ARPA-E Rare Earth and Critical Materials Workshop
Breakout Session: Magnetics

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Rare Earths in Magnets

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Pacific Northwest National Laboratory

ARPA-E Workshop, Dec 06, 2010
Permanent Magnet and RE Consumption

Applications of Permanent Magnets

<table>
<thead>
<tr>
<th>Category</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motors</td>
<td>Alternator, generator, starter, stepper motors</td>
</tr>
<tr>
<td>Acoustic Device</td>
<td>Loudspeakers, headphones, microphones, pick-ups</td>
</tr>
<tr>
<td>Magneto-Mechanical</td>
<td>Holdings, magnetic couplings, bearings, magnetic separation, actuators</td>
</tr>
<tr>
<td>IT, Telecom,</td>
<td>Data storage, switches, sensors, traveling wave guide, transducers</td>
</tr>
<tr>
<td>Measurement/Control</td>
<td></td>
</tr>
<tr>
<td>Medical</td>
<td>MRI tomography</td>
</tr>
</tbody>
</table>

Global RE Oxide Consumption (2008)

Background - Commercial State-of-the-Art Permanent Magnets – Fe$_{14}$Nd$_2$B

- How did we get here?
  - Result of cost and limited world supply of cobalt (Co-RE magnets)
- Attractive properties which must be equaled or exceeded:
  - High coercive field
  - Large magnetization

Application limits: Coercivity of Fe$_{14}$Nd$_2$B rapidly deteriorates when temperature exceed 80 °C.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Function</th>
<th>Desired Property</th>
<th>Weakness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Nd</td>
<td>Hard phase</td>
<td>High coercivity</td>
<td>Low saturation</td>
</tr>
<tr>
<td>2 Fe</td>
<td>Soft phase</td>
<td>High saturation</td>
<td>Low coercivity</td>
</tr>
</tbody>
</table>
Potential R&D Needs/Directions

- Alloy and microstructural design to substitute rare earth function
- Create strong textural/uniaxial anisotropy
- Achieve stable nanocrystalline structure
- Develop low temperature consolidation methods
- Fabrication technology amenable for bulk or thick cross-sections
- Molding/shaping technology to achieve optimal magnet product
- High $B_r$, $H_c$; Increase $T_c$
Approaches to New Generation of Permanent Magnetic Materials & Non-Rare Earth Containing Electric Machines

Frank Johnson, Christina Chen, Steve Duclos, Nathan Forbes, Ayman El-Refaie, and Kiruba Haran

GE Global Research
Niskayuna, NY 12309
Where We Are For New Generation of Permanent Magnetic Materials

- The concept of a nanocomposite consisting of exchange-coupled magnetic hard & soft phases was established in the early 1990s: Thin films (pseudo-2D) had some successes.
- Major challenges for bulk nanocomposites (3D) are unsolved, including the difficulty making hard phase nano-precursor with high $H_{ci}$.
- Nano-precursor of hard phase was made with SmCo$_5$ nanoflakes – $H_{ci}$ up to 21 kOe.
- Novel technologies are needed to process the nanocomposite.
- New magnetic phases, especially the non-rare earth permanent magnets, are needed for our energy strategy.

8. Wang, Li, Rong, and J.P. Liu, Nanotechnology 18, 465701 (2007).
Transformational nanostructured permanent magnets

Nanocomposite phases:
NdFeB: (Hard)
  \( H_c = 10,000 - 12,000 \, \text{Oe} \)
  \( B_r = 11-15 \, \text{kG} \)
Fe: (Soft)
  \( H_c = 0.05 \, \text{Oe} \)
  \( B_r = \sim 22 \, \text{kG} \)

Core@Shell Hard/Soft Exchange Spring Coupled Nanocomposite Magnets with:
• 80 MGOe (vs 59 MGOe NdFeB)
• 59 MGOe with 80% less rare earth

Nanocomposite exchange spring coupled permanent magnets with high energy product and less rare earths
Other Possible Approaches:

1. Non-Rare Earth Bulk Permanent Magnets

- Bulk alloys of Fe$_{59.75}$Pt$_{39.5}$Nb$_{0.75}$ and its modification have good magnetic properties reaching up to 4.5 kOe of $H_{ci}$ and 21 MGOe of $(BH)_{max}$ $^{[1,2]}$
- The cost of Pt limits its applications.
- However, many other compositions without such expensive component are also possible if we set our minds to search and explore.

1. Q.F. Xiao, E. Bruck, Z.D. Zhang, F.R. de Boer, and K.H.J. Buschow
   J. MMM, 280 (2004) 381-390
2. Private communication to and tested by C.H. Chen (2009)
Abundant Elements have the Source of Magnetic Moment: Moving Electric Charge

Extensive exploring the potential magnetic compounds in nano-structured form will benefit the discovery of new generation permanent magnets.

Bohr Magneton Number

3d transition metal

4d transition metal

4f transition metal

5d transition metal

La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb

Bohr Magneton Number

0 1 2 3 4 5 6

Sc Ti V Cr Mn Fe Co Ni Cu Zn

Y Zr Nb Mo Tc Ru Rh Pb Ag Cd

La Gd Tb Lu Hf Ta W Re Os Ir Pt Au Hg

GE imagination at work
Other Possible Approaches:

1. Non-Rare Earth Permanent Magnets

- **Alnico**: Commercial available up to 11.5 MGOe\(^1\). Possible Hci > 6 kOe with nano-grains \(^2\), if anisotropic nanograin can be made by novel technology, 25 MGOe is possible.

- **Fe-Cr-Co**: \(B_r\) up to 12.7kG, Hci up to 0.7kOe \(^3\), composition modification may enhance anisotropy, 30 MGOe would not be impossible.

- **Mn-Al-C**: \(B_r\) of 8 kG was obtained \(^4\). Mn has high Bohr Magneton. Other Mn compounds?

- Search for high coercivity non-rare earth new compounds with enhanced crystalline anisotropy.

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Other Possible Approaches:

2. Low-Rare-Earth Permanent Magnets

- Surfactant assisted milling For the hard phase nano-precursor with full crystallinity: SmCo$_5$ [7] or others

- Novel technologies with the capability to make fully dense nanocomposites of hard and soft phases

- Advanced magnet process for reducing the critical heavy rare earth elements: Non-Dy-containing NdFeB with (BH)$_{\text{max}} > 50$ MGOe and H$_{\text{ci}} > 28$ kOe (by limiting the grain size to $\sim 1 \ \mu$m [6])

- Search for new phases with lower rare earth contents and high anisotropy

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Non-Rare Earth Containing Electric Machines

- **Non-Rare Earth PM Machines**
  - Advanced Machine Topologies
  - Advanced Materials Development
  - Advanced Thermal Management
  - Advanced Control Concepts

- **Superconducting Machines**
  - Advanced Machine Topologies to enable use of low cost superconductors
  - Increased reliability of cryo-system for industrial and renewable energy applications
  - Advanced Materials with better mechanical properties, high Tc
The Magnetic Material Challenge

