

Permanent Magnets...

Why Rare Earths?

Steve Constantinides, Director of Technology
Arnold Magnetic Technologies Corporation

July 1, 2015

Argus Americas Rare Earths Summit

June 29 - July 1, 2015
Four Seasons | Las Vegas, Nevada

- What I hope to convey to you is that rare earths are uniquely required for high performance magnets.

What we do...

Performance materials enabling energy efficiency



Magnet Production & Fabrication

- Rare Earth Samarium Cobalt (RECOMA®)
- Alnico
- Injection molded
- Flexible Rubber



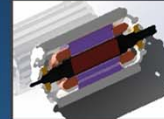
Precision Thin Metals

- Specialty Alloys from 0.000069"
- Sheets, Strips, & Coils
- Milling, Annealing, Coating, Slitting
- ARNON® Motor Lamination Material
- Light-weighting



Permanent Magnet Assemblies

- Precision Component Assembly
- Tooling, Machining, Cutting, Grinding
- Balancing
- Sleeving



Ultrahigh Performance Motors

- Smaller, Faster motors
- Power dense package
- High RPM magnet containment
- >200°C Operation

Engineering | Consulting | Testing
Stabilization & Calibration | Distribution

- First a quick introduction to Arnold – the company I’ve worked for since 1992.
- Arnold’s history in magnetics and magnetic materials extends back to 1895 and has included almost every commercially supplied permanent and soft magnetic product.
- Today Arnold is focused on: SmCo, Alnico and bonded permanent magnets; precision thin metals – both magnetic and non-magnetic; magnetic assemblies for motors, magnetic levitation, sensing and separation technologies; and most recently we have responded to customer requests to develop and supply ultra-high performance permanent magnet motors for select applications.

Agenda

- **What makes rare earth elements special?**
 - Small applications
 - Powerful applications

- Let's start by answering this question: What makes rare earth elements so special?

The rare earth elements

PERIODIC TABLE
Atomic Properties of the Elements

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce
physics.nist.gov

Frequently used fundamental physical constants
For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ¹³³Cs

speed of light in vacuum $c = 299\,792\,458 \text{ m s}^{-1}$ (exact) ($h = hc/2\pi$)
 Planck constant $h = 6.6261 \times 10^{-34} \text{ J s}$
 elementary charge $e = 1.6022 \times 10^{-19} \text{ C}$
 electron mass $m_e = 9.1094 \times 10^{-31} \text{ kg}$
 proton mass $m_p = 1.6726 \times 10^{-27} \text{ kg}$
 fine-structure constant $\alpha = 1/137.036$
 Rydberg constant $R_\infty = 10\,973\,732 \text{ m}^{-1}$
 $R_\infty c = 3.289\,842 \times 10^{15} \text{ Hz}$
 $R_\infty hc = 13.6057 \text{ eV}$
 Boltzmann constant $k = 1.3807 \times 10^{-23} \text{ J K}^{-1}$

Group	Periodic Table																Standard Reference Data Group																	
	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9 VIII	10 VIII	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA																
1	H 1.00794 1s	He 4.002602 1s																	He 4.002602 1s															
2	Li 6.941 1s ² 2s	Be 9.012182 1s ² 2s ²																	B 10.811 1s ² 2s ² 2p	C 12.0107 1s ² 2s ² 2p ²	N 14.0064 1s ² 2s ² 2p ³	O 15.9994 1s ² 2s ² 2p ⁴	F 18.9984032 1s ² 2s ² 2p ⁵	Ne 20.1797 1s ² 2s ² 2p ⁶										
3	Na 22.989769 [Ne]3s	Mg 24.304 [Ne]3s ²																	Al 26.9815385 [Ne]3s ² 3p	Si 28.0855 [Ne]3s ² 3p ²	P 30.9737619 [Ne]3s ² 3p ³	S 32.065 [Ne]3s ² 3p ⁴	Cl 35.453 [Ne]3s ² 3p ⁵	Ar 39.948 [Ne]3s ² 3p ⁶										
4	K 39.0983 [Ar]4s	Ca 40.078 [Ar]4s	Sc 44.955910 [Ar]3d ¹ 4s	Ti 47.88 [Ar]3d ² 4s	V 50.9415 [Ar]3d ³ 4s	Cr 51.9961 [Ar]3d ⁵ 4s	Mn 54.938044 [Ar]3d ⁵ 4s	Fe 55.845 [Ar]3d ⁶ 4s	Co 58.933200 [Ar]3d ⁷ 4s	Ni 58.6934 [Ar]3d ⁸ 4s	Cu 63.546 [Ar]3d ¹⁰ 4s	Zn 65.409 [Ar]3d ¹⁰ 4s	Ga 69.723 [Ar]3d ¹⁰ 4s ² 4p	Ge 72.64 [Ar]3d ¹⁰ 4s ² 4p ²	As 74.92160 [Ar]3d ¹⁰ 4s ² 4p ³	Se 78.96 [Ar]3d ¹⁰ 4s ² 4p ⁴	Br 79.904 [Ar]3d ¹⁰ 4s ² 4p ⁵	Kr 83.798 [Ar]3d ¹⁰ 4s ² 4p ⁶																
5	Rb 85.4678 [Kr]5s	Sr 87.62 [Kr]5s	Y 88.90585 [Kr]4d ¹ 5s	Zr 91.224 [Kr]4d ² 5s	Nb 92.90638 [Kr]4d ⁴ 5s	Mo 95.94 [Kr]4d ⁵ 5s	Tc 98.906250 [Kr]4d ⁵ 5s	Ru 101.07 [Kr]4d ⁷ 5s	Rh 101.90550 [Kr]4d ⁸ 5s	Pd 106.42 [Kr]4d ¹⁰ 5s	Ag 107.8682 [Kr]4d ¹⁰ 5s	Cd 112.411 [Kr]4d ¹⁰ 5s	In 114.818 [Kr]4d ¹⁰ 5s ² 5p	Sn 118.710 [Kr]4d ¹⁰ 5s ² 5p ²	Sb 121.760 [Kr]4d ¹⁰ 5s ² 5p ³	Te 127.60 [Kr]4d ¹⁰ 5s ² 5p ⁴	I 126.90547 [Kr]4d ¹⁰ 5s ² 5p ⁵	Xe 131.293 [Kr]4d ¹⁰ 5s ² 5p ⁶																
6	Cs 132.90545 [Xe]6s	Ba 137.327 [Xe]6s																	Hf 178.49 [Xe]4f ¹⁴ 5d ² 6s	Ta 180.9479 [Xe]4f ¹⁴ 5d ³ 6s	W 183.84 [Xe]4f ¹⁴ 5d ⁴ 6s	Re 186.207 [Xe]4f ¹⁴ 5d ⁵ 6s	Os 190.23 [Xe]4f ¹⁴ 5d ⁶ 6s	Ir 192.222 [Xe]4f ¹⁴ 5d ⁷ 6s	Pt 195.078 [Xe]4f ¹⁴ 5d ⁹ 6s	Au 196.96655 [Xe]4f ¹⁴ 5d ¹⁰ 6s	Hg 200.59 [Xe]4f ¹⁴ 5d ¹⁰ 6s	Tl 204.3833 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p	Pb 207.2 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ²	Bi 208.98038 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ³	Po 209 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁴	At 210 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁵	Rn 222 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁶	
7	Fr [223] [Rn]7s	Ra [226] [Rn]7s																	Rf [261] [Rn]5f ¹⁴ 6d ² 7s	Db [262] [Rn]5f ¹⁴ 6d ³ 7s	Sg [266] [Rn]5f ¹⁴ 6d ⁴ 7s	Bh [264] [Rn]5f ¹⁴ 6d ⁵ 7s	Hs [277] [Rn]5f ¹⁴ 6d ⁶ 7s	Mt [268] [Rn]5f ¹⁴ 6d ⁷ 7s	Uun [281] [Rn]5f ¹⁴ 6d ⁸ 7s	Uuu [272] [Rn]5f ¹⁴ 6d ⁹ 7s	Uub [285] [Rn]5f ¹⁴ 6d ¹⁰ 7s	Uuq [289] [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p	Uuq [289] [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p	Uuh [292] [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ²	Uuh [292] [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ²	Uuh [292] [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ²	Uuh [292] [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ²	Uuh [292] [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ²
			Lanthanides														Actinides																	
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr		
			138.9055	140.118	140.90766	144.24	(145)	150.36	151.964	157.25	158.92534	162.500	164.93032	167.259	168.93421	173.04	174.967	(189)	232.0377	231.03688	231.03688	238.02891	(241)	(243)	(247)	(247)	(251)	(252)	(257)	(259)	(261)			
			[Xe]5s ² 5d ¹ 6s	[Xe]5s ² 5d ¹ 6s	[Xe]5s ² 5d ¹ 6s	[Xe]5s ² 5d ² 6s	[Xe]5s ² 5d ² 6s	[Xe]5s ² 5d ² 6s	[Xe]5s ² 5d ² 6s	[Xe]5s ² 5d ² 6s	[Xe]5s ² 5d ² 6s	[Xe]5s ² 5d ² 6s	[Xe]5s ² 5d ² 6s	[Xe]5s ² 5d ² 6s	[Xe]5s ² 5d ² 6s	[Xe]5s ² 5d ² 6s	[Xe]5s ² 5d ² 6s	[Rn]6s ²	[Rn]6s ² 7s	[Rn]6s ² 7s	[Rn]6s ² 7s	[Rn]6s ² 7s	[Rn]6s ² 7s	[Rn]6s ² 7s	[Rn]6s ² 7s	[Rn]6s ² 7s	[Rn]6s ² 7s	[Rn]6s ² 7s	[Rn]6s ² 7s	[Rn]6s ² 7s	[Rn]6s ² 7s			
			5.3769	5.5387	5.473	5.5250	(5.582)	6.437	5.6704	5.9738	6.1979	6.2817	6.42	6.414	6.843	6.2542	5.4259	5.17	6.3067	5.89	6.1941	6.2657	6.0260	5.9738	5.9914	6.1979	6.2817	6.42	6.58	6.65	4.9 ?			

