NEODYMIUM: SUPPLY, DEMAND, SUBSTITUTION, AND RECYCLING

Karl A. Gschneidner, Jr.
Ames Laboratory, U.S. Department of Energy and
Department of Materials Science and Engineering
Iowa State University
Ames, Iowa 50011-3020,USA

Critical Materials Flow in an Age of Constraint
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IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY
THE Ames Laboratory
Creating Materials & Energy Solutions
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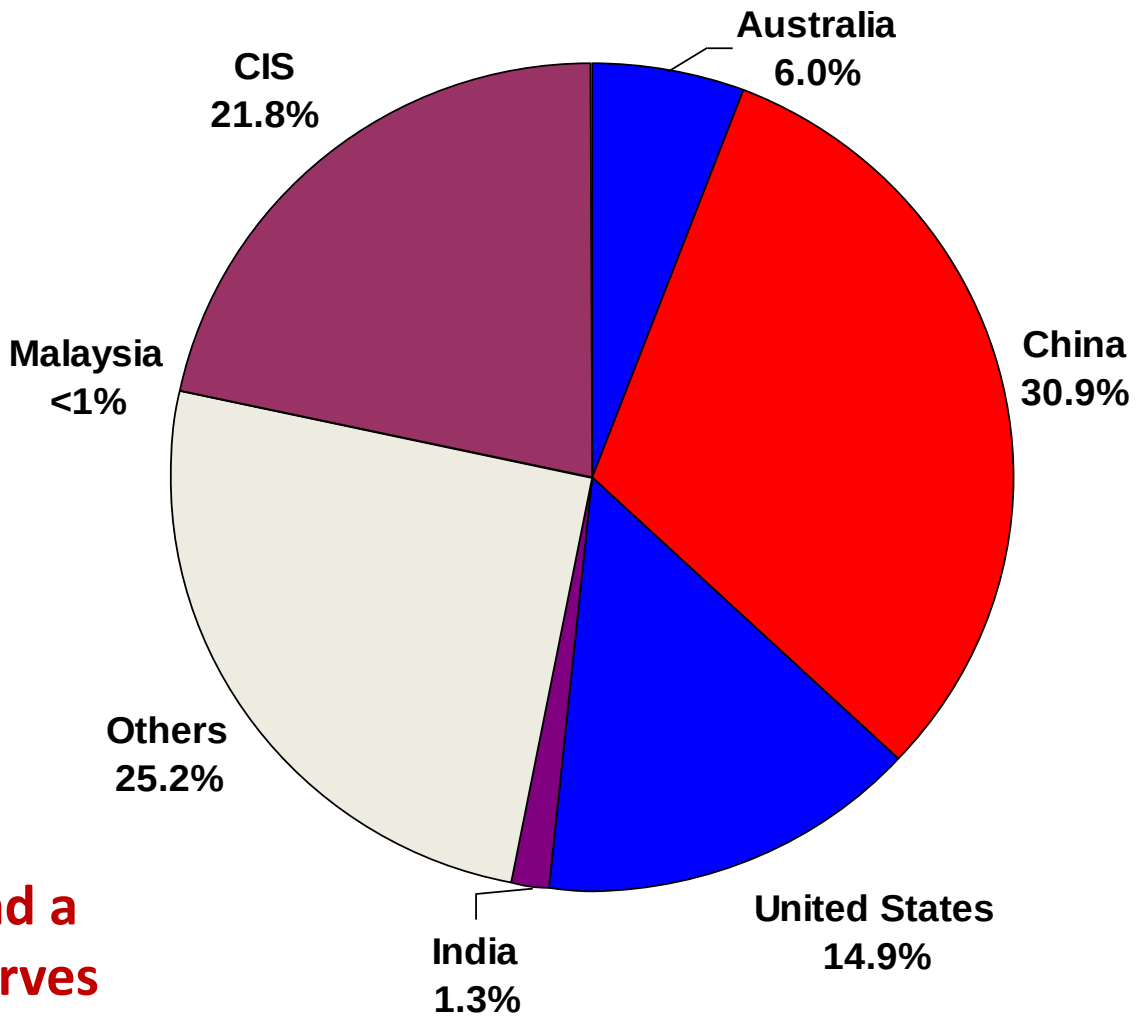
RE MINERAL RESERVES

