RARE EARTH METALS: SUPPLY, DEMAND, RECYCLING, AND SUBSTITUTION

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IOWA STATE UNIVERSITY
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THE Ames Laboratory
Creating Materials & Energy Solutions
U.S. DEPARTMENT OF ENERGY

THE RARE EARTH ELEMENTS IMPACT EVERYONE

Many times a day

- car
- TV
- cell phone
- i-pod
- computer
- electronic displays

They can’t be avoided, except . . .

THE ONLY WAY TO AVOID THE RARE EARTHS

Pack-up a sleeping bag

Head for the deep woods or a cave in the desert

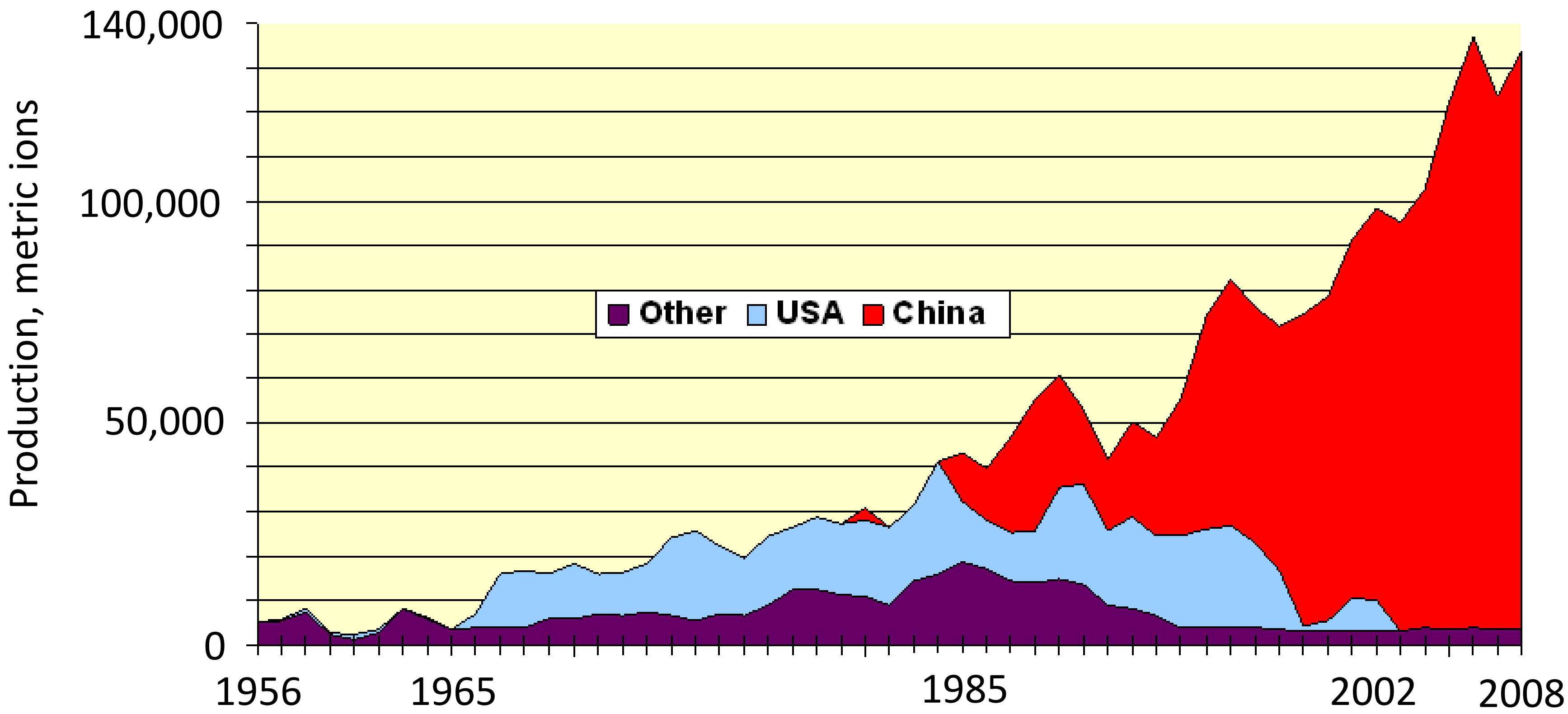
But don't bring your cell phone or lighter flint