Legend: Solids (blue), Liquids (green), Gases (red), Artificially Prepared (yellow)

Atomic Number, Ground-state Level, Symbol, Name, Atomic Weight, Ground-state Configuration, Ionization Energy (eV)

4

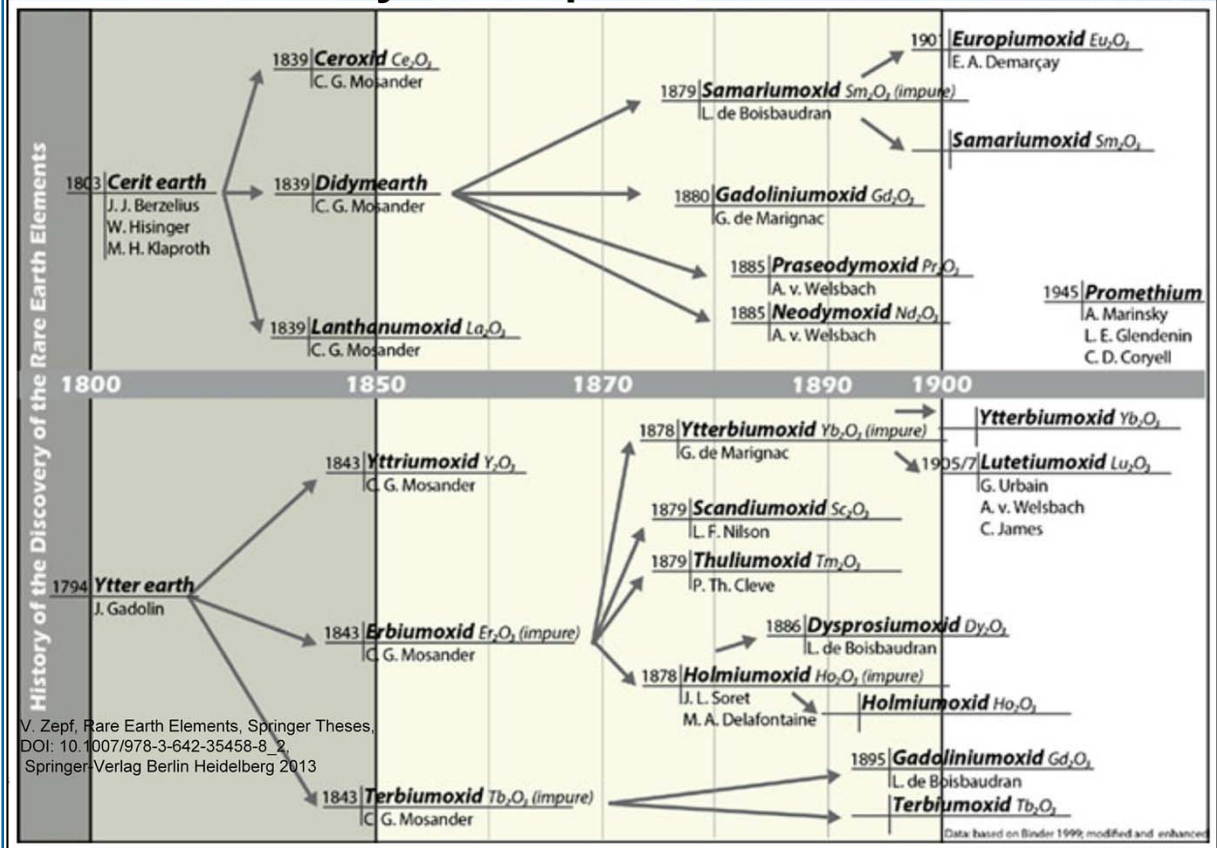
Based upon ¹²C. (i) indicates the mass number of the most stable isotope.

For a description of the data, visit physics.nist.gov/data

NIST SP 966 (September 2003)

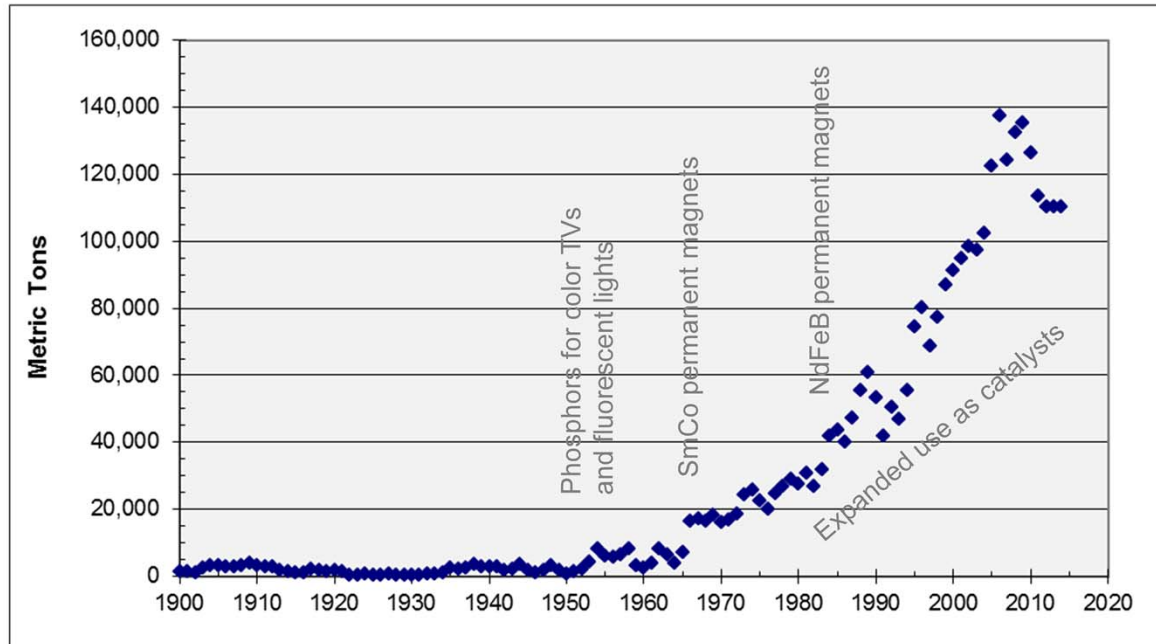
- The rare earth elements consist of the 15 lanthanide elements (lanthanum to lutetium) plus yttrium and scandium.
- Yttrium and scandium are directly above lanthanum in the periodic table and have chemical properties that are very similar to the lanthanides – that is why they are usually included with them.
- Note cesium and barium precede lanthanum in row 6 of the periodic table and that hafnium, element number 72, continues row 6 right after lutetium, the lanthanide with the highest atomic number, 71.
- Note too, row 4 of the table which contains the transition elements including iron, cobalt and nickel. We'll be making some comparison between the two groups of elements in later slides.

REEs: discovery and separation timeline



- Rare earth elements (REEs) have considerable chemical similarities thus making them difficult to separate from each other.
- That is one reason they were late in being discovered, isolated and incorporated in alloys and compounds.
- In this table from Volker Zepf, we see that some separated materials were found to comprise multiple elements and required further separation.
- The last stable rare earth element, lutetium, was separated in 1905-7.
- Promethium is a highly unstable and far more rare element and was not identified until 1945-7.
- It is my contention that REEs should be considered “modern materials” as their commercial use was not common until the late 1950s.

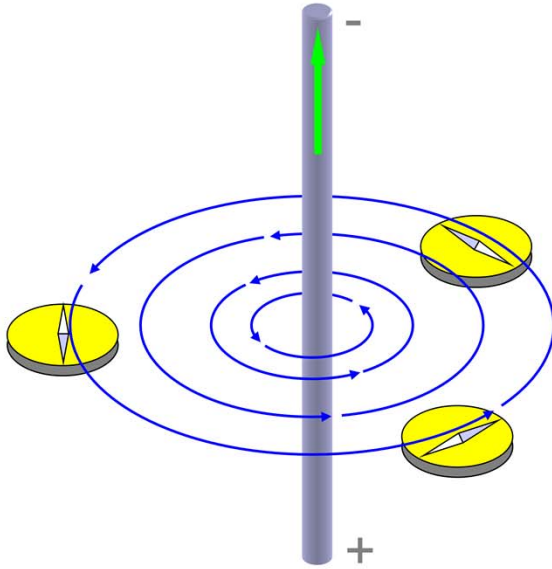
Global production of REO



Source: Multiple including USGS

- The commercial production of rare earth elements (quantities expressed as oxides) was small until the 1950s and has grown rapidly since then with the discovery of more uses and expansion of existing ones.

Magnetic Field from Current in a Conductor



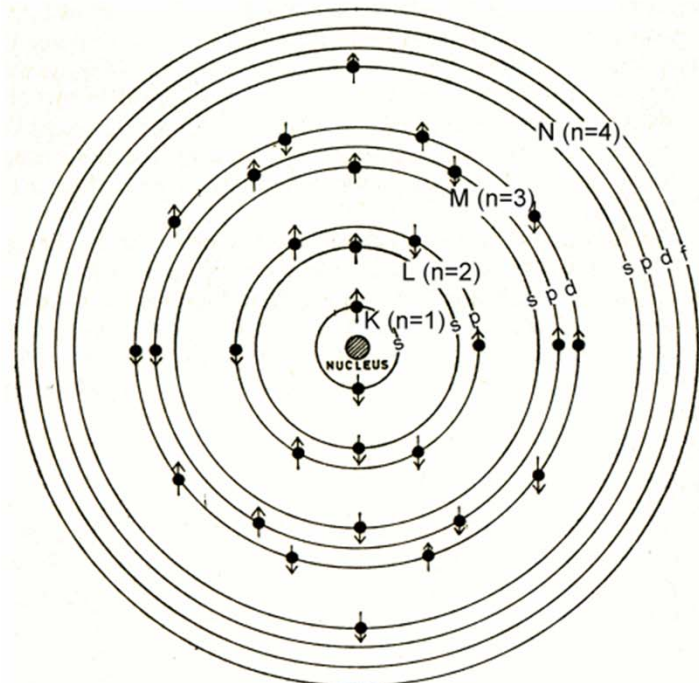
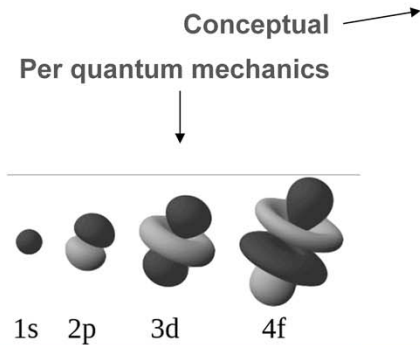
When current flows in a conductor, a magnetic field is generated around the wire in the pattern shown here.

But what is the source of a magnetic field from a permanent magnet?