88 million metric tons of contained rare-earth oxide (REO)

Enough rare earths for >700 years at current production levels

Enough rare earths for ~69 years at a 10% growth rate per annum

Enough rare earths For ~75 years at a 10% growth rate and a 1% increase of reserves per annum



RE WORLD MINERAL PRODUCTION IN 2010

~15% is Nd_2O_3

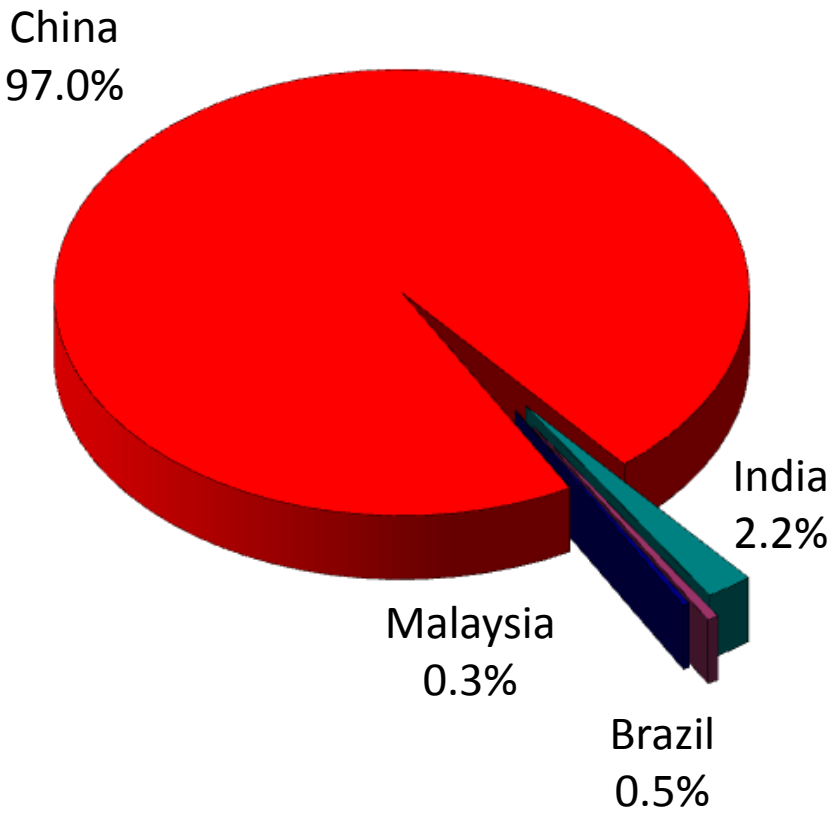
DEMAND: 124,000 metric tons of contained rare-earth oxide (REO)

PRODUCTION: 130,000 metric tons of contained rare-earth oxide (REO)

Black market: 10 to 15% of reported production, mostly smuggled out of China*

*". . . This region of southern China, long plagued by gangsters who illegally mine some of the worlds sought-after industrial metals. The gangs reap profits that can rival drug money, while leaving pollution and violence in their wake."

The New York Times, Global Business, Dec. 30, 2010



NEODYMIUM USES (2010)

Material	Current Demand	Major Uses
Mixed REO	40 kton REO (6 kton Nd_2O_3) balanced	Petroleum cracking (FCC) catalysts Mischmetal ductile iron Ni metal hydride batteries Polishing compounds
Nd_2O_3	23 kton Nd_2O_3 tight (slight shortage)	$Nd_2Fe_{14}B$ permanent magnets electric motors (largest use) computer hard drives (second largest use) wind turbines Ceramics and glass Lasers
Total Nd_2O_3	29 kton	
Pr_6O_{11}	5 kton Pr_2O_3 (equivalent)	Substitute for Nd in magnets –

THE RARE EARTHS MARKET TODAY

- Estimated demand in 2010: 124,000t REO
- Average price: US$63/kg REO; January 2011

Mixed RE oxides	$15/kg REO
Ce	$60/kg REO
Y, La	$70/kg REO
Nd, Pr	$89/kg REO
Dy	$290/kg REO
Eu, Tb	$620/kg REO