ACKNOWLEDGEMENT

Some of the slides for this presentation were taken from talks presented by the following persons at recent conferences or workshops on the rare earth crisis

Dudley J. Kingsnorth	Industrial Minerals Company of Australia, Pty. Ltd.
James B. Hedrick	U.S. Geological Survey – retired
Mark A. Smith	Molycorp Minerals
Yasushi Watanabe	Geological Survey of Japan

REE PRODUCTION TRENDS



Monazite-placer era | **Mountain Pass era** | **Chinese era → ?**

Source: USGS Fact Sheet 087-02 updated with recent USGS Minerals Yearbook

In 2010 China produced (mined) 97% of the rare earths utilized in commerce

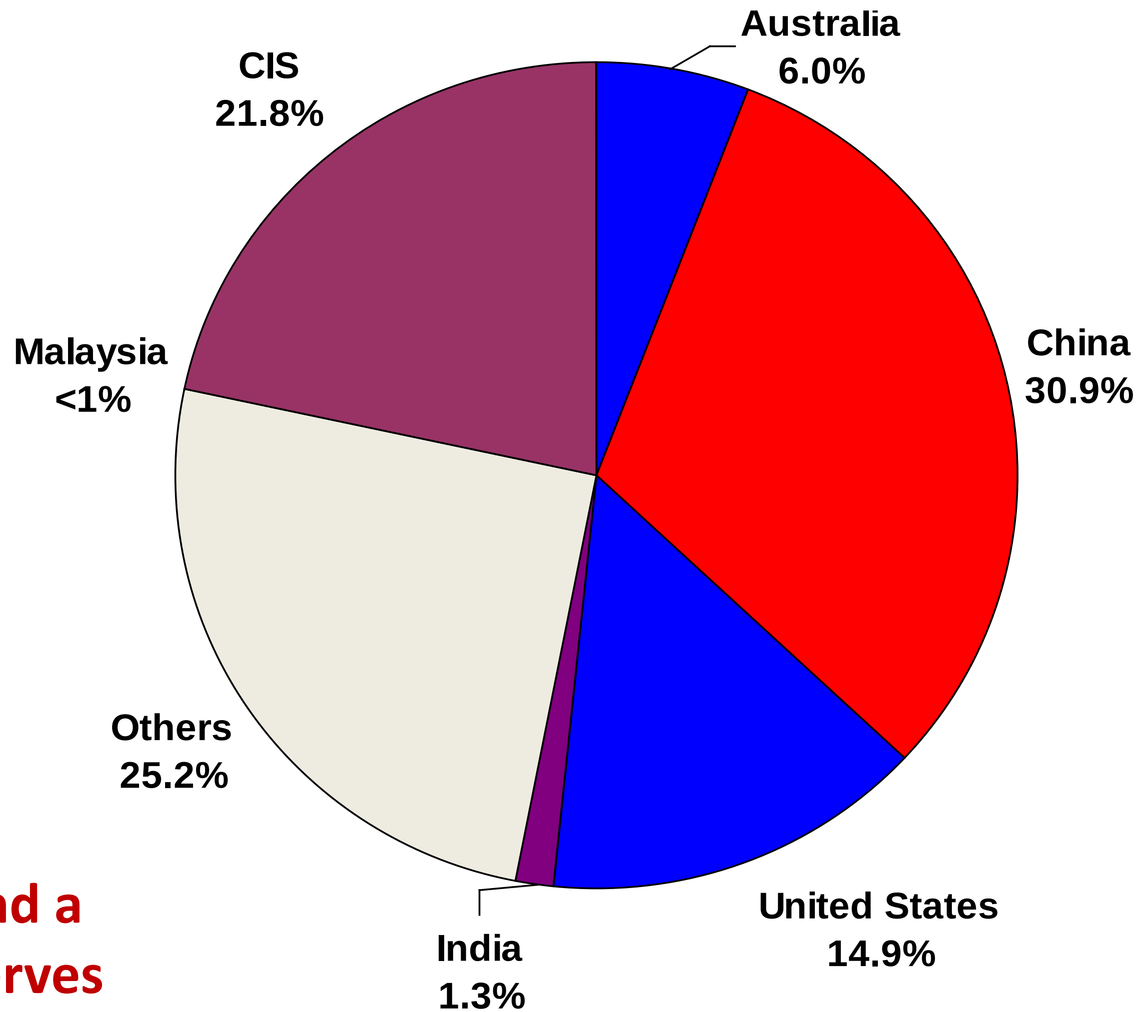
REE MINERAL RESERVES

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



RESERVES
(in percent)