- Since this talk is focused on the use of REEs in the field of magnetism, the first issue we should deal with is why REEs are so important.
- We will start with a very basic introduction to (electro)magnetism.
- Electrons flowing in a conductor generate a magnetic field around the conductor as shown by the alignment of these compasses in proximity to the current-carrying wire.
- Summary: moving electrons generate magnetic fields!

Origin of the Field - 1

- A permanent magnet (PM) produces a magnetic field without external assistance
- This field is derived from the electron spin in specified electron orbitals and occurs naturally in Fe, Ni and Co



Electron Spins in Zinc

- Atoms of a material consist of numerous entities including protons, neutrons, mesons, gluons, etc. - and electrons.
- Electrons exist in spatial orbit around the nucleus. The exact positions are beyond our ability to detect, but quantum mechanics allows us (or capable physicists) to calculate a probability of a location. These probability fields have unusual shapes as shown by a few illustrations at the bottom left of the slide.
- For simplicity, we will use the illustration to the right which shows a nucleus at the center surrounded by groups of rings.
- Each group, or “shell”, has a name, a letter, starting with “K” and continuing with L, M, N, O, P, etc.
- Each shell is also assigned a principle quantum number starting with 1 for the K shell, 2 for the L shell, etc.
- Within each shell are sub-shells, called orbitals, designated by the letters s, p, d, and f (all lower case letters).
- Each orbital can contain a fixed maximum number of electrons. The s orbital can contain 2, p can contain 6, d contains up to 10 and f contains up to 14.
- Electrons have “spin” designated as positive or negative and represented here by either an upward pointing arrow or downward pointing arrow.

Origin of the Field - 2

- Filling of the 3d shell doesn't proceed until the 4s shell is filled
- Incomplete filling of the 3d shell is key to magnetism

Atomic number	Element	Shell		K (1)			L (2)			M (3)			N (4)			Number of unpaired spins (circles)
		Sub-shell		1s	2s	2p	3s	3p	3d	4s	4p	4d	4f			
21	Scandium			↑ ↓	↑ ↓	↑↑↑ ↓	↑	↑↑↑ ↓	↑	↑			↑			1
22	Titanium			↑ ↓	↑ ↓	↑↑↑ ↓	↑	↑↑↑ ↓	↑	↑			↑			2
23	Vanadium			↑ ↓	↑ ↓	↑↑↑ ↓	↑	↑↑↑ ↓	↑	↑			↑			3
24	Chromium			↑ ↓	↑ ↓	↑↑↑ ↓	↑	↑↑↑ ↓	↑	↑↑↑↑↑			↑			5-1
25	Manganese			↑ ↓	↑ ↓	↑↑↑ ↓	↑	↑↑↑ ↓	↑	↑↑↑↑↑			↑			5
26	Iron			↑ ↓	↑ ↓	↑↑↑ ↓	↑	↑↑↑ ↓	↑	↑↑↑↑↑			↑			4
27	Cobalt			↑ ↓	↑ ↓	↑↑↑ ↓	↑	↑↑↑ ↓	↑	↑↑↑↑↑			↑			3
28	Nickel			↑ ↓	↑ ↓	↑↑↑ ↓	↑	↑↑↑ ↓	↑	↑↑↑↑↑			↑			2
29	Copper			↑ ↓	↑ ↓	↑↑↑ ↓	↑	↑↑↑ ↓	↑	↑↑↑↑↑			↑			1
30	Zinc			↑ ↓	↑ ↓	↑↑↑ ↓	↑	↑↑↑ ↓	↑	↑↑↑↑↑			↑			0

Pairing of electron spins
in selected transition metal elements

- This is an illustration of the electron arrangement for the element zinc.
- Note there are two electrons in the 1s orbital, the maximum possible number, and that one arrow is pointing up and one down.
- In other orbitals where there is a small “o” under an arrow, it indicates there is an absence of an electron resulting in a “spin imbalance”.
- Where ever there is a spin imbalance, there is a net magnetic field created by the moving electron that is not “balanced” by one of opposite spin.
- The magnitude of the field can be calculated and is called the magneton – actually it is the Bohr magneton named in honor of Niels Bohr, one of the founders of quantum mechanics.
- Thus, the greater the number of spin imbalances, indicated in the right-most column, the greater the net magnetic field generated by the material.
- However, neither chromium nor manganese, for example, exhibit natural ferromagnetism. Why is that?

Origin of the field - 3



Hans Bethe



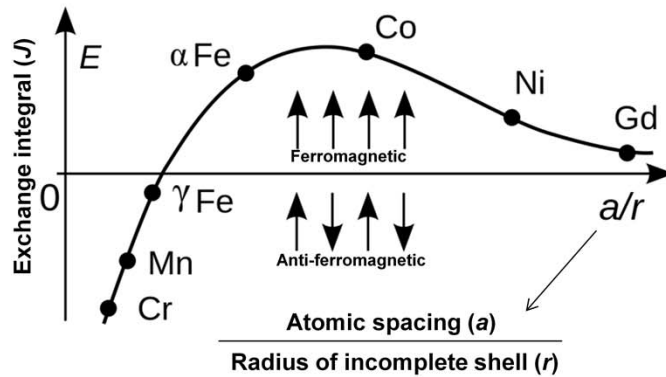
John C. Slater

Exchange Interaction

Heisenberg: quantum theory explanation for ferromagnetism

In physics, the exchange interaction is a quantum mechanical effect which increases or decreases the expectation value of the energy or distance between two or more identical particles when their wave functions overlap.

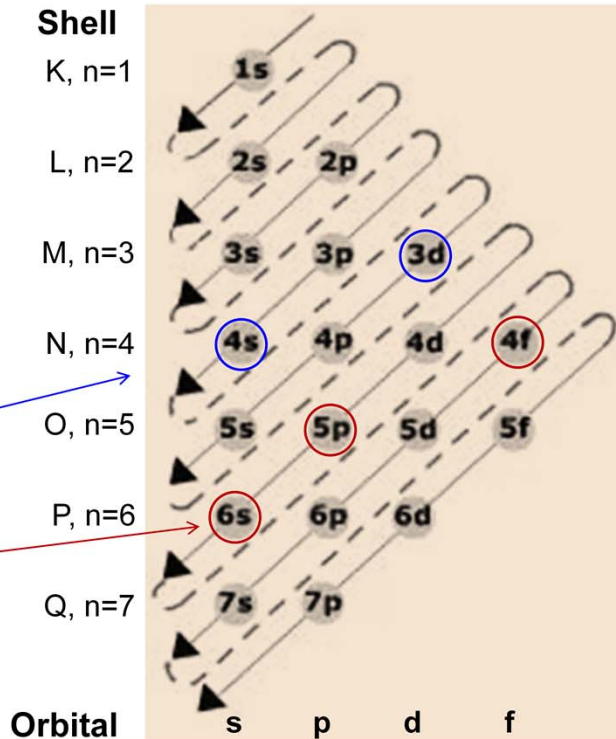
Bethe-Slater Curve



- Materials exist as collections of atoms – usually in a crystalline form.
- The proximity of one atom to another causes an interaction of the electrons of each atom.
- Heisenberg, using the quantum theory, in 1928 explained that as atoms with partially filled electronic shells at large distances from each other move closer to one another their shells begin to overlap and quantum mechanical exchange forces arise between the incomplete shells. The corresponding energy appears in the mathematical formulation as an “exchange integral”.
- When the exchange energy is positive, as it is for Fe, Co and Ni, ferromagnetic properties are exhibited. This occurs when the atomic spacing (a) is about 3-4 times the radius of the incomplete shell (r).
- Additionally, some combinations of otherwise weak magnetic materials have strong magnetic characteristics. Examples are MnAlC and MnBi. Alloying modifies the atomic spacing between adjacent manganese atoms changing the exchange interaction for manganese, moving it from a negative value to positive and causing the material to exhibit ferromagnetism.
- Conversely, when iron transforms into a FCC crystal structure, interatomic distances cause it (gamma Fe) to become anti-ferromagnetic.
- Metallic gadolinium, a rare earth element, exhibits natural ferromagnetism.

Aufbau (Madelung) Principle

- Electrons fill the orbitals starting with the lowest energy orbital
- The sequence of orbital fill follows the solid and dashed lines in this illustration
- For Fe, Co and Ni, the 4s electrons are added prior to 3d electrons
- For the rare earths, the 5p and 6s orbitals are filled prior to the 4f orbital



- As we move to higher atomic numbers, electrons are added according to certain rules.
- These include: Hund's 3 rules, the Pauli exclusion principle, and the Aufbau principle (Madelung energy ordering rule) which incorporates Hund's and Pauli's rules.
- Simply stated, the electron arrangement that results in the lowest atomic potential energy is created first.
- This means, for many elements, adding electrons to some of the outer orbitals prior to filling the inner orbitals.

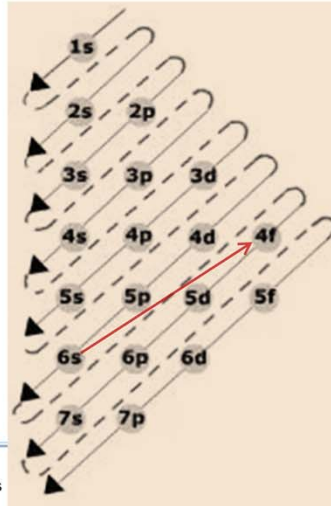
Structure of REEs

“The rare earth ions... owe their magnetic properties to $4f$ electrons. These electrons are in inner shells, and seem less affected by their environment than are the $3d$ electrons of the first transition series.”

“It is generally assumed that the origin of the interactions lies in a spin coupling between the localized $4f$ electrons and the conduction electrons.”

