



Rare-Earth Industry Overview and Defense Applications

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U.S. Department of the Interior
U.S. Geological Survey

Rare Earths Defined

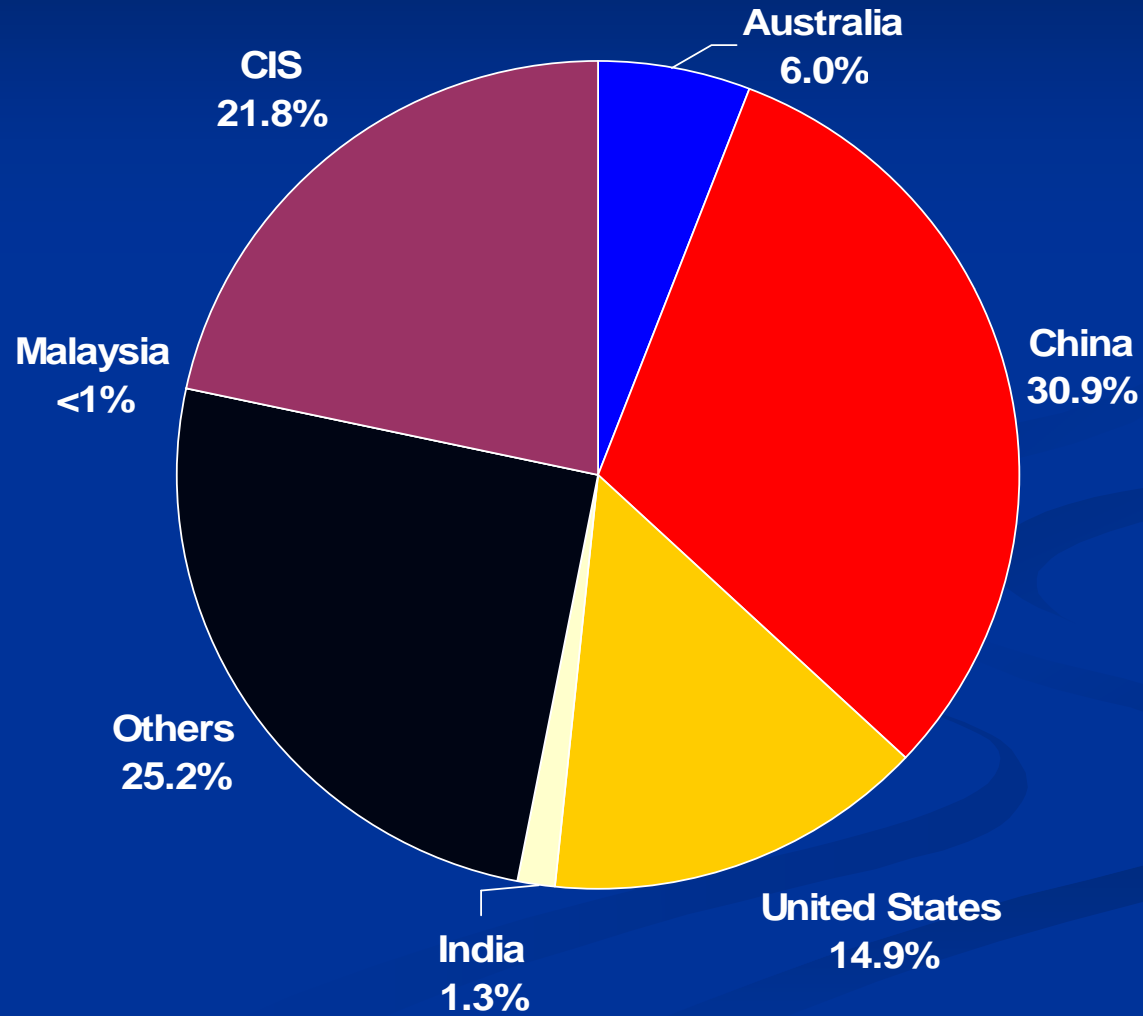
- The rare earths are not rare, nor are they earths
- Rare earths are a group of 17 elements comprising scandium, yttrium, and the lanthanides
- The lanthanides are a group of 15 elements: lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium
- The rare-earth elements are abbreviated “REE”