Steve Constantinides
ARPA-E Workshop
Rare Earth and Critical Materials
December 6, 2010 in Arlington, VA
• These are two interesting photographs.
• The car is a Tesla. While hybrids and full electric vehicles mostly use permanent magnet motors, the Tesla uses an induction motor, that is, the traction motor does not contain permanent magnets. However, it does contain considerable soft magnetic steel.
• Large, commercial wind tower generators used wound field (induction) designs until “generation-4” which uses neo permanent magnets. Off-shore generators use permanent magnets to minimize maintenance.
• Lesson: the market is dynamic, and when given time, adjusts to changes in technology, material availability, installation cost, maintenance cost, and market pricing of production output.
Permanent Magnet Figures of Merit

- **Br**, Residual Induction: Magnetic strength
- **Hci** (H_{cj}), Intrinsic Coercivity: Resistance to Demagnetization
- **BH**, Energy Product: A measure of the energy in the magnet in the magnetic circuit
  - BHmax is the maximum energy product
  - BHmax is a key figure of merit for motors and generators
- “**Straight Line**”: Describes the shape of the Normal demagnetization curve in the second quadrant
  - Also called “square loop” when the intrinsic curve is referenced
  - Ferrite, Neo and SmCo magnets are considered straight line materials

- Industry has become spoiled by “straight line” (“square loop”) materials. We design devices to use these better material options.
- Motors and generators benefit from a combination of large energy product and high resistance to demagnetization.
- The two materials that supply both of these are SmCo and Neo and Neo sales have now exceeded 55% of all PM sales on a dollar-basis.
- But on a weight-basis, the inexpensive ferrite magnets represent more than 85% of permanent magnets sold – despite that their energy product is 10% of the Neo’s.
A typical demag curve shows what these characteristics represent on the 2\textsuperscript{nd} quadrant of a magnetic hysteresis loop.
Recent History of Permanent Magnets

<table>
<thead>
<tr>
<th>Material</th>
<th>First Reported</th>
<th>BH(max)</th>
<th>Hci</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remalloy</td>
<td>1931</td>
<td>1.1</td>
<td>210</td>
</tr>
<tr>
<td>Alnico</td>
<td>1931</td>
<td>1.4</td>
<td>490</td>
</tr>
<tr>
<td>PtCo</td>
<td>1936</td>
<td>7.5</td>
<td>4,300</td>
</tr>
<tr>
<td>Cunife</td>
<td>1937</td>
<td>1.8</td>
<td>590</td>
</tr>
<tr>
<td>Cunico</td>
<td>1938</td>
<td>1.0</td>
<td>450</td>
</tr>
<tr>
<td>Alnico, field treated</td>
<td>1938</td>
<td>5.5</td>
<td>640</td>
</tr>
<tr>
<td>Vicalloy</td>
<td>1940</td>
<td>3.0</td>
<td>450</td>
</tr>
<tr>
<td>Alnico, DG</td>
<td>1948</td>
<td>6.5</td>
<td>680</td>
</tr>
<tr>
<td>Ferrite, isotropic</td>
<td>1952</td>
<td>1.0</td>
<td>1,800</td>
</tr>
<tr>
<td>Ferrite, anisotropic</td>
<td>1954</td>
<td>3.6</td>
<td>2,200</td>
</tr>
<tr>
<td>Lodex®</td>
<td>1955</td>
<td>3.5</td>
<td>940</td>
</tr>
<tr>
<td>Alnico 9</td>
<td>1956</td>
<td>9.2</td>
<td>1,500</td>
</tr>
<tr>
<td>RECo5</td>
<td>1966</td>
<td>16.0</td>
<td>20,000</td>
</tr>
<tr>
<td>RECo5</td>
<td>1970</td>
<td>19.0</td>
<td>25,000</td>
</tr>
<tr>
<td>RE₂(Co,Fe,Zr,Cu)₁₇</td>
<td>1976</td>
<td>32.0</td>
<td>25,000</td>
</tr>
<tr>
<td>RE₂TM₄B</td>
<td>1984</td>
<td>26.0</td>
<td>25,000</td>
</tr>
<tr>
<td>RE₂TM₄B</td>
<td>2010</td>
<td>30.0</td>
<td>35,000</td>
</tr>
<tr>
<td>RE₂TM₄B</td>
<td>2010</td>
<td>52.0</td>
<td>11,000</td>
</tr>
</tbody>
</table>

• The 20th century saw rapid and impressive improvements in strength of PM materials and in their resistance to demagnetization.
• A chart presentation of the energy product emphasizes the improvements.
• All the materials presented here are still used in selected applications where their combination of price and performance is superior to the others.
• For example, even though ferrite magnets are far weaker than the rare earths, they continue to dominate in sales on a weight basis representing 85% + of permanent magnets sold in the free world.
• However, the focus on device low weight and small size has driven usage of rare earth magnets so that neo magnets now represent over half all magnet sales on a dollar basis.
Relative Magnet Sizes

Relative magnet size and shape to generate 1000 gauss at 5 mm from the pole face of the magnet.

- These improvements in energy product can be pictorially demonstrated.
- Wherever small size and low weight are a preferred, rare earth magnets are necessary.
- System size depends also on the steel flux path. So a larger, weaker magnet requires a larger structure which requires more steel.
• Temperature of the application also puts constraints on material choices.
• Ferrite, a workhorse of our society between -40 and 150 °C, is barely usable at higher temperatures.
• By 150 °C ferrite has lost 25% of the flux output observed at room temperature.
• And to have Neo magnets perform satisfactorily above 80 °C means using the difficult-to-obtain and expensive element Dysprosium.
• A, even more important issue than availability of neodymium is the current “shortage” of dysprosium.
• As produced from existing mines dysprosium is about 3% of the rare earths.
• However, in terms of total output, dysprosium is less than 1% of all rare earths.
Rare earths have been mined and made commercially available for over half a century with one of the primary sources having been Molycorp’s Mt. Pass mine in California.

The data presented here (through 2009) has been collected and tabulated by USGS.

Between 1998 and 2001, Molycorp greatly reduced its processing output due to low market prices and environmental issues at the mine.

China now supplies 97%+ of the rare earths in the global market.

Looking at 2012 to 2015, we see a resurgence of the Molycorp production (green bar at the top) and the addition of suppliers in Australia, Canada and South Africa.

Estimates of demand for REO in 2014 range from 160 to over 200 thousand tons with a consensus developing at about 185 thousand.

This chart assumes that China will continue to produce at 2009 levels though they have stated they will increase output, if necessary, to prevent disruption of the market.

China has also announced the establishment of a stockpile to bridge a period of rebuilding of the concentration/separation facilities to be more environmentally friendly and to operate at a higher yield.

This chart also assumes that new facilities will come on-stream as advertised by the respective companies. That depends in large part on permitting and on availability of financing - - these are very capital intense business models.