Magnetism, Vol. 1, G. Rado and H. Suhl, editors, Academic Press, 1963, p.21

<http://pdg.lbl.gov/2011/reviews/rpp2011-rev-elements-electronic-struct.pdf>

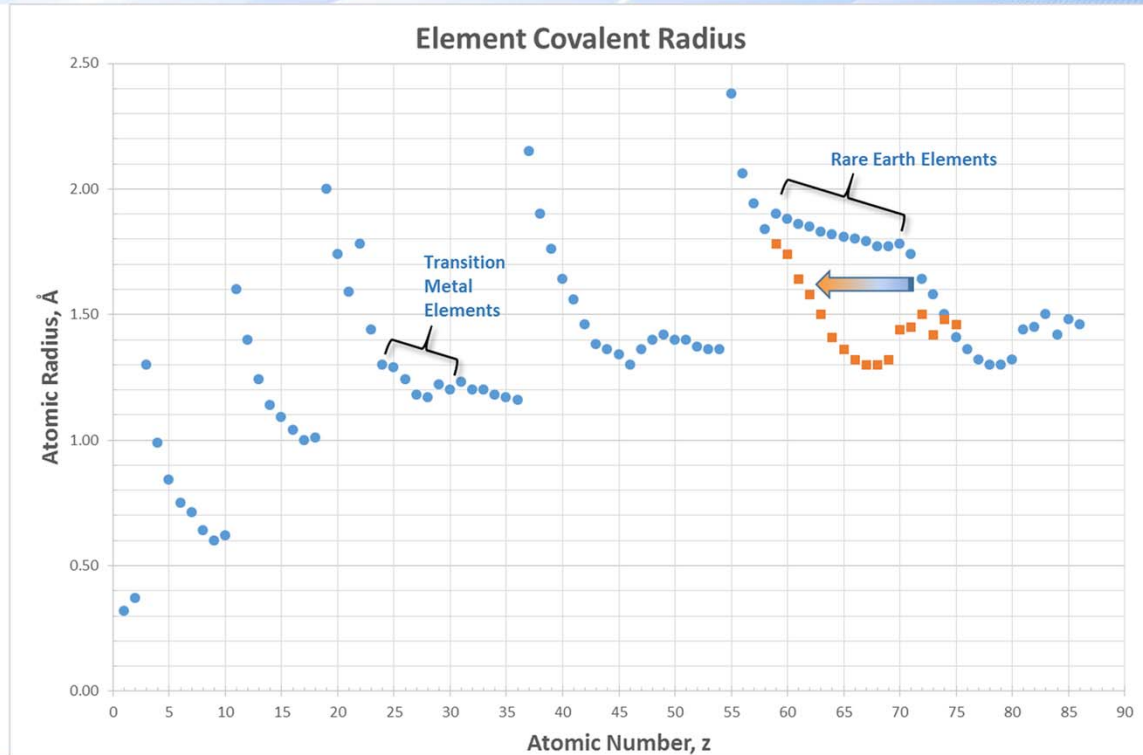


	Sub-shell	4f	5d	6s	Unpaired Electrons
56	Barium			↑ ↓	
57	Lanthanum		↑ ○	↑ ↓	1
58	Cerium	↑ ○	↑ ○	↑ ↓	1 + 1
59	Praseodymium	↑↑↑ ○○○		↑ ↓	3
60	Neodymium	↑↑↑↑ ○○○○		↑ ↓	4
61	Promethium	↑↑↑↑↑ ○○○○○		↑ ↓	5
62	Samarium	↑↑↑↑↑↑ ○○○○○○		↑ ↓	6
63	Europium	↑↑↑↑↑↑↑ ○○○○○○○		↑ ↓	7
64	Gadolinium	↑↑↑↑↑↑↑ ○○○○○○○	↑ ○	↑ ↓	7 + 1
65	Terbium	↑↑↑↑↑↑↑ ↓↑○○○○○		↑ ↓	5
66	Dysprosium	↑↑↑↑↑↑↑ ↓↓↑○○○○		↑ ↓	4
67	Holmium	↑↑↑↑↑↑↑ ↓↓↓↑○○○○		↑ ↓	3
68	Erbium	↑↑↑↑↑↑↑ ↓↓↓↓↑○○○		↑ ↓	2
69	Thulium	↑↑↑↑↑↑↑ ↓↓↓↓↓↑○○		↑ ↓	1
70	Ytterbium	↑↑↑↑↑↑↑ ↓↓↓↓↓↓		↑ ↓	0
71	Lutetium	↑↑↑↑↑↑↑ ↓↓↓↓↓↓	↑ ○	↑ ↓	0 + 1

- The rare earth elements owe their magnetic properties to the $4f$ electrons. Unpaired electrons increase to a maximum of $7+1$ for gadolinium, the only rare earth to exhibit natural ferromagnetic behavior.
- “In solid-state physics, the valence band and conduction band are the bands closest to the Fermi level and thus determine the electrical conductivity of the solid. The valence band is the highest range of electron energies in which electrons are normally present at absolute zero temperature, while the conduction band is the lowest range of vacant electronic states. On a graph of the electronic band structure of a material, the valence band is located below the Fermi level, while the conduction band is located above it. This distinction is meaningless in metals as the highest band is partially filled, taking on the properties of both the valence and conduction bands.”

From https://en.wikipedia.org/wiki/Valence_and_conduction_bands

Trends in atomic radii



- An interesting aberration of the lanthanide series resides in the progression of the radii of the atoms.
- Cref. “lanthanide contraction”: “The effect results from poor shielding of nuclear charge (nuclear attractive force on electrons) by 4f electrons; the 6s electrons are drawn towards the nucleus, thus resulting in a smaller atomic radius.”
- Thus, as electrons are added to the 4f orbital, increased shielding of the nuclear force allows the 5p and 6s electrons to expand, partially offsetting the natural reduction in radius that would otherwise occur.
- If the elements from hafnium and greater atomic number are shifted to the left in the chart on this slide, we see their radii would then fit into the natural progression of radii.
- A similar, but smaller effect is noted in the 3d transition metals which include Fe, Co, and Ni.

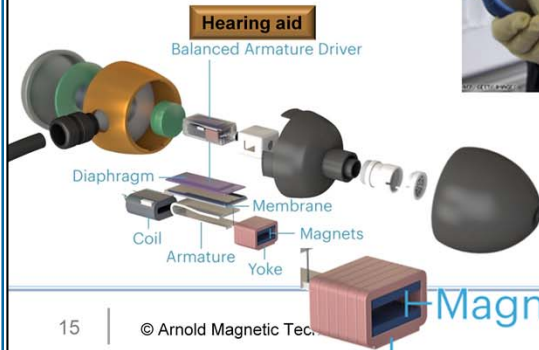
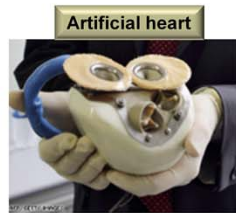
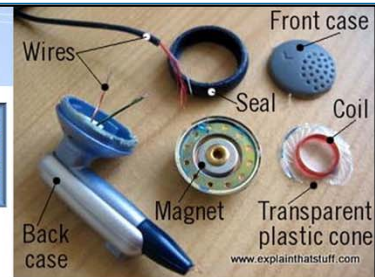
Agenda

- What makes rare earth elements special?
- **Small applications**
- Powerful applications

- When rare earth elements are combined with the 3d transition elements, especially iron and cobalt, the result is a number of ferromagnetic alloys.
- The most powerful magnet materials are, in order of discovery and commercialization: SmCo 1:5, SmCo 2:17, NdFeB and SmFeN.
- Since SmFeN is only available in powder form suitable for bonded magnets, its magnet strength is severely diluted by the non-magnetic binder.
- Between SmCo 1:5 and SmCo 2:17, the more powerful is SmCo 2:17.
- The two rare earth magnets of most commercial importance are therefore, SmCo 2:17 and NdFeB.
- It is these materials that permit very small devices and very powerful ones.

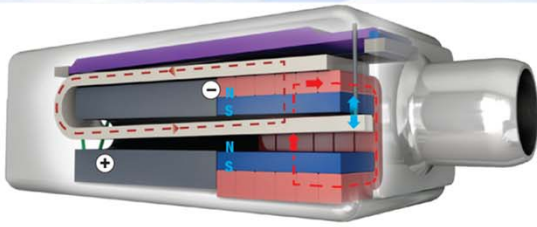
Small applications

- Portable electronics
 - Smart phones
 - Speaker(s)
 - Vibrator motor
 - Ear buds
 - Speaker
 - Hearing Aids
 - Speaker
 - Recorder/players
 - Speaker
- Cameras
- Medical instruments

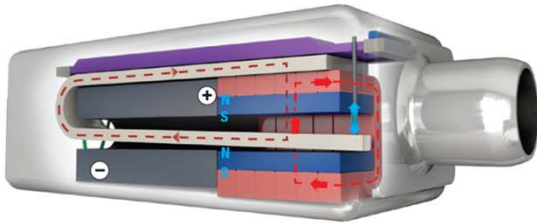


- Some of the more conventional commercial small-magnet applications are shown here.
- For example, the “ear bud“ magnet is approximately 0.2 gram per ear bud. At a production quantity of 200,000,000 units, total mass is about 40 tons of magnets.
- While this may seem like a lot, several magnet companies can produce over 5,000 tons per year – 40 tons is inconsequential.
- Due to the small size of these devices, use of magnets other than rare earth magnets is not feasible.

Hearing aid speakers



Armature (Reed) in Up Position



Armature (Reed) in Down Position

Sound output directly into ear channel or transmitted through hollow tube to ear channel

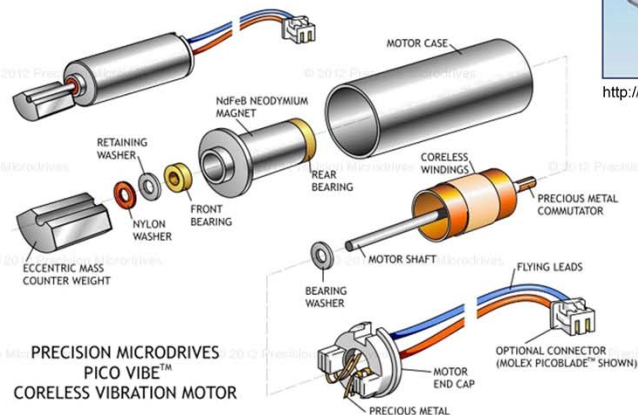


<http://www.knowles.com/eng/premiumsound/The-Science-of-Premium-Sound-Using-Miniature-Transducers>

- If you imagine a hearing aid fitting within the ear channel, size of the sound generating device (“acoustic generator”) becomes almost unimaginably small.