- Total value: US$ 15 billion pa

THE THREE ASPECTS OF THE RARE EARTH CRISIS

I Mining, production of mixed REO, separation individual REs, metal preparation

IIA Production of magnets, batteries, phosphors, catalysts

IIB Manufacture of consumer products: electric motors, cell phones, monitors, fluorescent lamps

III Lack of intellectual infrastructure - training of scientists, engineers, technicians, and technical business managers

FIRST ASPECT OF THE RARE EARTH CRISIS:

Mining, production of mixed REO, separation
individual REs, metal preparation

Solution well underway

Molycorp (Mountain Pass, CA) started mining January 2, 2011
5,200 tons in 2011
20,000 tons in 2012
40,000 tons in 2013

Lynas (Mount Weld, Australia) started mining May 14, 2011
~2,000 tons in 2011
11,000 tons in 2012
22,000 tons in 2013-14

One can see the light at the end of the tunnel

WHAT ARE WE GOING TO DO WITH THE COMPOUNDS AND METALS PRODUCED IN THE U.S.A.?

Send them back to Southeast Asia, India, China for manufacture of intermediate products (e.g. magnets) and consumer products?

The second aspect of the rare earth crisis!

SECOND ASPECTS (DOWN THE SUPPLY CHAIN) OF THE RARE EARTH CRISIS:

A Intermediate Products: production of magnets, batteries, phosphors, catalysts

B Consumer Products: electric motors, cell phones, monitors, fluorescent lamps, computers, i-pods

Solutions:

Loan guarantees: 2011 House Bill H.R. 618 (Boswell) and 1388 (Coffman)

Companies need to fully automate

Companies need to vertically integrate or form alliances to cover the complete supply train (mining to products)

WHO IS GOING TO DO THIS?

Where are the trained personnel?

What talents do we need?

The third aspect of the rare earth crisis!

THIRD ASPECT OF THE RARE EARTH CRISIS:

Lack of intellectual infrastructure - training of students to be scientists, engineers, technicians, and technical business managers

- undergraduate, graduate, post-doctorate
- chemistry, chemical engineering, materials science & engineering, physics, electrical engineering

Research projects funding

NSF, DOE, DOD, NIST

National Research Center for Rare Earths and Energy

- Educational institution with a strong tradition on REs
- Link with industry and national laboratories
- Subsidiary branches at other universities

Reference: K.A. Gschneidner, Jr., *Magn. Busin. & Tech.* **10**,[1] 6-8 (Spring 2011)

DEMAND

$Nd_2Fe_{14}B$ Permanent Magnets

Electric Motors

Computer Hard Drives

Wind turbines

- New rapidly growing market – 50% per year through 2015
- 25% permanent magnets – direct drive generators
- 1:3 (direct drive to gear box) ratio expected to be constant to 2011-2015
- 1.5 MW generator requires 1000 kg $Nd_2Fe_{14}B$ magnetic (or 250 kgNd)
- World-wide demand in 2015 – 35 ton

CONSEQUENCES OF GIANT WIND ENERGY GROWTH

Kingsnorth's (2010) projection of 40 kton total Nd_2O_3 demand in 2015 is too low by ~15 kton

Molycorp's and Lynas' combined Nd_2O_3 production is ~9 kton

-11 kton Nd_2O_3 shortfall

Considering the use of Nd+Pr in permanent magnets the shortfall is still about 8 kton

Additional production from other companies is critical

Substitution or replacement of $Nd_2Fe_{14}B$ magnets is crucial

Recycling is necessary

SUBSTITUTION

Difficult, if Not Impossible

Most critical applications – magnets, phosphors, lasers - depend on the 4f electronic levels (each lanthanide is different) and the crystal environment

Nd – lasers

Nd, Sm, Dy – permanent magnets

Yes

None for permanent magnets

Partial Substitution

Pr for Nd in NdFeB magnets; 4Nd atoms per 1Pr in original ore

No

(People have been looking – but no luck)

Nd – permanent magnets; used for ~28 years – yet no substitute

Sm – permanent magnets; used for over 31 years – yet no substitute

SUBSTITUTION/REPLACING

REPLACEMENT

Wind turbines – magnetic field generated by $YBa_2Cu_3O_7$ superconductor at 50 K