The cost is mainly in the separation facilities and is between $12 and $25 million per thousand tons per year (tpa) output of REO.
### Supply – Mining Company Projections

- **Lynas – Mt. Weld**
  - 22,000 tpa REO, 2012
- **Molycorp – Mountain Pass**
  - 19,000 tpa REO, 2012; may ramp to 40,000 tpa
- **Arafura – Nolans**
  - 20,000 tpa REO, 2015
- **GWMG – Steenkampskaal**
  - 2,700 tpa REO, 2013
- **Magnequench – Brazil in mine**
  - 5,000 tpa REO, TBD
- **Avalon – Nechalacho (Canada)**
  - 10,000 tpa REO, 2015
- **Others**
  - Viet Nam (Dong Pao)
  - Kazakhstan (Kazatomprom)
  - Rare Element Resources (Wyoming)
  - GWMG (Douglas River, Canada) TBD

**ROW sources are finally nearing production and are expected to fill the ROW needs as shown on the previous chart.**
• The process for establishing a rare earth element supply is at least 10 years long and can take up to 20 years.
• As defined by Dudley Kingsnorth, it is a 10-step process.
• And funding the beneficiation is very capital intensive ranging from $15,000 to $25,000 per ton per year of REO output.
• Lynas’ investment will total almost $600 million to produce 22,000 tpa REO.
• Molycorp’s investment is to be $400-450 million for 19,000 tpa TEO.
• With the recent increase in pricing of rare earth elements, numerous mining activities have started.
• This slide shows mine locations and those named have promising short or mid-term performance expectations.
• As a rule, when the ore is milled, concentrated and separated, all of the elements present in the ore are extracted.

• It is financially inconvenient to be unable to sell all of the materials which are refined from the ore.

• Demand imbalance will force price rationalization: the most utilized will bear the cost of the least utilized.

• According to this IMCOA/Roskill data, magnets represented about 21% of the market for rare earth elements in 2008 and are expected to rise to 24% by 2012.
• Neo Magnet sales are recovering after the “Great Recession” and are forecast to continue up.
• Figures through 2008 are industry data; 2009 is estimated and 2010 is forecast.
• Of the many applications for rare earth permanent magnets, hard disk drives, CD’s and DVD’s continue to represent the largest segment.
• Motors are the second largest and will grow as conversion from induction to PM motors takes place for efficiency gains.
• The two newest growth categories are hybrid (and EV) drive systems and wind power generation.
Major and Developing Uses of Neo Magnets

- **HDD (Global):** existing and growing market
  - Overall HDD shipments for 2008 would total 593.2 million units, up 14.9% compared to 2007 (iSuppliCorp)
  - IDC forecasts 13.4 per cent growth in worldwide shipments in 2009 and 12 per cent in 2010……IDC, a technology research group based in Framingham, Mass. Use 10% growth in 2011 and 2012
  - Magnet total weight consumed in 2012 is estimated = **14,200 tonnes**

- **Wind turbines (Global):** generation IV permanent magnet generators just ramping up
  - Generation 4 Wind Turbines use permanent magnets
  - Between 250 and 600 kg neo magnets per MW output; use 400 kg in calculations
  - Replacement of a 1 GW coal-fired power plant would require 400 tonnes of neo magnets
  - Approx 220 GW of wind power to be installed by 2030; peak annual magnet usage in the period **2018 through 2025** is estimated at 6,400 tonnes / yr
  - Peak global usage is estimated at 2.5 times this = **16,000 tonnes**

- **Hybrid vehicles (Global):** in rapid growth phase
  - Estimates of between 6 and 10 million hybrids to be manufactured in 2012
  - Each hybrid drive utilizes an average of 1.25 kg of neo magnets
  - Total neo magnet usage in 2012 for 6 million vehicles = **7,500 tonnes**

- **EB (electric bicycles) (primarily in Asia):** large and growing application especially in 3rd world nations
  - 300-350 grams of neo magnets per EB
  - 20 million sold in China in 2009; forecast to 30 million per year in 2012
  - Annual neo magnet usage = **9,700 tonnes**

For these uses alone approximately 25,000 tons of magnet REO’s (Nd, Pr, Dy) are required.
Magnets REO’s are ~21% of all REO; 117,000 tons total REO must be made.

The growth in demand for magnet rare earth elements will be driven by many factors, not the least of which are these existing and new uses.

- In 1990 Hard Disk Drives (HDD’s) represented approximately 75% of the usage of neo magnets. Today the percentage is lower only because other applications have grown.
- If China’s growth of the wind power industry remains on-track, they will probably consume more magnets than the U.S.
- Europe, India and other oil-import dependent countries are likely to expand their wind power programs as well.
- Direct drive wind generators consume between 500 and 625 kg per MW while intermediate speed generators use between 165 and 250 kg/MW.
- Global magnet usage for wind could easily exceed 16,000 tonnes/year by 2020 depending upon the rate of adoption of PM generators, investment in wind power and design utilized (induction, permanent magnet, direct drive, intermediate speed, etc.).
- Considering hybrid vehicles only, i.e. not full electric, 7,500 metric tons of magnets will be required per year by 2012.
- People in developing countries can ill afford purchasing and maintaining automobiles. Many depend upon bicycles and increasingly on motor bikes for transportation.
- These four applications alone will require the separation of ~100,000 tons of REO.
• One of the newest drivers for increased neo magnet usage is wind power, specifically 1) the increase in wind tower installations and 2) the conversion from wound field to permanent magnet generators.

• In addition to wind power, other environmentally friendly generators are being designed and installed such as this Tidal Turbine, some using PM generators.

• The Clipper Turbine shown here uses four PM generators geared off the main drive shaft.

• The “competitor” turbine is a wound field type showing the size of the gear box and generator.
GE Gen-4 Wind Power Generator

www.popsci.com/technology/article/2010-03/next-gen-wind-turbine
• All of these systems utilize permanent magnet generator designs.
Wind Power Pushing Neo Production
USA only data shown here

<table>
<thead>
<tr>
<th>Year</th>
<th>Wind Turbines Installed MW</th>
<th>Percent Rare Earth PM Drives</th>
<th>REO Demand @ 0.25 t/MW</th>
<th>Magnet Demand tons</th>
<th>Value million USD</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>8,500</td>
<td>4%</td>
<td>80 t</td>
<td>165</td>
<td>6</td>
</tr>
<tr>
<td>2009</td>
<td>11,000</td>
<td>8%</td>
<td>225 t</td>
<td>464</td>
<td>19</td>
</tr>
<tr>
<td>2010</td>
<td>14,500</td>
<td>12%</td>
<td>435 t</td>
<td>897</td>
<td>42</td>
</tr>
<tr>
<td>2011</td>
<td>18,500</td>
<td>16%</td>
<td>740 t</td>
<td>1,525</td>
<td>84</td>
</tr>
<tr>
<td>2012</td>
<td>24,000</td>
<td>20%</td>
<td>1,200 t</td>
<td>2,474</td>
<td>143</td>
</tr>
<tr>
<td>2013</td>
<td>31,500</td>
<td>24%</td>
<td>1,900 t</td>
<td>3,916</td>
<td>239</td>
</tr>
<tr>
<td>2014</td>
<td>41,000</td>
<td>28%</td>
<td>2,670 t</td>
<td>5,504</td>
<td>352</td>
</tr>
</tbody>
</table>

Based on Mark Smith presentation at DMTC, spring 2010. Magnet demand and value calculated by Arnold; $/kg inflated at ~5% per year, 2011 through 2014; REO demand is total oxide demand, all rare earths in bastnäsite ore plus HRE at 5%.