Country	1980[a]	1992	2010
Australia	3	6.1	6.0
China	70[a]	51.3	30.9[b]
India	4	2.7	1.3
CIS	2	0.5	21.8
Malaysia	--	<1	<1
USA	20	15.0	14.9
Other	1	24.4	25.2
Total (M metric tons)	26	84	88

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[a]In 1970 it was 75%.

[b]The actual tonnage of the known Chinese reserves increased by almost 300% from 1980 to 2010.

China: RE Export Transition

- 1970s: Rare earth mineral concentrates.
- 1980s: Mixed rare earth chemical concentrates.
- Early1990s: Separated rare earth oxides and metals.
- Late 1990s: Magnets, phosphors, polishing powders.
- 2000s: Electric motors, computers, batteries, LCDs, mobile phones.

PROBLEMS FOR USA

Military Security

All US weapon systems depend on rare earths – especially $Nd_2Fe_{14}B$ permanent magnets in electric motors, computers, guidance systems, optical displays

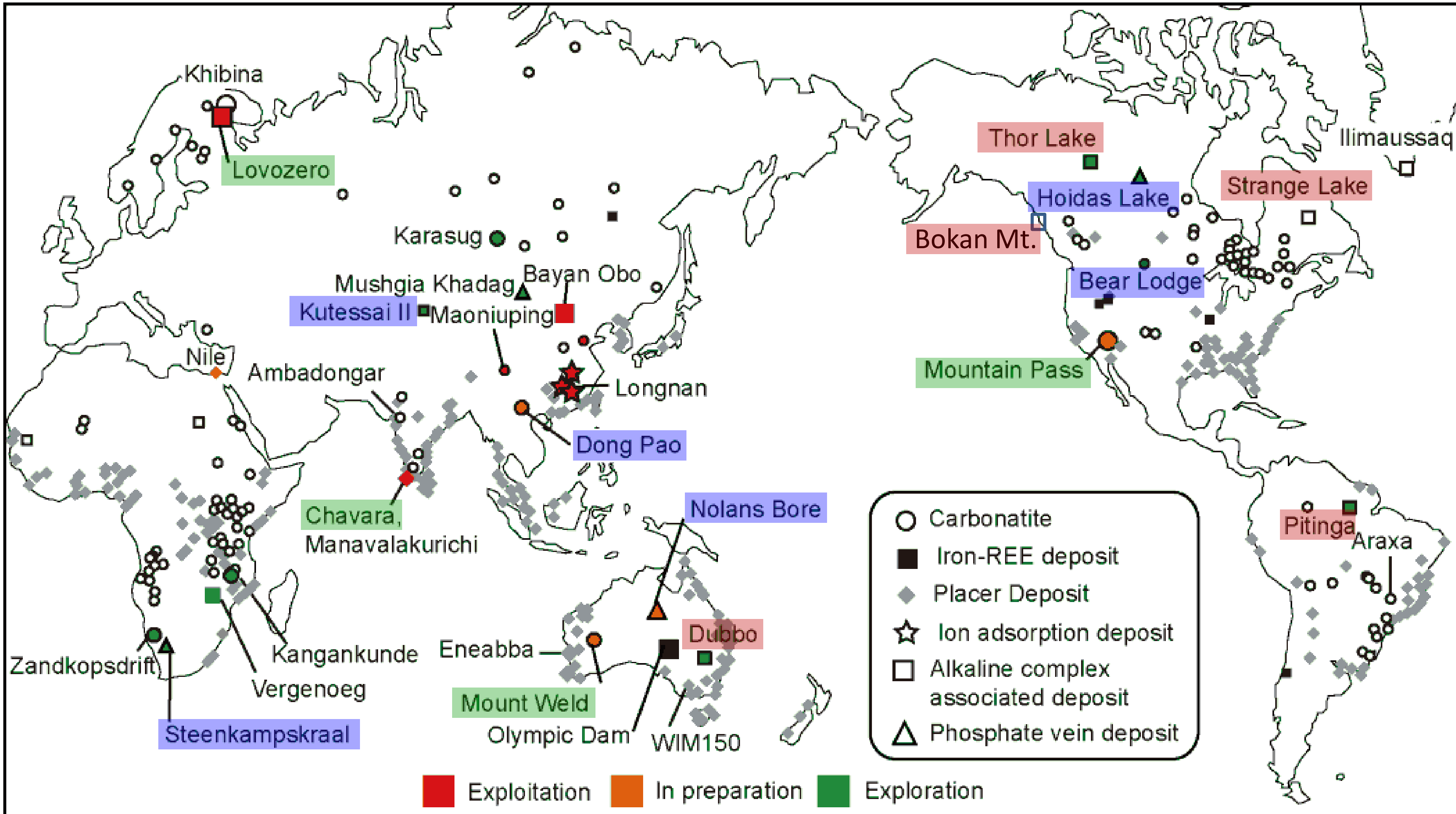