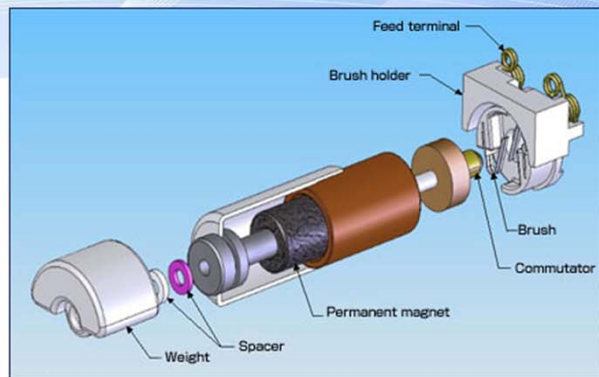
Mini- motors

Example...
Vibrator motors for phones

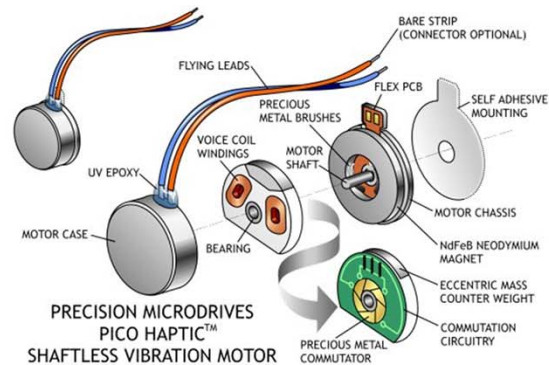


PRECISION MICRODRIVES
PICO VIBE™
CORELESS VIBRATION MOTOR

<https://propelsteps.wordpress.com/2013/10/12/curious-questions-how-do-vibration-mode-works-on-cell-phones/>



<http://www.buqutech.com/magnetyze/Blog/post/Cell-Phones-and-Vibration-Motors-026>



PRECISION MICRODRIVES
PICO HAPTIC™
SHAFTLESS VIBRATION MOTOR

- Cell phones can be set to “vibrate mode” – as I trust yours are now.
- The vibration is generated by an eccentric cam on a motor – a motor containing a small permanent magnet.
- Cell phone sales in 2013 were 1.8 billion with 1 billion of them being smart phones.
- Each phone has at least one speaker and a vibrator both using rare earth (NdFeB) magnets.
- That’s a lot of magnets. But they are very small so tonnage is limited.
- Point: these are only possible, at this small size, by using rare earth magnets.

Mini-motors for photonics



Faulhaber 0816 SR Series DC Motors
(MICROMO)

CLEARWATER, Fla., June 26, 2013 — Micromo's Faulhaber high-power 0816 SR Series DC coreless micromotors deliver continuous torque up to 0.7 mNm and a stall torque of 1.2 mNm. They are 8 mm in diameter and weigh 4.5 g, making them suitable for battery-operated device integration.

Through the use of materials such as **rare-earth magnets**, the motors deliver a performance curve of 11,000 rpm/mNm. They feature nominal voltage versions of 3, 6, 9 and 12 V, with sintered bearings standard and optional ball bearings available for higher radial shaft loads.

<http://www.photonics.com/Product.aspx?PRID=54231>

- Numerous small commercial motors are produced, such as this one.
- They are used for micro-tools and micro-motion.
- Some are used in toys such as small cars and trains to provide motive force.

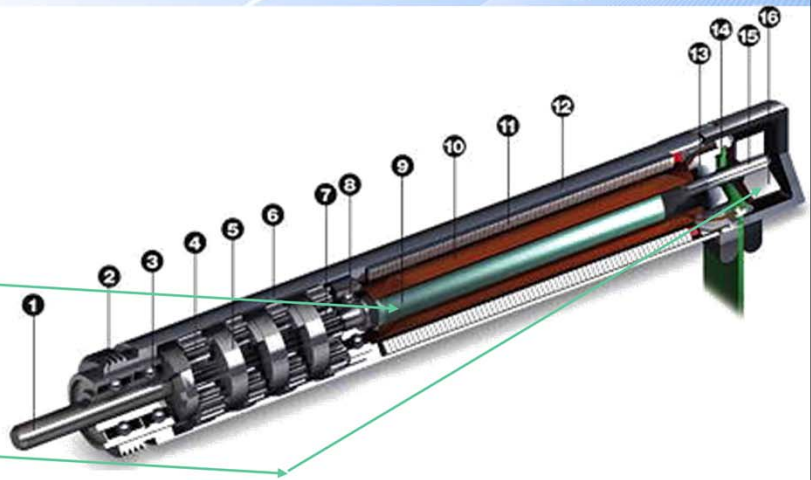
Mini- and micro-motors – medical & diagnostic

maxon gear GP 4

- 1 Output shaft
- 2 Flange
- 3 Ball bearings
- 4 Planetary wheels
- 5 Ceramic planetary carrier
- 6 Ring gear
- 7 Motor pinion (sun wheel)

maxon EC motor EC 4

- 8 Ball bearings
- 9 Permanent magnet
- 10 Winding
- 11 Stator stack
- 12 Housing
- 13 Ceramic bearing
- 14 Circuit board with Hall sensors
- 15 Shaft
- 16 Control magnet



The motor's speed/torque gradient is 50,000 rpm mN/m, with a continuous torque of 0.4mNm. It is available in a long version with a nominal power rating of 1W, or a shorter version with a 0.5W rating.

Maxon expects the motors to be used for applications such as micropumps, analytic and diagnostic devices, surgical devices, laboratory robots, and endoscopes.

http://www.drivesncontrols.com/news/fullstory.php/aid/3799/4mm_micromotor_delivers_power_from_a_standstill.html#sthash.4rWQJSog.dpuf

- An example is shown here of a motor for medical applications.

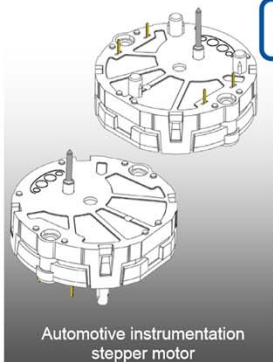
Instrument panel gauges (stepper motors)



Cars and small trucks
Average 4 gauges per
85 million vehicles/year
~340 million gauges/year



JUKEN Swiss Technology



Automotive instrumentation
stepper motor

X27



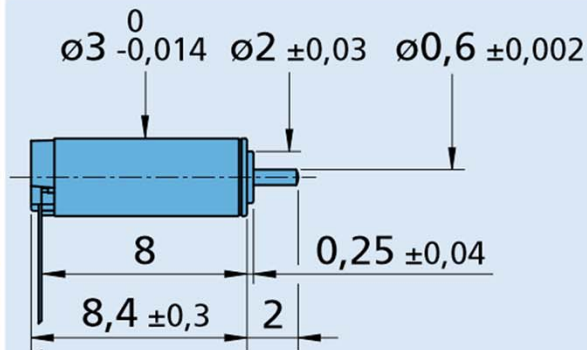
- 1/3° resolution per partial step
- High rotation speed up to 600°/s
- High efficiency over full automotive Temperature range
- Dome option for large pointers
- Front or rear contacts



http://christopherbradshaw.net/The_Project_Bin/2005%20Trailblazer%20Instrument%20Cluster%20Repair%20Inside%20Stepper%20Motor.jpg

- One small device is the stepper motor used to align pointers on gauges in the instrument cluster of cars, trucks, boats, and other transportation vehicles.
- Some of these use ferrite magnets, but most utilize the superior strength of rare earth magnets to provide fast and reliable gauging.
- Quantities are high, but the size of the magnet is small – minimizing total tonnage.

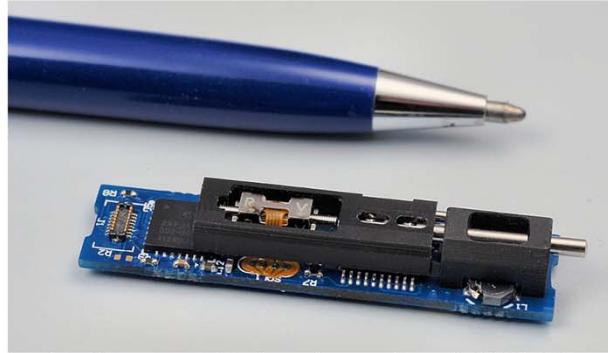
Alternate technologies – When motors get really small



**Brushless
DC motors**

<http://www.micromo.com/products/brushless-dc-motors/brushless-dc-micromotors>

Piezoelectric motors



<http://www.newscatech.com/press-releases/pr121107.php>

- As with most product situations, if an alternative technology exists, selection of device will be made based on a number of factors, such as performance, cost and availability.
- One small motor technology does not use copper wire, a steel flux guide or a magnet. This device is based on piezoelectric properties of the motor components that cause physical motion with the direct application of electric potential (voltage).

Agenda

- What makes rare earth elements special?
- Small applications
- **Powerful applications**

- Rare earth magnets are enabling materials.
- In addition to enabling very small devices, rare earth magnets are useful, even necessary, in some large and powerful applications.

Powerful Applications

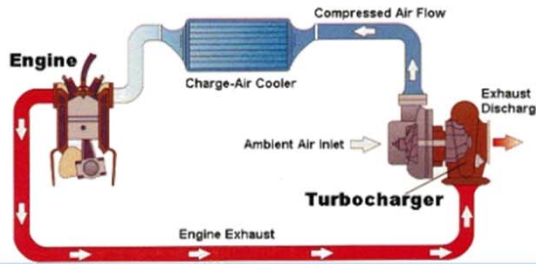
- Large, powerful systems
 - Motors >1,000 horsepower
 - Generators: wind power, tidal current
 - MRIs
- Power-dense systems
 - Aerospace generators
 - e-turbo chargers
 - Oil/gas drilling motors
- Size/weight/cost critical applications
 - Traction drive motors (transportation)



www.drs.com



F1 Hybrid Turbo



www.aeronamic.com

- Examples shown here range from large (MRIs) to very power-dense (electric turbo).
- One example, the aerospace generator (bottom right), is limited in size and weight, but requires high power output. Typical designs utilize SmCo magnets, thin gauge lamination steel and high temperature wire insulation. They are sealed devices and run-temperatures can approach 220 °C.
- Another power dense application is the newly developed electric turbo drive (e-Turbo) which uses an ultra-high performance motor to temporarily power a turbo boost on car and truck engines. Standard systems are powered off exhaust gases. When acceleration is suddenly demanded, there is not enough exhaust gas pressure to provide the turbo boost. This momentary lag is mitigated with a fast starting, high power output electric motor.
- Let's examine some more large and powerful applications.