- Dudley Kingsnorth (IMCOA) has summarized data for wind power implementation.
- This chart presented by Mark Smith of Molycorp in early 2010 is a recent revision of the earlier Kingsnorth data.
- I’ve added columns for magnet demand and value to make it more informative regarding the magnet industry.
- In 2014 REO demand is estimated to be a bit over 10% of Molycorp’s planned output (of magnetic rare earth elements).
- Even at the peak consumption period (2018 to 2026), demand will be about half of the magnet rare earths generated from the 19,000 tons planned output of Molycorp.
- Nevertheless, that is a substantial additional usage over existing consumption and represents demand in the US only.
• Unlike the LME, where details of transactions can be observed, the rare earth market is closed. Sales of rare earth materials are private purchases.
• The pricing we see originates from Chinese sources (Asian Metals) and may represent a premium to that actually paid.
• Nevertheless, there have been substantial increases in pricing of rare earths including of Neodymium, Praseodymium and Samarium.
• In reality, material prices are simply returning to their levels of 15 to 30 years ago (1980 to 1995).
• When we add in dysprosium pricing, one can see why high temperature grades of neo with up to 10 weight per cent dysprosium are increasing in price.
• With the introduction of inexpensive rare earths from China, prices dropped, reaching a minimum in 2003.

• Dysprosium, neo and praseodymium have all increased from 2003 to the present by about the same amount – a 13-fold increase.

• While samarium has also risen in price, it is far more moderate.
• But the plot thickens - - China domestic pricing is substantially below that for product to be sold outside of China.
• Since Arnold has a JV with a RE mining company in China, we can confirm this 2-tier pricing situation.
Legislation

• S.3521, Murkowski
  – Rare Earths Supply Technology and Resources Transformation Act of 2010 (RESTART Act)
• H.R. 4866, 29-Mar-2010, Coffman
  – Rare Earths Supply-Chain Technology and Resources Transformation Act of 2010
• H.R. 6160, 22-Sep-2010, Dahlkemper
  – Rare Earths and Critical Materials Revitalization Act of 2010
• H.R. 5136, 26-Apr-2010, Skelton
  – Fiscal Year 2011 National Defense Authorization Act
• P.L. 111-84, (H.R. 2647/S. 1390), Skelton, Coffman and Bayh

References:
www.fas.org/sgp/crs/natsec/R41347.pdf  
www.govtrack.us/congress/billsearch.xpd

• Price increases and threats of shortages have stimulated legislative action.
• I encourage you to visit both of these websites to read more.
Neo in USA – Patents & Licensing

• Hitachi patent(s)
  – Magnequench Cobalt patent expires in 2012
  – Key Hitachi US 5,645,651 (‘651) patent expires in July 2014
  – Hundreds of additional Hitachi patents
  – Hitachi has refused to license additional manufacturers
    • This is a continuation of the Sumitomo policy announced in late 2003/early 2004.

• Magnequench patent(s)
  – Magnequench US 5,411,608 patent expires May 2012: directed generally to neo alloys containing cobalt
  – Several additional patents related to neo composition variations

There are 5 licensees in China, 3 in Japan, 2 in Germany and 0 in the USA.

• Regarding manufacture of alloy and magnets in the US, we still have the issue of license requirements.
• As soon as the alloy is melted and cast, it will fall under one or both of these two key patents.
• Hitachi has literally hundreds of additional patents to lock of the neo technology.
The Politics of Rare Earths

- Rare Earth “War”
- China Industry Regulation
- Conservation of a limited resource
- Environmental disaster mitigation
- Installation of newer, more efficient refining
- Stockpiling in China
- Rare earths as a bargaining instrument, embargos
- Development of China domestic industry (export quotas)
- Undervaluation of rare earths
- Elimination of Black Market materials

- China has proclaimed that they will not “hold the world hostage” – that they will endeavor to supply market demands while western sources are developed.
- Western governments are expressing support for development of the industry.

A web search returns hundreds of thousands of hits on the subject of rare earth, China, embargos, etc.

These are some of the issues in articles on the web.

The media gains readership by creating a sense of crisis. The reality is somewhat more benign.

It has been written that to maintain domestic tranquility, China must create 30 million new jobs each year for the next ten years. To do so, they will need to produce more finished products and sell less raw material.

China has also proclaimed that they will not “hold the world hostage” – that they will endeavor to supply market demands while western sources are developed.
Our World Touches Your World Every Day…

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The Challenge

• Develop a new permanent magnet material with properties comparable or superior to those of neo
• Do so using a combination of materials that will be available from multiple geographic regions
• And will cost less than rare earth magnet materials
• Easily manufactured to final shape and size

•Our magnet challenge…
The Millennial Magnet Stakes

- **New Phase** – 5:1 against
- **Strong Ferromagnet** – 12:1 against
- **Exchange Hardening** – 2:1 against
- **Heavy Lanthanide** – 20:1 against
- **Actinide** – 40:1 against

Source: Michael Coey and Ralph Skomski, CEAM c.1993

Though we should try, it may not be possible to develop a superior permanent magnet with no rare earth.

Success should be recognized for significant reduction in the rare earth content.

Actinide magnets are not recommended as the constituents are hazardous materials.
OXIDE TO MAGNET (OR BATTERY) IN ONE STEP – THE IMPOSSIBLE DREAM – OR IS IT?

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Ames Laboratory, U.S. Department of Energy and Department of Materials Science and Engineering
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ARPA-E Workshop on Rare Earths and Critical Materials
Arlington, Virginia
December 6, 2010
CURRENT PROCESS

\[ 2 \text{Nd}_2\text{O}_3 \xrightarrow{\text{Electrolytic Cell}} \text{NdF}_3\text{-LiF Flux} \xrightarrow{10,000 \ \text{Amps}} 1100^\circ\text{C} \rightarrow 4\text{Nd} + 3\text{O}_2(g) \uparrow + \text{some F}_2(g) \uparrow \]

COMMENT: oxide solubility in the flux is small; control of amount oxide is critical and difficult to do; some NdF$_3$ may be reduced to Nd + F$_2$(g) when Nd$_2$O$_3$ is consumed.