DOE's RESEARCH EFFORTS FOR SUBSTITUTION OR REPLACEMENT – EERE

Vehicle Technology

Replacement of rare earth magnets by enhanced AlNiCo magnets

Other avenues to reduce the critical rare earth content (Nd,Dy) in currently available NdFeB magnets

Ames Laboratory, DOE lead organization in a consortium of several universities and a company

SUBSTITUTION/REPLACING

DOE's RESEARCH EFFORTS FOR SUBSTITUTION OR REPLACEMENT – ARPA-E

Two Contracts Awarded

University of Delaware (plus 4 universities & 1 company)

High energy density, low RE content: double energy density over current materials

General Electric

Transformational Nano Structure Permanent Magnets

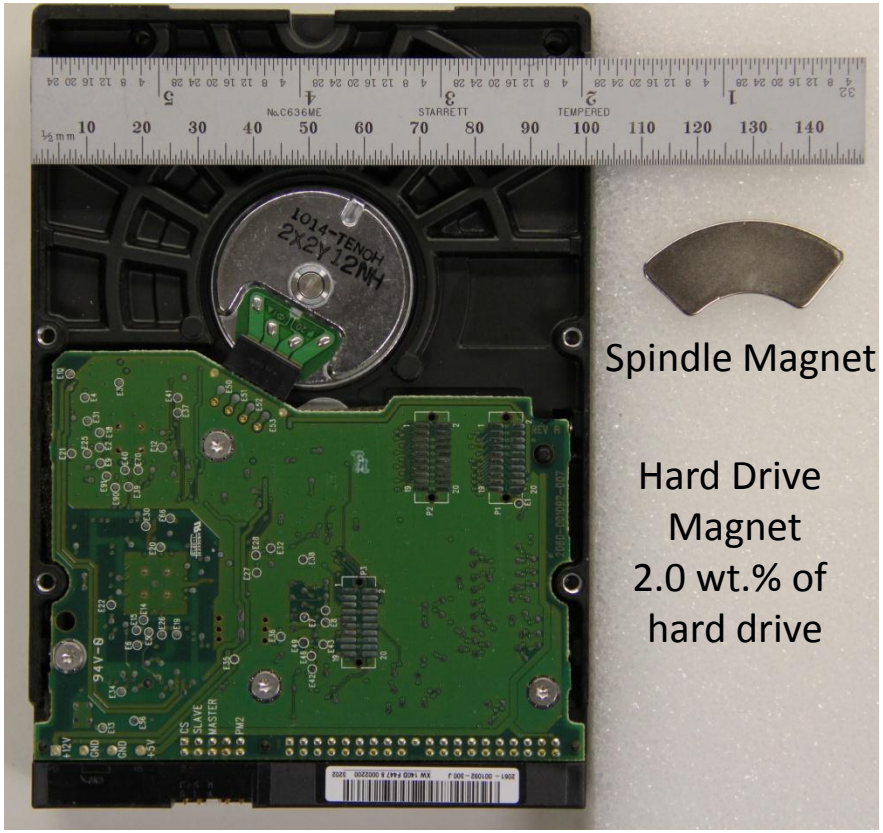
Current solicitation: REACT (Rare Earth Alternatives in Critical Technologies)