Energy Security

Electric motors and batteries, wind turbines, petroleum refining, optical displays, fluorescent lighting, oxygen and electrical sensors (automotive engines)

U.S. Teenager; Yourself

i-pods, cell phones, TVs, automobiles (gasoline, catalytic converters)

ORE SOURCES AND MINING OPERATIONS



Operational in 2011/12

Operational by 2015/16 (HRE)

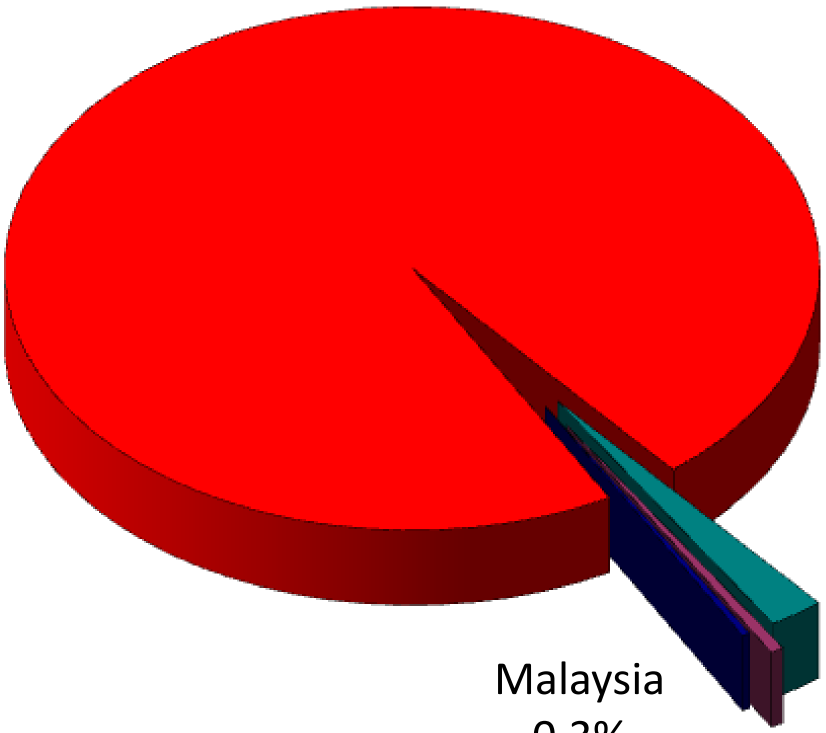
Operational by 2015/16 (LRE)

REE WORLD MINERAL PRODUCTION IN 2010

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

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
- Constraints on Chinese exports are creating opportunities for non-Chinese projects
- Many non-Chinese rare earths projects being evaluated

U.S. AND CANADIAN RARE EARTH DEPOSITS

Ref. K.R. Long *et al.*, U.S. Geological Survey, Scientific Investigations Report 2010-5220