Electric motor driven naval vessels

Photo # NH 92199 USS Jupiter, prior to World War I

Jupiter

Published March 19, 2011. The First U.S. Naval Ship Powered by Electric Motors

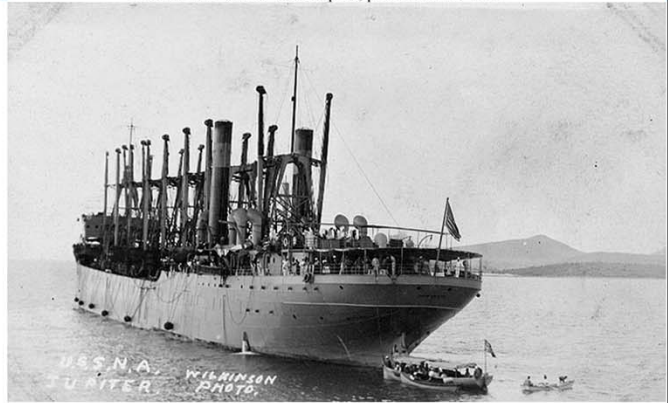
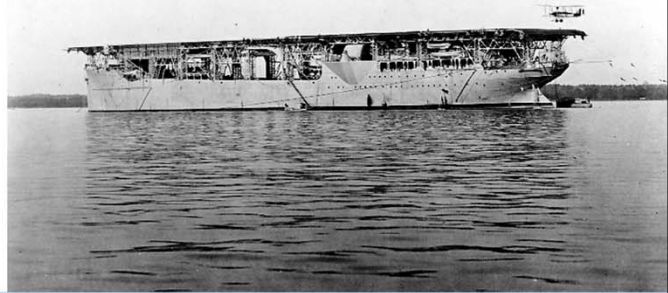


Photo # NH 63545 Aeromarine 39-B landing on USS Langley, circa 1922

She was later converted into the first aircraft carrier (see image below) and renamed the USS Langley.



- The first electric motor powered (USA) navy vessel dates back to ~1911, so the concept is not new.

Electric motor driven naval vessels

Characteristics

Length	600 ft	Displacement	14,564 LT
Beam	80.7 ft	Installed Power	78 MW
Draft	27.6 ft	Crew Size	142 (incl. Aviation detachment)
Speed	30 kt		

Sensors

- Dual Band Radar
- S-Band VSR
- X-Band MFR
- HF & MF Bow Sonar Arrays
- Multi-Function Towed Array
- EO/IR System
- ES System

Superstructure
Composite structure

Aviation
MH60R and (3) VTUAVs
(Capacity for 2 MH 60Rs)

Integrated Power System

- (2) Main Turbine Generators (MTG)
- (2) Auxiliary Turbine Generators (ATG)
- (2) 34.6 MW Advanced Induction Motors
- Integrated Fight Through Power

Boats
(2) 7m RHIBs
(sized for (2) 11m RHIBs)

Weapons

- (80) Advanced vertical launch cells for Tomahawk, ESSM, Standard Missile
- (2) AGS 155 mm guns
- (600) 155 mm rounds
- (2) 57 mm Close In Guns
- Torpedo Defense (Space Reservation)
- Anti-Terrorism (Space Reservation)

Hull
Wave-piercing tumblehome

“...the Zumwalt’s propellers and drive shafts are turned by electric motors, rather than being directly attached to combustion engines. Such electric-drive systems, while a rarity for the U.S. Navy, have long been standard on big ships. What’s new and different about the one on the Zumwalt is that it’s flexible enough to propel the ship, fire railguns or directed-energy weapons (should these eventually be deployed), or both at the same time.”

<http://cleantechnica.com/2013/11/05/us-navy-launches-new-all-electric-zumwalt-destroyer/>

- For the past few years, design and construction has taken place on the US Navy’s Zumwalt destroyer which is driven by an “advanced induction motor” – no permanent magnets.

Electric motor drives for submarines

An Integrated Electric Power System:

the **NEXT STEP**

by ADM Frank L. "Skip" Bowman, USN



Two early nuclear-powered electric drive submarines: USS Tullibee (SSN-597, top), and USS Glenard P Lipscomb (SSN-685, bottom). Immature electric-drive technology in the 1960s and 1970s limited the performance of these boats in comparison to their mechanical-drive counterparts.



http://www.navy.mil/navydata/cno/n87/usw/issue_9/power_system.html

Advantages for Submarines

Stealth Enhancement: Stealth is the single most important operational advantage of any submarine. It permits use of the submarine in politically sensitive or militarily contested areas to gain and sustain access for the rest of the battle force. It creates uncertainty, fear, and disproportionate diversion of resources on the part of the adversary. It allows submarines to be used in many covert and non-provocative, intelligence collecting operations. An integrated electric power system will enable necessary changes to key propulsion plant parameters, afford more flexibility in equipment selection and location, and permit use of other quieting methods. Electric drive opens the door to new methods for improving stealth by leveraging state-of-the-art technology with good future growth potential.

- However, Ohio Class replacement submarines will use electric motor drives.
- Unlike these earlier electric motor driven submarines, newer technologies have greatly improved performance and efficiency.
- The low noise signature is a compelling reason to pursue electric drive technology.

Electric Motors for ship propulsion

Specifications: 36.5 MW PM Machine for Electric Ship Propulsion

Performance	
Output	50,000 HP (36.5 MW)
Speed	1-127 RPM
Torque	>2 M ft. lbs. (2.7M Nm)
Motor Efficiency	97.5%
Mechanical	
Motor Length	202 inches (5.1 meters)
Motor Width	214 inches (5.4 meters)
Motor Height	209 inches (5.3 meters)
Motor Weight	280,000 lbs. (127 tonnes, 127,000 kg)
Cooling Method	Fresh water
Electrical	
Voltage	1450 VAC
Phases	Doubly-fed, 3-phase
Insulation Class	R (220° C)
Temperature Rise	H (180° C)



<http://www.drs.com/index.aspx>

- One of the possible drive motors is shown here.
- DRS specializes in large motor systems.

Mid-size hybrid drive system

Hybrid Electric Ship Propulsion Motors/Generators



Highlights

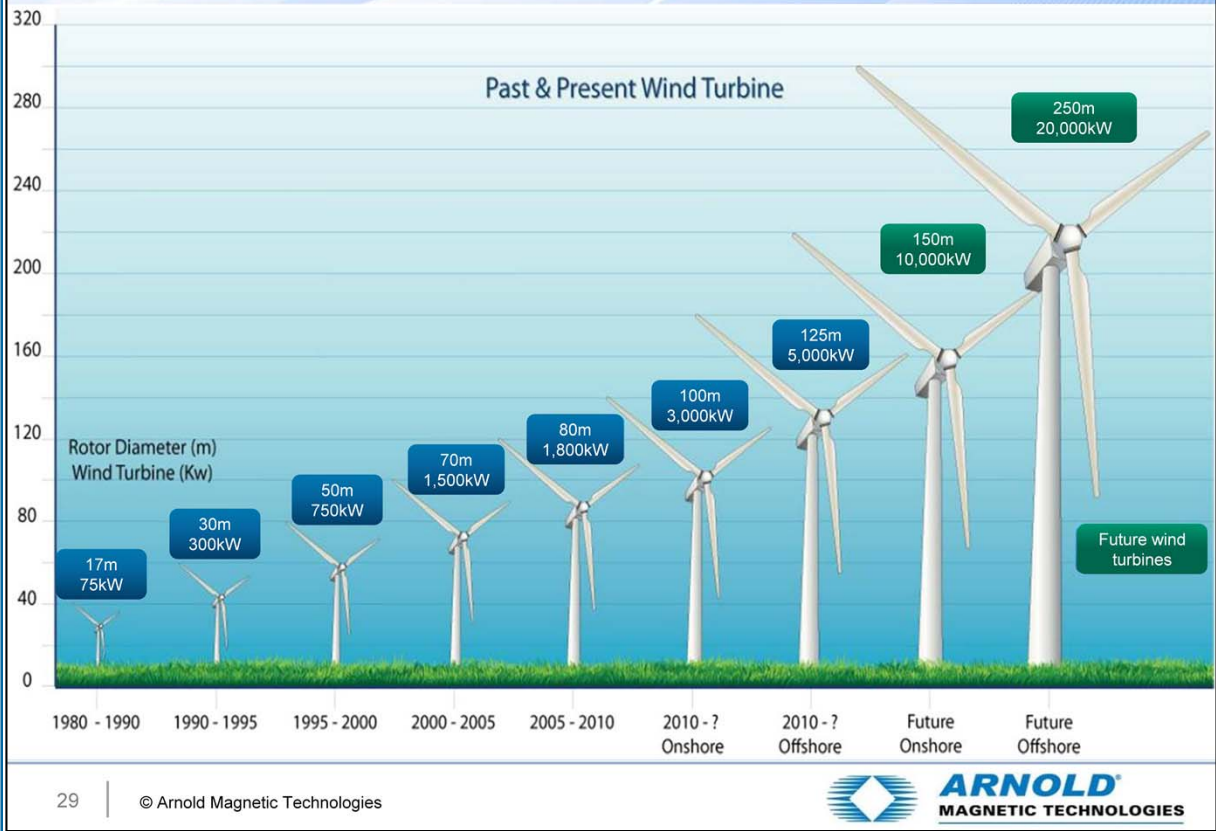
- Space & weight benefits - High torque in a compact package means minimal engine room impact
- Fuel savings - Using PM power at low speeds can save thousands of barrels of fuel
- Life cycle costs - Reduced gas turbine or diesel motor operation time saves on maintenance costs
- Easy integration and minimum impact to engine room
- DRS PM machines provide a mature technology: evolved from a lineage of fielded permanent magnet motors with a history of performance in extreme operating conditions

<http://www.drs.com/index.aspx>

- An intermediate size motor is available from DRS for hybrid ship drive systems.
- Both this and the previous motor are dependent upon rare earth magnets.

Wind Power

<http://www.sbc.slb.com/SBCInstitute/Publications/~media/Images/SBC%20Energy%20Institute/Wind/Typical%20Commercial%20Wind%20Turbine%20Growth%20in%20Size.ashx>



- In an earlier presentation, we learned about wind power as a renewable, “green” technology for producing electricity.
- The number of and size of installations continues to grow.