Nd Metal (10-15 kg) collected in a pot below cathode

Poured into a graphite mold

Reacted with Fe+B+other additives to make Nd$_2$Fe$_{14}$B permanent magnet
BASIC PROCESS

\[ 2\text{Nd}_2\text{O}_3 + 14\text{Fe}_2\text{O}_3 + \text{B}_2\text{O}_3 + 51\text{Y} \xrightarrow{\text{X, cat.}} 2\text{Nd}_2\text{Fe}_{14}\text{B} + 51\text{Y}_{z}\text{O}_{w} \]

- Y is a reductant (several possibilities)
- X is a catalyst (several candidate materials)
- Flux is crucial (metallic, non-metallic)
- Temperatures > 1100°C required
- z and w have a value between 1 and 4
- Bottom pour Nd$_2$Fe$_{14}$B alloy into a water cooled mold

Several possible variations have been examined theoretically
  e.g. substitute Fe for Fe$_2$O$_3$ and B for B$_2$O$_3$
  Two variations may be two step processes (e.g. oxide to metal, metal to magnet)

FOR BATTERIES

- La$_2$O$_3$ or MM$_2$O$_3$ for Nd$_2$O$_3$
- Ni,Co etc. oxide(s) for Fe$_2$O$_3$

ADVANTAGES

- Environmentally - a green technology – no by-products
- Cost – about half of current process.
Development of Advanced Permanent Magnets

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The single most important application for permanent magnet materials is in electric motors and power generators.

Permanent magnet stator for a dc motor

Alnico magnet  Ceramic ferrite  Rare-earth magnet
Applications of Permanent Magnets

- The strength of permanent magnets (PMs) is the single factor affecting the power density and energy efficiency of countless devices.

Wind turbines with PM generators are very efficient at low wind speeds. Hybrid electric vehicles are particularly demanding for power density of their PM motors.

PM hydroelectric turbine generators eliminate need for gearboxs.

In this generator buoy, the floater moves coils relative to the PM to induce voltages.

Efficient and fail-safe Inductrack maglev train.
Hysteresis Loops

Response of ferromagnetic materials to magnetic field \((H)\).

- Area under hysteresis loop represents the energy losses which are converted to heat.

\[
B = \mu_0 (H + M) \quad (\text{SI})
\]

\[
B = H + 4\pi M \quad (\text{CGS})
\]
Permanent Magnets-Energy Product: Strength of a Permanent Magnet

The higher the \((BH)_m\) the smaller the \(V_m\)!

Permanent magnet materials must have:

i) a high remanence to produce a large magnetic induction.

ii) a high \(H_c\) \((H_c \geq M_r/2)\) to avoid easy demagnetization.

iii) a high \(T_c\) to resist thermal demagnetization.

Energy Product, \((BH)_m\) characterizes the magnet strength.

Current high performance permanent magnets are based on Fe(Co)-rich rare-earth alloys:

- Fe(Co) provides the high magnetization and high Curie temperature.
- Rare earth metals, such as Sm, Nd, Pr, provide the high anisotropy and coercivity.

\[
(BH)_m = (4\pi M_s/2)^2
\]

144 MGOe for Fe-Co if it had a high K
A large remanence $M_r$ is obtained by the alignment of all grains/particles. This important requirement for the magnet texture and fine microstructure can be best fulfilled through powder metallurgy/sintering. Virtually all commercially available magnets with $(BH)_{max} > 25$ MGOe are sintered from oriented powders. Additional heat treatment may be necessary, especially for Sm(Co,Fe,Cu,Zr)$_2$ magnets.

Polymer-bonded magnets with inferior properties are manufactured from ground, rapidly solidified or hydrogen-treated permanent magnet alloys. The binder dilutes the magnetization; most of these magnets are not textured.

Some other manufacturing methods, such as hot pressing or hot extrusion, are known but rarely used.

Several recent attempts of direct chemical synthesis were reported, but so far without much progress.
Material requirements:

1) A high anisotropy
2) A proper microstructure

Coercivity mechanisms:

i) Magnetization rotation (Coherent (SW)&Incoherent)
ii) Nucleation of reversed domains (Nucleation Magnets)
iii) Domain wall pinning (Domain Wall Pinning Magnets)
Magnetic Anisotropy and Coercivity

I. Magnetocrystalline Anisotropy

Spin-Orbit Coupling

\[ E_k = K_1 \sin^2 \Theta \]

Coercivity (Coherent rotation)

\[ H_{c, max} = \frac{2K_1}{M_s} \]

II. Shape Anisotropy

\[ K_s = \frac{1}{2}(N_a - N_c)M^2 \]

Coercivity (Coherent rotation)

\[ H_{c, max} = (N_a - N_b)M_s \]
In these magnets the domain walls move easy inside the grains and grain boundaries prevent their propagation into adjacent grains. Therefore, the structure and morphology of grain boundaries are important. These areas are most susceptible to nucleation of reversed magnetization; they can also seal the grains and restrict reversal of magnetization within the grain.

The increase of $H_c$ with decreasing particle size can be more consistently explained via the decreasing probability of inhomogeneities which may serve as nucleation sites for reversed magnetization.

Shown is the microstructure of sintered Nd-Fe-B magnet with Nd$_2$Fe$_{14}$B grains separated by thin layers of the Nd-rich phase. This is a typical nucleation-controlled magnet.
In these magnets the coercivity originates from domain wall pinning at defects/inhomogeneities.

These pinning-controlled magnets must have very fine and uniformly distributed pinning sites – areas where the domain wall energy is much higher or much lower than that of the main material.

Typical pinning-controlled magnets are sintered Sm(Co,Fe,Cu,Zr)_{7-8.5}. Their key feature is a network of the Sm(Co,Cu)_5 phase in the Sm_2(Co,Fe)_{17} matrix developed via complex heat treatment.
Spinodal decomposition in Fe-Al-Ni-Co alloys (Alnico) leads into Fe-rich rods embedded in an Fe-depleted matrix. The large shape anisotropy of rods leads to a high coercivity. Coherent rotation predicts a coercivity:

\[ H_c = (N_a - N_b)M_s. \]

Anisotropic magnets can be obtained via magnetic annealing and directional solidification.

However, the theoretical \((BH)_{\text{max}}\) of nearly 36 MGOe (67% Fe phase) has never been realized, in particular, because of imperfect shape of the precipitates.
WORLD'S STRONGEST Nd-Fe-B MAGNET

$(BH)_M \sim 59$ MGOe

- Because of their low Curie temperature ($300 \, ^\circ C$) the Neo magnets are used for applications less than $180 \, ^\circ C$
High Temperature Sm-Co Magnets

- **2:17 Sm-Co** based magnets have a higher Curie temperature (~ 800°C) which makes them good for high temperature applications.

- These magnets have a cellular structure of 2:17(R) cells and 1:5 cell boundaries coexisting with Zr-rich lamellae. DW are pinned at the 1:5 cell boundaries.

- A fine tune of the microstructure and microchemistry (AFOSR MURI Program) was found to affect the coercivity and its temperature dependence and lead to permanent magnets with higher operating temperature.

- These magnets are now made commercially by EEC with $(BH)_m$ in the range of 25-32 MGOe and $T_{op}$ up to 550 °C!
High performance magnets are based on the discovery of anisotropic compounds—SmCo$_5$, Sm$_2$Co$_{17}$, Nd$_2$Fe$_{14}$B, Sm$_2$Fe$_{17}$N$_x$.

The $(BH)_{max}$ limits set by the intrinsic properties of these compounds are nearly reached.

Probability exists for discovery of new compounds; but search is extremely difficult and requires a systematic study.