U.S. MINES

Expected Dates for the Beginning of Mining

Mountain Pass, California Carbonatites	Molycorp[a]	2010
Bokan Mountain, Alaska[b] Peralkaline Igneous	Ucore Uranium (Canada)	2014
Bear Lodge, Wyoming Carbonatites	Rare Element Resources	2015
Lemhi Pass, Idaho Vein deposit		>2015
Pea Ridge Mine, Missouri[b,c] Fe mine, by-product		>2015
Mineville, New York[b] Fe mine, by-product		>2015

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[a]Mined 3000 tons in 2010, full production (20,000 tons) in 2012; 40,000 tons in 2013
[b]Deposits listed in green print are heavy rare earth deposits
[c]Iron mine being reopened in 2012.

CANADIAN MINES

Expected Dates for the Beginning of Mining

Hoidas Lake, Saskatchewan phosphate vein	Great Western	2015
Thor Lake, Northwest Territories fergusonite (R-Fe-Nb-Ti-Ta) – zircon deposit	Avalon	2015

RECENT DEVELOPMENTS

Molycorp buys controlling interest in Silmet,
Ida-Virumaa, Estonia
500 tons loparite from Kola Peninsula, Russia
2500 tons from open market, now Molycorp

Molycorp buys Santoku America, Inc, Tolleson, AR
manufacture rare alloys and metals

Mongolia (not Inner Mongolia) begins shipping rare earth mineral concentrates for processing
somewhere in ROW via Trans-Siberian Railway
(Russia) to Vladivostok
By-product of Ta mining (?)

Applications For Rare Earth Elements

Catalysts
- Petroleum refining
- Chemical processing
- Catalytic converter
- Diesel additives
- Industrial pollution scrubber

Electronics
- Display phosphors (CRT, PDP, LCD)
- Medical imaging phosphors
- Lasers
- Fiber Optics
- Optical temperature sensors

Glass
- Polishing compounds
- Optical glass
- UV resistant glass
- Thermal control mirrors
- Colorizers/ Decolorizers

Rare Earths

Other


- Water Treatment
- Fluorescent lighting
- Pigments
- Fertilizer
- Medical Tracers
- Coatings

Ceramics


- Capacitors
- Sensors
- Colorants
- Scintillators

Magnets


- Motors
- Disc drives & disk drive motors
- Power generation
- Actuators
- Microphones & speakers
- MRI
- Anti-lock brake system
- Automotive parts
- Communication systems
- Electric drive & propulstion
- Frictionless bearings
- Magnetic storage disk
- Microwave power tubes
- Magnetic refrigeration
- Magnetostrictive alloys

Metal Alloys


- Hydrogen storage (NiMH batteries, Fuel cells)
- Steel
- Lighter flints
- Aluminum/ Magnesium
- Cast iron
- Superalloys

SUBSTITUTION

Difficult, if Not Impossible

- Most critical applications – phosphors, magnets
  - Depend on the 4f electronic levels (each lanthanide is different) and crystal environment
    - Eu – red phosphor: TV and color displays
    - Tb – green phosphor: TV and color displays
    - Nd – lasers
    - Nd, Sm, Dy – permanent magnets
    - Er – fiber optics
    - La, Y, Gd – absence of 4f level – optical & electronic

- Applications of unseparated rare earths
  - Depend upon the valence state and average atomic size of the rare earths in the mixture
    - petroleum cracking catalysts (FCC catalysts)
    - alloy additives – Mg, Al, cast iron

- Mixed valence applications
  - CE(III)-CE(IV) – glass polishing, UV resistant glass, catalytic converters

SUBSTITUTION – YES or NO EXAMPLES

YES

Mischmetal for La in Ni metal hydride batteries

Rouge (Fe oxides) for CeO_2/Ce_2O_3 in glass polishing

(However Ce is not in short supply – excess)

PARTIAL SUBSTITUTION

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

Y – high temperature superalloys – used for ~30 years

Al, Cr, could be utilized instead of Y

NO (People have been looking – but no luck)