Size of wind towers



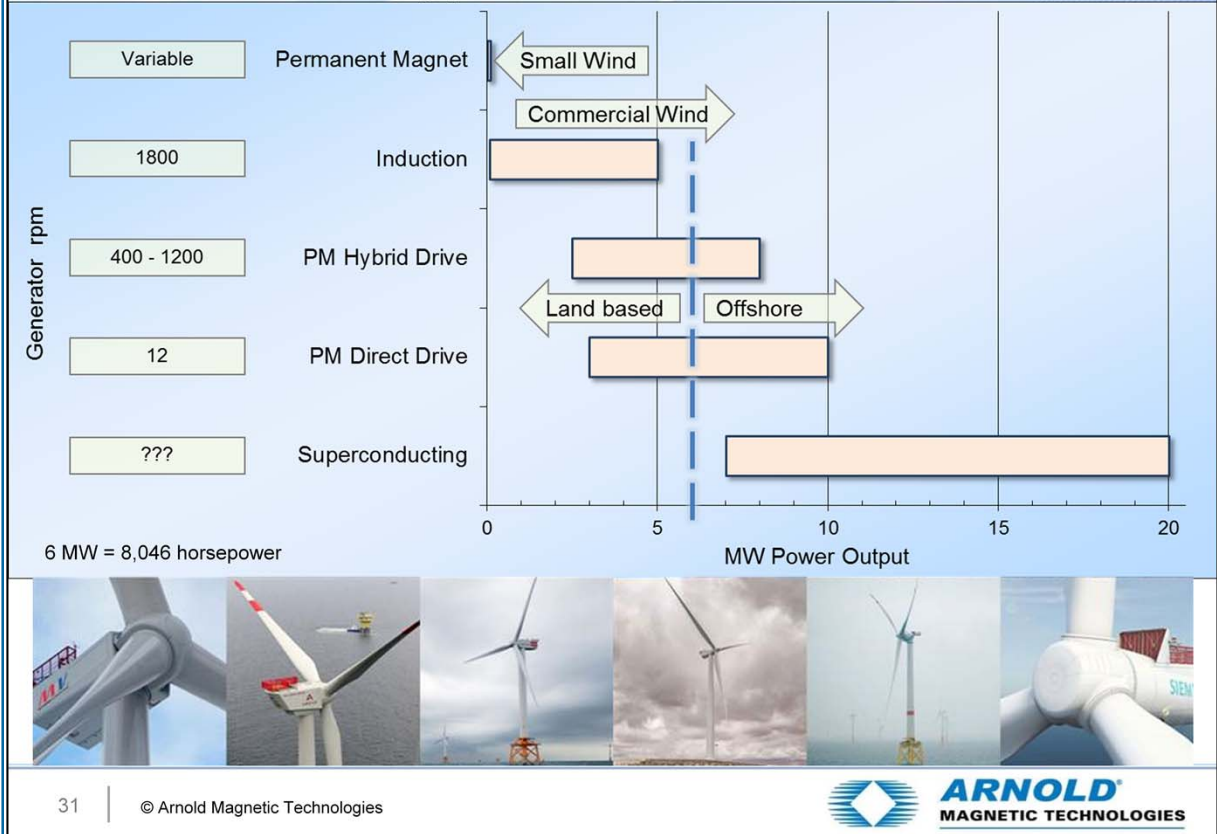
The SeaTitan™ 10MW wind turbine designed by American energy technologies company AMSC is currently the biggest wind turbine in the world. The direct-drive turbine, with 190m rotor diameter, has a rated power capacity of 10MW and hub height of 125m.

The turbine design incorporates a high temperature superconductor (HTS) generator with a speed of 10rpm making it much smaller and lighter than a conventional wind turbine generator.

AMSC started developing the turbine in 2010 and completed the design in 2012. The generator for the wind turbine has been tested by the US Navy in harsh offshore conditions. AMSC is currently negotiating with potential partners to build and commercialize the SeaTitan 10MW wind turbines.

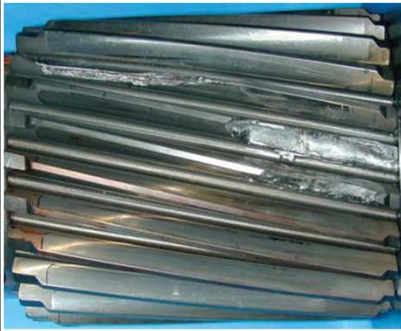
- Current commercial scale power generating systems are large!
- As size increases, alternate technologies, such as the one illustrated on the right – a superconducting generator – may be necessary.

Wind Power - Types and Locations



- Larger capacity is more efficient to install and operate – this is especially true for off-shore installations.
- Why move from an induction generator to permanent magnet (PM) generator? Smaller size, lower weight, reduced or eliminated gear box, larger power output potential...

Why NdFeB Magnets – gearbox wear and failure



- ...and lower maintenance.
- Permanent magnet generators permit reducing the gear box to 2-stage (from 3) or eliminating it altogether in direct drive generators.

Offshore Turbine development

TOP TEN OFFSHORE TURBINES *The wind industry's biggest, heaviest and most expensive products compared and contrasted*

Model	IEC class	Power rating	Rotor diameter	Drive system	Noteworthy
MHI-Vestas V164-8.0MW (Denmark)	S	8MW	164m	MSG, PMG	Clever combination of evolutionary and innovative design features; flanged tube-shaped drivetrain, favourable 500-tonne head mass
Ming Yang SCD 6.0 (China)	IIB	6MW	140m	MSG, PMG	Innovative two-blade downwind turbine with compact semi-integrated drivetrain and single rotor bearing, focused at typhoon-prone markets
Siemens SWT-6.0-154 (Germany)	I	6MW	154m	DD, PMG	Single rotor bearing; largest rotor diameter in 6MW class, converter and transformer in nacelle; favourable head mass
Alstom Haliade 150-6MW (France)	I	6MW	150.8m	DD, PMG	Stationary main shaft (pin); "pure torque" principle decouples rotor-bending moments and generator drive torque
Siemens SWT-4.0-130 (Germany)	I	4MW	130m	HSG, IG	Evolutionary development and optimisation of SWT-3.6-120 model, which has been the offshore market leader for several years
Senvion 6.2M152 (Germany)	S	6.15MW	152m	HSG, DFIG	Developed from pioneering 5MW turbine introduced in 2004; prototype of more powerful model with longer blades installed in 2014
Areva M5000-135 (France)	S	5MW	135m	MSG, PMG	Extensive upgrade of M5000-116 introduced in 2004; features clever pioneering low-speed hybrid-drive design
Gamesa G128-5.0MW (Spain)	IB	5MW	128m	MSG, PMG	Pioneer tube-type drivetrain; builds on 2009's G128-4.5MW platform; new variant with 132m rotor diameter has been announced
Hyundai HQ5500/140 (South Korea)	I	5.5MW	140m	HSG, PMG	Sister product of Dongfang 5.5MW, co-developed with AMSC; Sinovel SL5000/SL6000 uses same AMSC product platform
Goldwind GW 6MW (China)	I	6MW	150m	DD, PMG	Specification not verified; initial design basis 5MW power rating

BDFIG Brushless doubly-fed induction generator
CGFRE Carbon & glass-fibre reinforced epoxy
DD Direct drive
DFIG Doubly-fed induction generator
EESG Electrically excited synchronous generator

GFRE Glass-fibre reinforced epoxy
HH Hub height
HSG/LSG High-speed geared/Low-speed geared
IG Induction generator
MSG medium-speed geared

PMG permanent magnet generator
PCVS Pitch-controlled variable-speed

Source: <http://www.windpowermonthly.com/10-biggest-turbines>

- The largest generators have been designed for use off-shore.
- Of the current top ten generators, 8 are PM type.
- The largest to-date is the MHI-Vestas 8.0 MW generator.

Tidal Power Generation



Atlantis AK1000, Scotland
<http://www.lockheedmartin.com/us/products/wave-tidal-energy.html>
...and
<http://atlantisresourcesitd.com/>

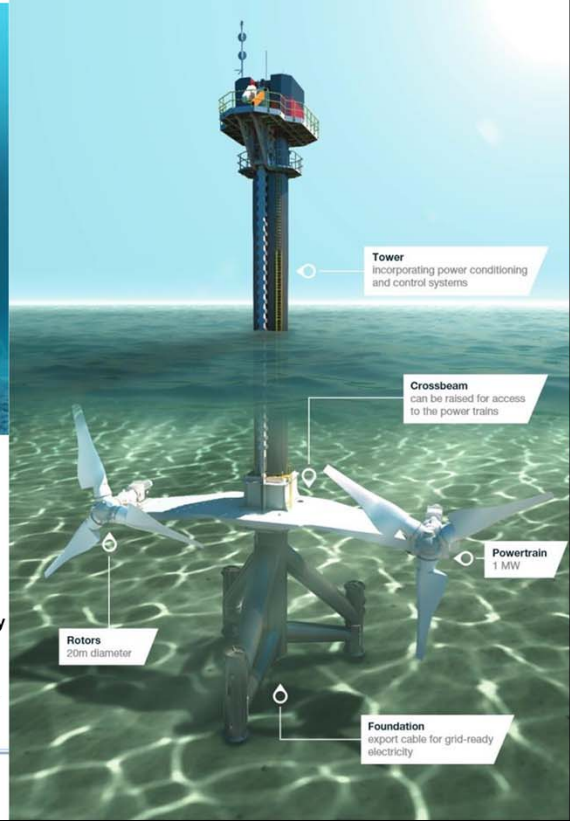


<http://inhabitat.com/worlds-first-tidal-farm-successfully-installs-100-foot-subsea-turbine/>

“SeaGen is the world's first large scale commercial tidal stream generator. It was four times more powerful than any other tidal stream generator in the world at the time of installation.” - Wikipedia

http://www.marineturbines.com/sites/default/files/FINAL_MCT_Product_Brochure_8pp_Seagen_UPDATE_E_HIRes.pdf

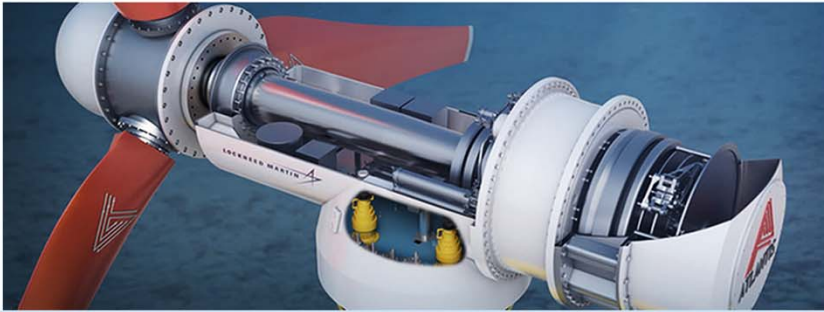
info-mct.energy@siemens.com



- Numerous companies are developing, testing and installing power generating facilities that depend on tidal current or wave motion.
- Water is far more dense than air, so higher output capacity is possible with smaller swept-area devices.
- The Atlantis AK1000 is pictured here prior to installation and now testing is completed.
- SeaGen is a product of MCT which is now a wholly owned subsidiary of Siemens.