A new concept of exchange-coupled nanocomposite magnets was proposed in late 80s.

Non-rare earth magnets a possibility
Magnetic exchange coupling allows us to combine the magnetic hardness of rare-earth compounds with the high magnetization of soft magnetic materials.

According to models (Skomski et.al.), the predicted \((BH)_{max}\) of the hard-soft composites exceeds 100 MGOe (59 MGOe is the present record for sintered Nd-Fe-B).

Because the exchange interaction has a very short range, the composite material must be of a nanoscale (Size of soft phase ~20 nm).
Development of Exchange-Coupled Magnets

Single Phase Isotropic Decoupled
\( M_r/M_s = 0.5 \)
\((BH)_{max} = 12\text{ MGOe}\)

Single Phase Isotropic Exchange-Coupled
\( M_r/M_s > 0.5 \)
\((BH)_{max} = 20\text{ MGOe}\)

Nanocomposites Isotropic Coupled
\( M_r/M_s > 0.5 \)
\((BH)_{max} = 23\text{ MGOe}\)

Nanocomposites Anisotropic Coupled
\( M_r/M_s > 0.5 \)
\((BH)_{max} \sim 100\text{ MGOe}\)

Fe / Nd\(_{2}\)Fe\(_{14}\)B

Hard phase

Soft phase

Magnetization
High-Energy Permanent Magnets for Hybrid Vehicles and Alternative Energy Uses
Novel Hard Magnetic Materials

- Search for RE-TM-X compounds with superior properties
- Inducing anisotropy in Fe-Co intermetallics

Nanocomposite Magnets

- Nd-Fe-B, Sm-Co, Sm-Fe-N
- Fe, Fe-Co

- Synthesis of high-$H_c$ nanoparticles
- Synthesis of high-$M_s$ nanoparticles
- Synthesis of core/shell nanoparticles

Comminuting

Alignment

Modeling

Blending

Alignment

Consolidation

New High-Performance Magnet
Superior Rare Earth-Free Magnets?

- Since late 1960s nearly all the R&D efforts were focused on perfecting the RE magnets.
- Recent years/months saw a renewed interest in the development of the RE-free alternatives.
- **RE-free** hard magnetic compounds exist: FePt, CoPt, MnBi, MnAl, Zr$_2$Co$_{11}$, ε-Fe$_2$O$_3$
- Even the Alnico-type magnets still have a room for improvement; their theoretical $(BH)_{max}$ is 49 MGOe and they have excellent temperature stability!

<table>
<thead>
<tr>
<th>Compound</th>
<th>Structure</th>
<th>Saturation magnetization</th>
<th>Curie temperature (°C)</th>
<th>Anisotropy constant $K_1$ (MJ/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co</td>
<td>hexagonal</td>
<td>17.6 kG</td>
<td>1115</td>
<td>0.53</td>
</tr>
<tr>
<td>FePt</td>
<td>tetragonal</td>
<td>14.3 kG</td>
<td>477</td>
<td>6.6</td>
</tr>
<tr>
<td>CoPt</td>
<td>tetragonal</td>
<td>10.0 kG</td>
<td>567</td>
<td>4.9</td>
</tr>
<tr>
<td>Co$_3$Pt</td>
<td>hexagonal</td>
<td>13.8 kG</td>
<td>727</td>
<td>2.0</td>
</tr>
<tr>
<td>MnAl</td>
<td>tetragonal</td>
<td>6.2 kG</td>
<td>377</td>
<td>1.7</td>
</tr>
<tr>
<td>MnBi</td>
<td>hexagonal</td>
<td>7.8 kG</td>
<td>357</td>
<td>1.2</td>
</tr>
<tr>
<td>BaFe$<em>{12}$O$</em>{19}$</td>
<td>hexagonal</td>
<td>4.8 kG</td>
<td>450</td>
<td>0.33</td>
</tr>
<tr>
<td>Zr$<em>2$Co$</em>{11}$</td>
<td>orthorhombic</td>
<td>≈70 emu/g</td>
<td>500</td>
<td>? ($H_A = 34$ kOe)</td>
</tr>
<tr>
<td>ε-Fe$_2$O$_3$</td>
<td>orthorhombic</td>
<td>≈16 emu/g</td>
<td>?</td>
<td>? ($H_c = 23.4$ kOe)</td>
</tr>
<tr>
<td>SmCo$_5$</td>
<td>hexagonal</td>
<td>11.4 kG</td>
<td>681</td>
<td>17.0</td>
</tr>
<tr>
<td>Nd$<em>2$Fe$</em>{14}$B</td>
<td>tetragonal</td>
<td>16.0 kG</td>
<td>312</td>
<td>5.0</td>
</tr>
</tbody>
</table>
Next Generation Magnets

Exchange-Coupled Hard/Soft Nanocomposite Magnets
- Top-Down Approach
  - Uniform Mixtures by HEBM in Liquid
    - Problems & Challenges
      - Thickness/uniformity
      - Chemical reaction
      - Oxidation
    - Consolidation

Search for New Compounds
- High $M_s$, $K_1$, $T_C$
- Bottom-Up Approach
  - Rare Earth – Transition Metal Nanoparticles
    - Problems & Challenges
      - Oxidation
      - Alignment
  - Melt-spinning, Mechanical Alloying
    - DTA, XRD, SAED

Change Fundamental Parameters ($K_1$, $T_C$) by Size Quantum Effects
- Nanoscale Processing
  - Thin films
  - Multilayers
  - Nanoparticles
- Shape Anisotropy Materials
Rare-earth Free Permanent Magnets for High Temperature Applications:
Hexagonal Mn-Bi-(X) and Ba-Ferrite (BaFe$_{12-x}$Al$_x$O$_{19}$) for Core-shell Magnet Design

Yang-Ki Hong: magnetic materials design, fabrication and characterization
Magnetic Materials and Device Laboratory
Department of Electrical and Computer Engineering

Oleg Mryasov: theoretical investigation of new magnets and understanding of exchange coupling and magnetostatics
Department of Physics

Nitin Chopra: synthesis of core-shell magnets
Department of Metallurgical and Materials Engineering
The University of Alabama
Tuscaloosa, AL 35487

December 6, 2010
Two Prospective Materials Systems

Hexagonal Mn-Bi-X

\[ H_k = 44.8 \text{ kOe}; \ T_c = 630 \text{ K}; \ M_s = 660 \text{ emu/cc at RT} \]

Hexagonal Ba(or Sr)-Ferrite (Ba(or Sr)Fe\(_{12-x}\)Al\(_x\)O\(_{19}\))

\[ H_k = 17 \text{ kOe (x = 0)}; \ T_c = 723 \text{ K}; \ M_s = 380 \text{ emu/cc at RT} \]

• Other hcp-based structure: MnGa; MnGa-X, etc.