Eu – red color in TV; used for ~50 years, yet no substitute

Nd – permanent magnets; used for ~27 years, , yet no substitute

Sm – permanent magnets; used for over 30 years, , yet no substitute

Ce – 3-way catalytic converters (automotive exhaust) – used for ~30 years – yet no substitute

Mixed REO FCC catalysts – used for ~47 years (Half-life of a new catalyst is ~5 years) – yet no substitute

RECYCLING - PHOSPHORS

Phosphors in fluorescent lighting Y, Eu, Tb
- Lamps also contain Hg

Government needs to require all fluorescent lamps be returned to a recycle center – remove Hg (and recover REs) – to keep Hg out of the waste stream, land fills

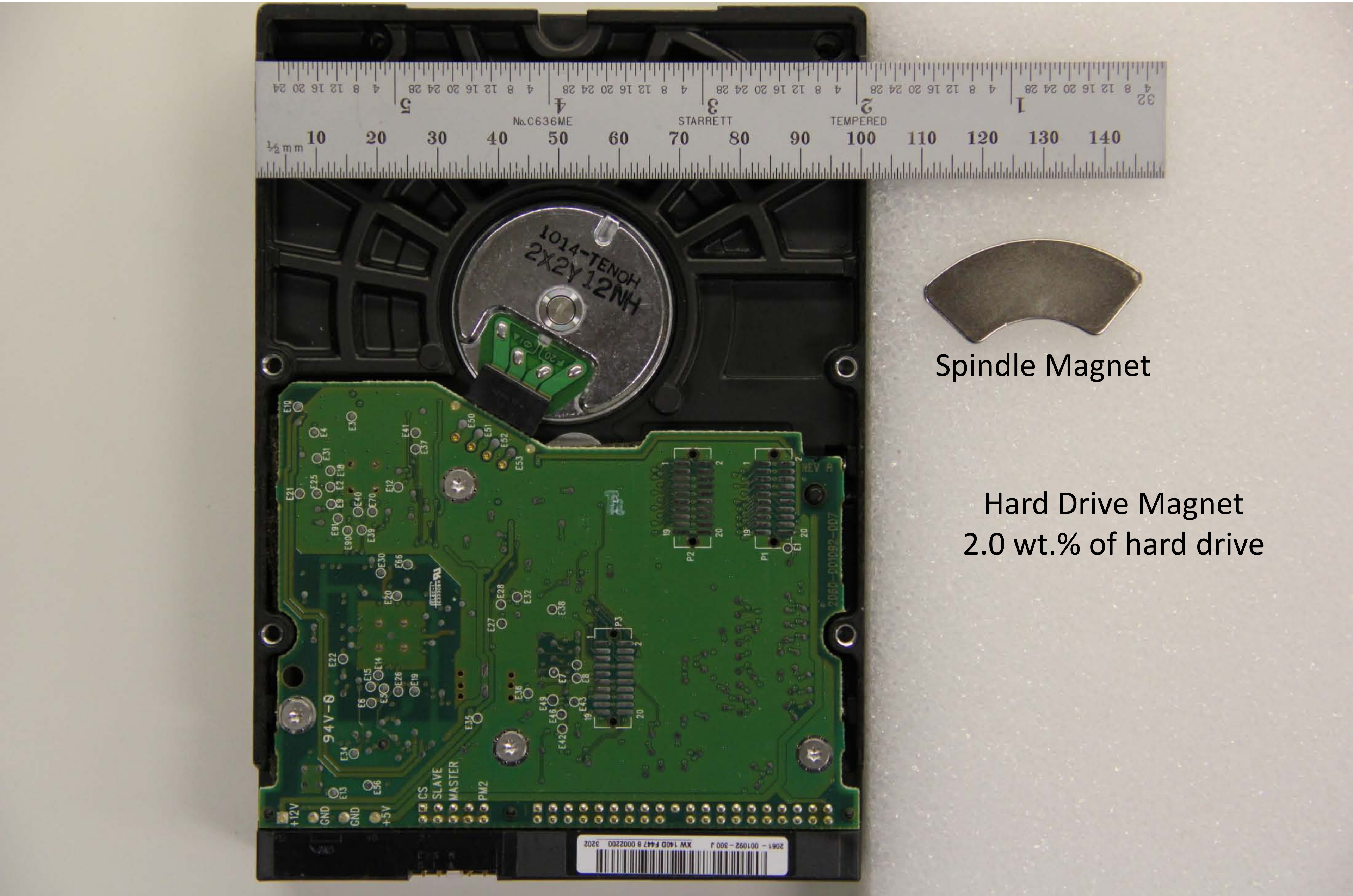
Some recycling research going on presently in USA
- CFC and long tubes

RECYCLING - BATTERIES

Today all car batteries have to be returned to centers to remove the lead.

