installation.

- We see that there are many materials that lie between the soft and the permanent (hard) magnetic materials.
- These have useful properties and are widely utilized.
- As for most magnetic materials, they are within the devices and invisible to the naked eye.
- Perhaps we should take more time to appreciate what these materials have done for us and improving our quality of life.