• Predictive theory of \( M_s, K, T_c, \) and phase stability
I. Two-phase Core-shell Design: $\delta$, $D$, $f_h$, $M_s(T)$, $K(T)$

II. Enhanced single phase properties: $M_s$, $K$, $T_c$
- Mn-Bi-X
- Substituted Ba-ferrite

III. Understanding of Interfacial role in $(BH)_{\text{max}}$
- Magnetostatics
- Exchange coupling

---

**Strategy for Enhancement of $(BH)_{\text{max}}$**

<table>
<thead>
<tr>
<th>Thickness (nm)</th>
<th>$(BH)_{\text{max}}$ (MGOe)</th>
<th>$M_s$ (T)</th>
<th>$K_h$ (MJ/m$^3$)</th>
<th>$K_s$ (MJ/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_s$</td>
<td>300 K</td>
<td>1.3 T</td>
<td>1.6 T</td>
<td>1.9 T</td>
</tr>
<tr>
<td>$\delta_s$, $D_h$ = 25 nm</td>
<td>14.8 MGOe</td>
<td>0.47 T</td>
<td>0.33 MJ/m$^3$</td>
<td>0.003 MJ/m$^3$</td>
</tr>
<tr>
<td>$\delta_s$, $D_h$ = 50 nm</td>
<td>12.5 MGOe</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta_s$, $D_h$ = 70 nm</td>
<td>10.5 MGOe</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta_s$, $D_h$ = 100 nm</td>
<td>8.5 MGOe</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta_s$, $D_h$ = 150 nm</td>
<td>6.5 MGOe</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta_s$, $D_h$ = 250 nm</td>
<td>4.5 MGOe</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---


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N$_2$Fe$_{14}$B: 7.4 g/cm$^3$
Sm$_2$Fe$_{17}$N$_3$: 7.6 g/cm$^3$
BaM: 5.3 g/cm$^3$
MnAl: 5.3 g/cm$^3$
Fe$_{35}$Co$_{65}$: 8.2 g/cm$^3$
FePt: 15.1 g/cm$^3$
MnBi: 9 g/cm$^3$
Fabrication Challenges, Our Preliminary Results, and Timeline for Research

- Manufacturing challenges for nanoparticles:
  - Single phase Mn-Bi-X nanoparticles, Single phase Ba(or Sr)-ferrite nanoparticles
  - Core-shell particles

- Manufacturing challenge for bulk magnets:
  - Bonded magnets (isotropic, anisotropic)
  - Sintered magnets (isotropic, anisotropic)

- Preliminary Results

- Timeline for Research
  - **Year I**: nanoparticles (sing phase Mn-Bi-X and Ba-ferrite) and investigation of new materials
  - **Year II**: core-shell magnet (Ba-ferrite/soft, Mn-Bi/soft) and fundamental understanding of exchange coupling and magnetostatics
  - **Year III**: consolidation and bonded/sintered magnets and new concept of magnetic anisotropy (isotropic, anisotropic)

- Investigation of new magnet s-hcp based structure: MnGa, MnGaPt, etc.

- Predictive theory of $M_s$, $K$, $T_c$ and phase stability

- 24-30 nm Ba-ferrite

- 21 nm Hematite: $\alpha$-$\text{Fe}_2\text{O}_3$


*IEEE Trans. Mag. (2009)*
Flux Coupling Machines and Switched Reluctance Motors to Replace Permanent Magnets in Electric Vehicles

Part I:
Novel Flux Coupling Machine Without Permanent magnets and Integration of Novel Flux Coupling Machine and Current Source Inverter

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ARPA-E Critical Materials Technology Workshop
Arlington, Virginia
December 6, 2010
The Problems of Motor Drive and Generation Systems:

- Rare earth permanent magnets (PM) are a major cost item in present day permanent magnet (PM) machines.
- These magnets have operating temperature limitations.
- The cost of electric vehicle traction drive systems (motor + power electronics) is too high ($36.6/kW -- 2006 Camry versus $8/kW -- DOE 2020 target). Same for the PM generation system.
- Voltage source inverters (VSIs) need bulky, expensive and temperature limited DC bus capacitors.
- As operational temperatures increase, the ability of film capacitors to handle ripple currents decreases, necessitating the addition of even more capacitance.
- The Novel Flux Coupling Machine’s core can be utilized to eliminate the inductor of a current source inverter for further cost reduction and performance improvement.
A Novel Flux Coupling Machine
Conclusions

1. Brushless electric motors and generators can be built without permanent magnets.

2. The excitation core of this new electric machine can be used as the inductor of a current source inverter to further reduce the system (i.e., machine + Inverter) cost and increase power density and performance.

3. New soft magnetic core materials need to be further developed to optimize both the DC and AC flux carrying capabilities.
Flux Coupling Machines and Switch Reluctance Motors to Replace Permanent Magnets in Electric Vehicles
Part II: Unconventional SRMs for Vehicle Propulsion

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Organization: ORNL
Email: burressta@ornl.gov
Phone: 865-946-1216

DOE Vehicle Technologies Program
Advanced Power Electronics and Electric Machines Research

ARPA-E Critical Materials Technology Workshop

Arlington, Virginia
December 6, 2010
Benefits of Switched Reluctance Motors (SRMs)

- No permanent magnet material
  - Back-emf and demagnetization is not an issue
  - Permits operation at high temperatures
- Low material and fabrication cost
- Capable of very high speeds
- Robust and reliable
  - Currently used in various applications including
    - Deep coal mining
    - Class 7+ Hybrid trucks and busses
    - Hybrid bulldozers
    - Household appliances (top brand vacuum cleaner)
    - Restaurant soda dispensers
    - Parking brake activator (e.g. 2010 Prius)
Problems With SRMs

• SRMs have inherent issues with torque ripple and acoustic noise, which is the primary deterrent for application in light duty/Class 1 vehicles (typical cars and trucks)

• For a given power rating, SRM drives typically require higher device ratings (10-20%) in comparison with PM drives
ORNL’s Unconventional SRM Approach

- Use of segmented stator facilitates
  - Distribution of torque (torque ripple reduction)
  - Reduction of
    • Structural modal tendencies
    • Noise/Vibration – use of potting compounds
    • Core losses
  - Possibility of exceptional heat transfer capabilities

![Diagram of conventional 8/6 (4-phase) and 12/10 prior to optimization SRMs]
Conclusions/Needs

• Motors, in general, can benefit from potting compounds with improved heat transfer
  – Must maintain electrical isolation
  – Must typically be rigid (to secure windings in place)
  – Must be capable of enduring sustained vibration and thermal cycling

• ORNL’s SRM design could benefit from a material similar to that above, but has improved capability to absorb vibrational energy

• Solutions exist, but break-throughs in these areas would greatly aid increased power densities, specific powers, and extended operation times

2010 Prius PM generator with segmented and potted windings
Parallel Path Magnetic Technology (PPMT™)

- Electric Motors, Generators and Actuators
- Highest Efficiencies and Power Densities
- Rare earth magnets not required
- Higher reliabilities
- Lowest Cost Solutions
- Patented: 6,342,746 - 6,246,561 & Prov/PCTs

- Currently being evaluated under contract with market share leading development partners and the NSF for automotive and HVAC applications, the DOE and NREL for wind turbines, the Navy and NSF for portable generation and NASA for mobility and robotics.
QM Power Parallel Path Magnetic Technology™
Comparison in Linear Systems

Conventional Magnetic Circuits

Parallel Magnetic Circuits

Doubling the flux squares the force (4X improvement)
QM Power’s magnetic circuit utilizes 50% or more of the active rotor-stator interface and all torque is generated with attractive permanent magnet flux. In addition, by adjusting the length of the permanent magnet pole faces ‘L1’ and ‘L2’ below, the flux across a stator pole of length ‘L3’ can be adjusted to be equal to the air gap flux densities achievable in a field wound machine, even with ceramic magnets. The PPMT™ machine geometry is superior because it makes that possible without adding the copper weight and suffering additional I²R losses, as would be the case in a field wound machine and eliminates the need for rare earth materials in permanent magnet designs.