zero and 10% of the amount of the REs in currently available magnets

RECYCLING – MAGNETS - I

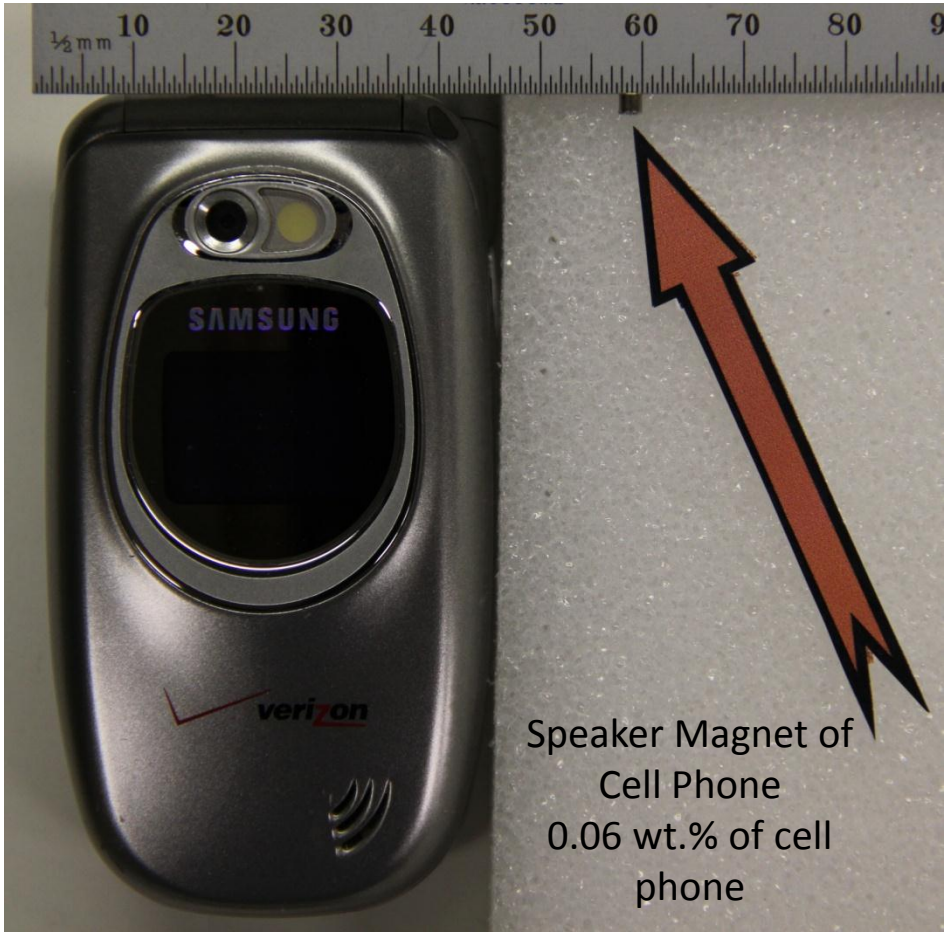
URBAN MINING

Recovering permanent magnets from computers (hard drives), cell phones, etc.



Spindle Magnet

Hard Drive Magnet
2.0 wt.% of hard drive



Speaker Magnet of Cell Phone
0.06 wt.% of cell phone

RECYCLING – MAGNETS - II

Hard drive: $Nd_2Fe_{14}B$ magnets – 2.0 wt.%

recycle the magnet to recover the Nd – 0.5 wt.%

Hitachi found it takes a worker 5 minutes to get a magnet out of the hard drive (12 units/hr.)

Hitachi developed a mechanical method to extract 100 units/hour

Need to increase this by a factor of 100 to be economical

Cell phone:

Speaker magnet: $Nd_2Fe_{14}B$ – 0.06wt.%

Not economical; unless recycled for another materials – already recycling for precious metals, so it may be economical

For comparison:

Best known RE ore source is Mountain Pass Mine: 6-8% REO or 1.5 to 2.0% Nd+Pr

The REO content needs to be >2% to be viable mine, unless it co-produced with another commodity

RECYCLING - FUTURE

Design objects for end-of-life re-utilization of energy critical components

So it is an easy and cost effective way to remove rare earth magnets from electric motors, computers, personal electronic devices

INDUSTRY

Strong US Government Support

Molycorp started RE mining January 2, 2011

beneficiation, separation

IT IS HAPPENING – 2010 House Bill H.R.6160 (Died, No Senate action)

– 2011 House Bill H.R.618 (Revised version of H.R. 6160)

– 2011 Senate Bill S.383 – Critical Minerals (Udall)

Future near-term action of support

- Premanufacture RE materials

  Nd, La, RE compounds
- Manufacturers of intermediate products

  magnets, batteries, phosphors, catalysts, etc.
- Manufacturers of commercial products containing rare earths

  electric motors, batteries, cell phones, monitors, CF lamps
- Loan guarantees in H.R. 618 (also in the 2010 H.R. 6160)

President Obama's 2012 Budget

- New Energy Innovation Hubs – three, one of which is

  critical materials and rare earth elements (EERE)

Companies

Vertically integrate

full spectrum of RE processing and manufacture

Alliances

companies involved in the supply train (mining to products)

SCIENTIFIC & ENGINEERING INFRASTRUCTURE

Training students

- undergraduate, graduate, post-doctorate
- chemistry, chemical engineering, materials science & engineering, physics, electrical engineering

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