Tidal Power Generation

- The AR1500 is the latest tidal power turbine system under development at Atlantis
- Rated capacity of 1.5MW at 3.0 m/s
- Design completed by Lockheed Martin Corporation during 2014
- AR1500 system will have pitching blades and full nacelle yaw rotation capability to facilitate operation in highly energetic deployment locations
- This turbine represents best in class, with features such as:
 - Variable pitch rotor blades for maximum energy capture
 - Integrated gearbox and bearing-less **permanent magnet generator**
 - Fast deployment and connection system; nacelle deployment less than 90 minutes
 - 360 degree yaw capacity and survival lock system
 - Multiple, fully redundant electrical systems for long term operation subsea
- The first unit is due for pre-delivery on-shore acceptance testing at the end of 2015.



<http://atlantisresourcesltd.com/turbines/ar-series/ar1500series.html>

- The first Atlantis Resources 1.5 MW generator is scheduled for delivery at the end of 2015.
- As noted, it was designed by Lockheed-Martin.

Wave motion generators

GOOD BUOY
 Much of the work done by Ocean Power Technologies' wave generator happens below the sea. As the yellow buoy bobs in the waves, the motion pushes a piston-like device up and down to drive a generator, which produces electricity. Each PowerBuoy can generate 150 kilowatts of electricity.

Labels: Float, Spar, Heave plate, Undersea substation, Cable from other PowerBuoys, Cable to shore.

Riding the Waves
 Developed by entrepreneurs hoping to harness the ocean's energy, these snake-like machines undulate on the surface as waves pass, using hydraulic equipment to convert wave energy into electricity.

Labels: Power modules, PELAMIS' WAVE ENERGY CONVERTER, WAVE FARM, Mooring lines hold the network of machines together in formation.

How It Works
HEAVE Side view: The motion caused by a wave swell is resisted by hydraulic rams.
SWAY Top view: Joints on the opposite side of the power module allow for a perpendicular sway motion.

POWER CONVERSION MODULE
 Hydraulic rams pump high-pressure fluid into chambers that feed the fluid to a motor. The motor drives a generator to create electricity.

Labels: Motor, Generator, Collection chamber, Hydraulic rams, Sway, Heave, Relaying the energy.

Source: Ocean Power Delivery, GRAHAM ROBERTS, The New York Times

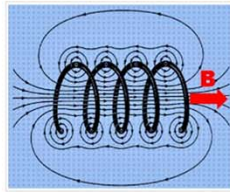
<http://www.emec.org.uk/about-us/wave-clients/pelamis-wave-power/>

Also see: http://hydropower.inl.gov/hydrokinetic_wave/pdfs/day1/09_heavesurge_wave_devices.pdf

- In addition to the previously shown “propeller-type” generator, numerous other methods have and are being investigated to use movement of water to power electric generators including long undulating segments and bobbing buoys.
- These technologies are still immature, but likely to utilize rare earth permanent magnets due to the slow movement of wave motion.



GE Signa 1.5T superconducting scanner

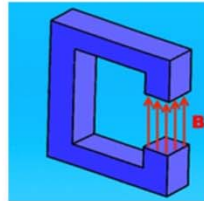


Magnetic field created by solenoid

Closed bore (cylindrical) configuration with superconducting solenoidal design. The coils are bathed in liquid helium allowing a stable, homogeneous field to be created, typically 1T and higher.



Hitachi Aperto 0.4T permanent magnet scanner

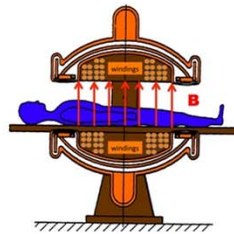


C-shaped permanent magnet

Most **open bore** scanners utilize permanent magnets in a C-shaped or horseshoe configuration. These operate at field strengths typically ranging from 0.2T to 0.7T.



Philips Panorama 1.0 T HFO superconducting scanner



Dipolar electromagnet design

The third design is a **dipolar electromagnet** configuration with coils on either side of the patient. These coils can be superconductive or resistive and range from 0.5T to 1.2T.

- Magnetic Resonance Imaging or MRI is a well-developed technology using interaction between a strong, static magnetic field and a modulating frequency wave generator. The combination of fields act differently on the human body depending on tissue type and density.
- The static magnetic field can be generated by permanent magnet, by a superconducting coil or by a conventional resistive coil.
- Size of the magnet structure depends on whether the scanner is “full-body” or designed to look at smaller sections of the body, such as an arm or leg.
- Early superconducting structures were shaped like a solenoid – a hollow cylinder. Sliding into the cylinder has caused claustrophobia and anxiety.
- To avoid these negative effects, newer designs are of the open type as in the second and third illustration on the slide.
- When permanent magnets are used, the most powerful permanent magnet possible is utilized. Magnet weight in the full body scanner can be 3 tons or more and is constructed of numerous large blocks of magnet, precision ground for close assembly and then “tuned” to provide a precisely uniform field.

SC versus PM

	Current Models	Discontinued Models	Totals
SC (superconducting)	27	15	42
PM (permanent magnet)	22	17	39
Totals	49	32	

The Four Leading Manufacturers

Current Models	GE	Hitachi	Philips	Siemens
SC (superconducting)	6	2	4	4
PM (permanent magnet)	0	1	0	1

<http://mri-q.com/brands-of-scanners.html>

- The maximum field strength in the opening of the MRI from strong NdFeB permanent magnets is about 0.7 Tesla (7,000 Gauss).
- Superconducting MRIs can produce fields 5 or more times stronger resulting in stronger signal output and clearer images.
- The cost of operating a superconducting MRI is higher than a PM type.
- However, the field of the PM can not be turned off and represents a danger during installation, use and transportation.
- The trend appears to be away from price-volatile NdFeB and to high-performing superconducting MRIs.

Directional drilling

Two examples and a cut-away



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© Arnold Magnetic Technologies

M

BRUSHLESS SERVO MOTOR

Customized to meet rigorous requirements (e.g. speeds up to 10,000 rpm) and torque up to 170 Nm) and deliver the long service life that meets the challenges of downhole HTHP drilling.



GEAR BOX

Moog will choose the correct integrated solution that meets the application needs, from available designs to an array of custom-designed multistage compound and conventional planetary gearboxes.



BALL SCREW

Moog screw technologies provide high efficiency and maximum load capacity, providing the highest power density in demanding applications.

ALTERNATOR

Moog application-specific alternators deliver reliable power and are designed to customer specifications for speed, voltage and load.

G

DOWNHOLE MOTOR CONTROLLER

Moog provides ruggedly designed motor controllers to operate in hostile downhole environments, capable of reliable torque, velocity or position control.



RESOLVER

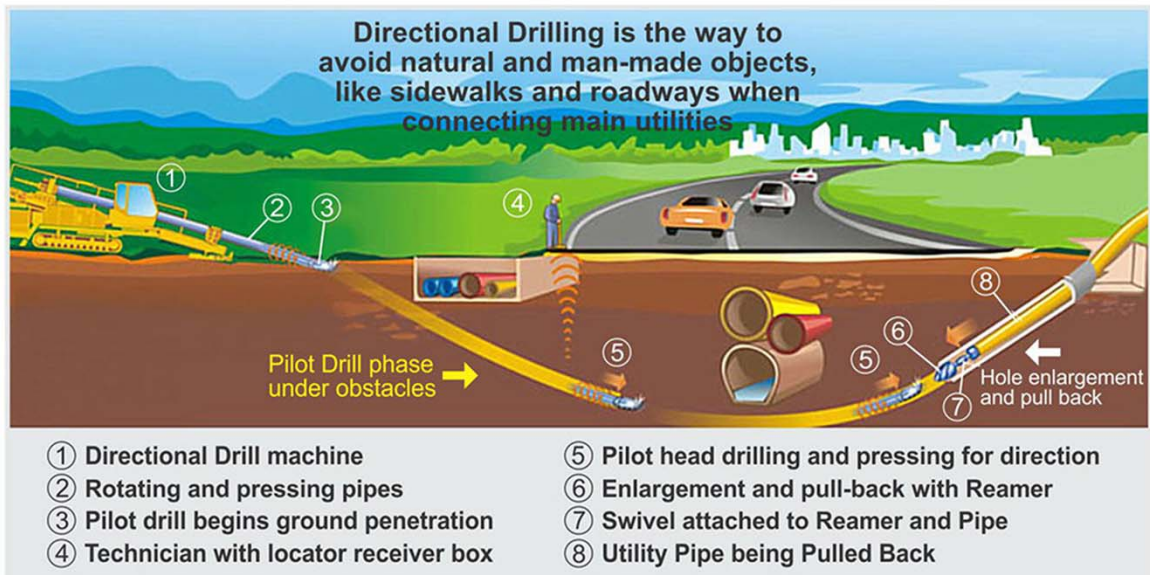
Providing reliable position and velocity feedback signals critical for controlling servo motors and actuators. They contain no internal electronics or optics, and are qualified for your HTHP environments.



www.moog.com/literature/ICD/Moog-OilAndGas-DownholeSolutions-Overview-en.pdf

- Directional drilling utilizes one or more PM motors to drive the drill bit and force it in the desired direction.
- Directional drilling is the technology behind “Unconventional well drilling” also called high volume hydro-fracking – or just plain “fracking”.

Directional drilling – more than oil & gas



- Directional drilling can and is being used for more than oil & gas drilling.
- It aids installation of utilities by avoiding obstacles – drilling under roads, under stream beds, under or around urban underground structures including previously installed utility services, and to avoid disturbing established lawns, trees, driveways, etc.

Wrapping it up



- Rare earth elements have unique chemical structures that make them excellent additions to iron and cobalt-containing magnet alloys
- The high energy of rare earth magnets makes them
 - Required for very small devices that benefit from high output
 - Required for large applications in order to minimize size and weight