• Note: Multiple other proprietary geometries currently in development.
Historical Information on the Development of Permanent Magnets

No commercially successful breakthroughs in the last 27 years!
Historical Perspective:
Supply chain vs. magnet development

- **1st generation RE magnet:** SmCo5 was developed in late 1960s
- **2nd generation RE magnet:** Co supply was very volatile back then (still true today), the desire to reduce Co content led to the development of Sm2(Co,Fe,Cu,Zr)17 magnets
- **3rd generation of RE magnet:** Fe-based magnet alloys became a very hot topic in the late 70s and 80s partially due to the supply of Co, which led to the discovery of Nd-Fe-B
- **4th generation of RE magnet (or magnet without RE):** RE supply has become a major problem. The cost of Sm tripled in the last 6 month, if you are lucky to get any. **ANOTHER HISTORICAL OPPORTUNITY?**
Requirements for good permanent magnets:

• High saturation magnetization (higher Fe content and lower RE content are desirable, even the RE supply is not a problem)

• High anisotropy (high coercivity)

• High Curie temperature
Rare Earth Research Needs for Transportation Materials

Frederick E. Pinkerton

General Motors R&D Center
ADVANCED PROPULSION TECHNOLOGY STRATEGY

- Improve Vehicle Fuel Economy and Emissions
- Displace Petroleum
- Traction motors
- Hybrid-Electric Vehicles (including Plug-in HEV)
- Battery-Electric Vehicles (including EVre)
- Hydrogen Fuel Cell-Electric Vehicles
- IC Engine and Transmission Improvements
- Petroleum (Conventional and Alternative Sources)
- Alternative Fuels (Ethanol, Biodiesel, CNG, LPG)
- Electricity (Conv. and Alternative Sources)
- Hydrogen

Energy Diversity

Accessory motors
ELECTRIFICATION STRATEGY

Portfolio of solutions for full range of vehicles that provide customer choice

- Petroleum and Biofuels
  (Conventional and Alternative Sources)

- Electricity and Hydrogen
  (Zero Emissions Energy Sources)

- Mild Hybrid
- Strong Hybrid
- Plug-in Hybrid
- Extended-Range Electric
- Battery Electric
- Fuel Cell Electric

Increasing Electrification
Electric Motor Development and Manufacture

- GM is the first U.S.-based automaker to design, develop, process, and manufacture its own electric motors.

- Facilities
  - Wixom, Pontiac, Indianapolis, Torrance – R&D and validation
  - White Marsh, Maryland – high-volume manufacturing

- GM is investing $270M in electric motors, electric drive, and components' facilities.

- Design and manufacture electric motors in-house, and work with our best suppliers to provide the very best electrified vehicle solutions to our customers.
Automotive requirements

- FreedomCAR targets for 2010, 2015 and 2020

- Difficult to achieve without high energy density RE permanent magnets
- Need maximum remanence $B_r$
- Need high temperature operation (> 150 °C desired)
- Must not demagnetize at high temperature (i.e., Nd-Fe-B needs high $H_{ci}$ at room temperature to have enough left at high T)

- And of course at low cost
The auto industry is dependent on rare earths for magnets

- Four elements – praseodymium, neodymium, dysprosium, terbium – are currently used for magnets in motors
- Rare earths account for ~80% of the material cost for a high coercivity Nd-Fe-B magnet (depending on magnet composition)
  - Dy can be more than half of the rare earth cost
- Currently, the alternatives to rare earths in magnets are significantly inferior
**Worldwide demand for RE magnets is expected to grow rapidly over the next few years**

- All major OEMs will have the same rapidly increasing need for magnets
- Rare earth magnets have many applications in wind turbines and electronics, among other uses, and these demands are also expected to grow

---

**Global Rare Earths Demand in 2010**

- **Magnets** 24%
- **Metal alloys, batteries** 21%
- **Polishing** 15%
- **Glass** 8%
- **Catalysts** 22%
- **Phosphors** 6%
- **Ceramics** 4%
Tight market conditions led to rapidly rising RE prices over the last few years, even with the global recession.

- Price for neodymium oxide has risen by 900% since 2005.
- The price increase was larger outside China than inside, due to export controls.
The auto industry can tolerate expensive technology... IF

For Nd-Fe-B and Sm-Co:

✓ Justified by performance
  – Customer experience
  – Regulatory requirements

✗ Cost is stable (predictable economics)

✗ Supply is reliable (non-strategic resource)

✗ Expected long-term trend toward lower cost
  – With increasing volume
  – With progressive technology improvements

Nd-Fe-B and Sm-Co permanent magnet technology is mature
Mitigation

- Sourcing strategy
- Fall-back technologies (sacrifice performance for certainty)
- Motor design tradeoffs
  - Run at lower temperature, more cooling, etc.
- Reduce or eliminate Dy and other heavy rare earths
  - Dy replacements
- Reduce total rare earth content of Nd-Fe-B based magnets
  - Aligned exchange-coupled magnets with less RE:
  - Hybrid magnets
- Disruptive technologies
  - New non-rare earth magnet materials
  - New motive technologies

Solutions will involve compromise...

We do not expect to equal or exceed Nd-Fe-B on all properties (the no-free-lunch theory)

- Remanence $B_r$
- Coercivity $H_{ci}$
- Power
- Weight
- Size
- Temperature coefficients
- Cost
- Supply
- Efficiency
- Torque

Magnet property tradeoffs expected
No one solution for all applications

We will design to a material
... but we’ll take a cheap drop-in replacement for Nd-Fe-B.
Bottom line: automotive perspective

- High performance permanent magnets
  - Maximum $B_r$, high temperature performance, enough $H_{ci}$ to not demagnetize, minimum cost
- The auto industry will be increasingly dependent on rare earth magnets as hybrid and electric vehicles grow market penetration
- Demand for RE magnets is growing rapidly for many uses, particularly wind turbine generators and vehicles, and demand is inelastic
- Supply of the heavy rare earths is limited and heavily concentrated in one geographical region, creating both business and political risks
- Tight market conditions led to sharp price increases over the last five years, with the Nd oxide price rising by 900% and Ce oxide rising by 3700%
- Rising demand and limited, inelastic, concentrated supply creates a high risk of a sustained RE price spike
- Mitigation should have high priority