Should be able to use these centers to recover the La or mixed rare earths, and the Ni

Ni is a carcinogen


Spindle Magnet
Hard Drive Magnet
2.0 wt.% of hard drive

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

RECYCLING – MAGNETS - I

URBAN MINING

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

RECYCLING ELECTRONIC DEVICES

- Joint venture between Creative Recycling and Green Rock (announced in March 2010)
  - Includes rare earths

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 material(s) – then perhaps 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, La-Ni metal hydride batteries, etc.

Rare Earths Project Essentials

- Compliant resource/reserve
- Rare earth minerals amenable to concentration
- Continuous pilot plant to demonstrate/provide:
  - Ability to produce products to customer specifications
  - Data for bankable feasibility study
  - Data for environmental impact statement, including radioactive waste management
  - Viability of project for investors and banks
- Access to labour, power, water and chemicals
- Realistic marketing strategy
- Adequate funding including working capital
- Realistic construction and start-up schedule

($\geq$ 500 M$)

15

IMCOA

About 10 years from initial start to having rare earths come out of the mine.

THE OUTLOOK FOR 2015

(Dudley Kingsnorth, IMCOA)

- Supply will be tight.
- ‘Balance’ will still be an issue; so prices for Nd, Tb, and Dy will remain strong.
- Potential large surplus of Ce. Chinese have raised prices and controlled exports.
- China will not ‘starve’ the ROW of rare earths.
- Several new projects should be on-stream
- Demand: 190-210,000tpa RWO – **will be met.**

WIND TURBINES

Demand by both China and ROW may invalidate Kingsnorth's predictions

Nd – supply will be extremely tight

mines may not produce enough Nd in ROW even in 2015.

1.5MW Generator

Requires: ~1000kg Nd-Fe-B magnet or ~250 kg Nd metal

WILL THE CHINESE CUT THE PRICE OF RARE EARTHS IN THE FUTURE?

NOT LIKELY – BECAUSE

South China clays will be depleted in 10 to 15 years (the main source for the heavy rare earths)

Chinese economy is growing so fast they will need all of Chinese rare earths by 2015 at the latest

Chinese do not want to use their vast, but finite, resources to supply the rest of the world (ROW) high tech products

GSCHNEIDNER'S FORECAST

USING

- Dudley Kingsnorth projections
- Published information from non-Chinese companies planning on mining RE ores

PREDICTION

- There will be a 13% surplus of REO on the market between 2015 and 2020
- Because of over production, weak companies will go out of business, the strong will survive.

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

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

JAPAN'S SUPPORT FOR RARE EARTH RESEARCH

$1.25B to develop rare earth market

$150M	for substitutions and reduction of RE content
$38 M	recycling
$490M	capital improvements to RE industry
$370M	new mine ventures
$180M	guarantee new mining debit
$25M	for the resource country

Also government support for

off-shore minerals reserve development including:

- exploration
- image analysis
- analytic costs

GLOBALIZATION

The rare earth deposits are everywhere in the world

No country has a stranglehold (in theory)

Some deposits are more economically viable

amount RE in ore body

infrastructure (transportation, power, water)

Rare earths are utilized everywhere

more so in developed world

less so in third world countries

SUSTAINABILITY

Difficult

- Amounts of rare earths in a given product is small recovery or recycling may not be economically feasible

Solutions

- Strive to reduce amount of REs in the product
- Improve the efficiency of the various processes in the manufacture of a product
- Find alternate non-rare earth materials to replace the rare earth components
- Design products so that at the end-of-life the critical materials (e.g. REs) are more easily recovered for recycling
- Design products to use the least amount of REs possible – do not over design