Periodic Table

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt									
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

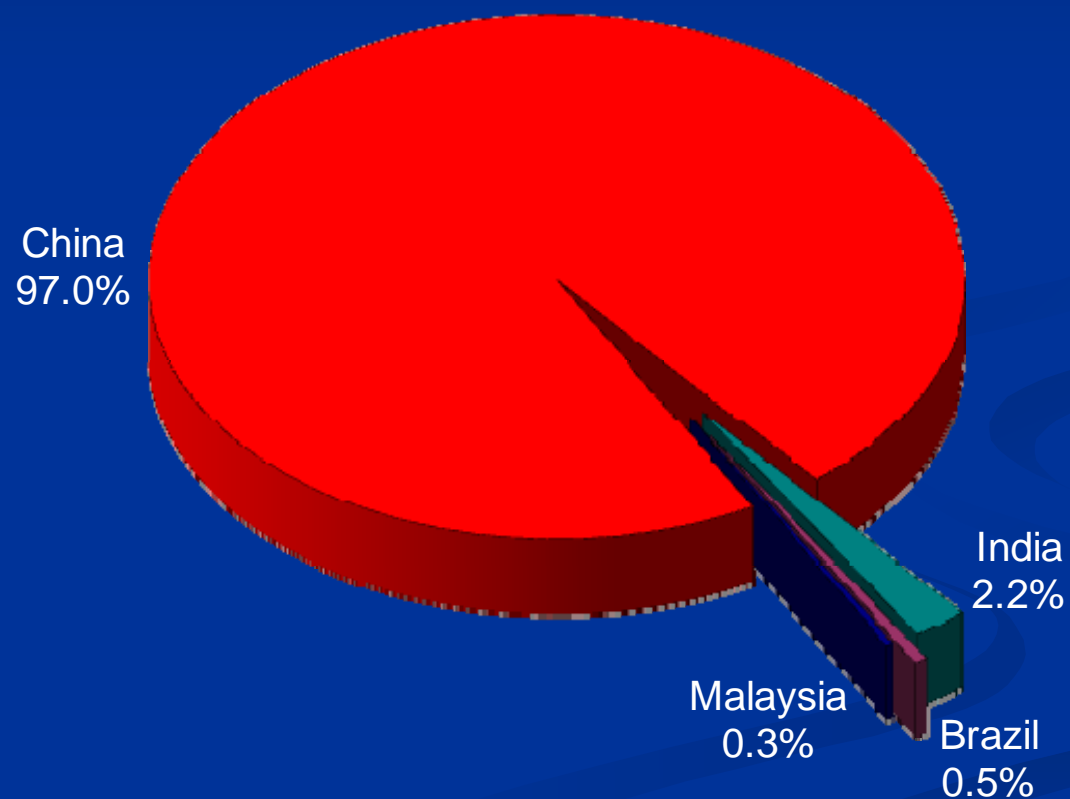
REE Mineral Reserves

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



REE World Mineral Production in 2008

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



Rare Earth Ores

- Bastnäsite-(Ce) $(\text{Ce, La, Nd, Pr})(\text{CO}_3)\text{F}$
- Monazite-(Ce) $(\text{Ce, La, Nd, Th})\text{PO}_4$
- Xenotime-(Y) YPO_4
- Loparite-(Ce) $(\text{Ce, Na, Ca})(\text{Ti, Nb})\text{O}_3$
- Ion adsorption type (IAT) REE ions adsorbed on clay- formed from lateritic weathering
 - Ion adsorption clay Y-rich
 - Ion adsorption clay La, Nd-rich

Principal Rare-Earth Deposits

■ Bastnäsite

- Mountain Pass, CA, USA
- Bayan Obo, Inner Mongolia, China
- Mianning, Sichuan Province, China
- Weishan Lake, Shandong Province, China

■ Monazite

- Kerala State, Tamil Nadu State, and Orissa State, India

■ Lateritic ion-adsorption clay

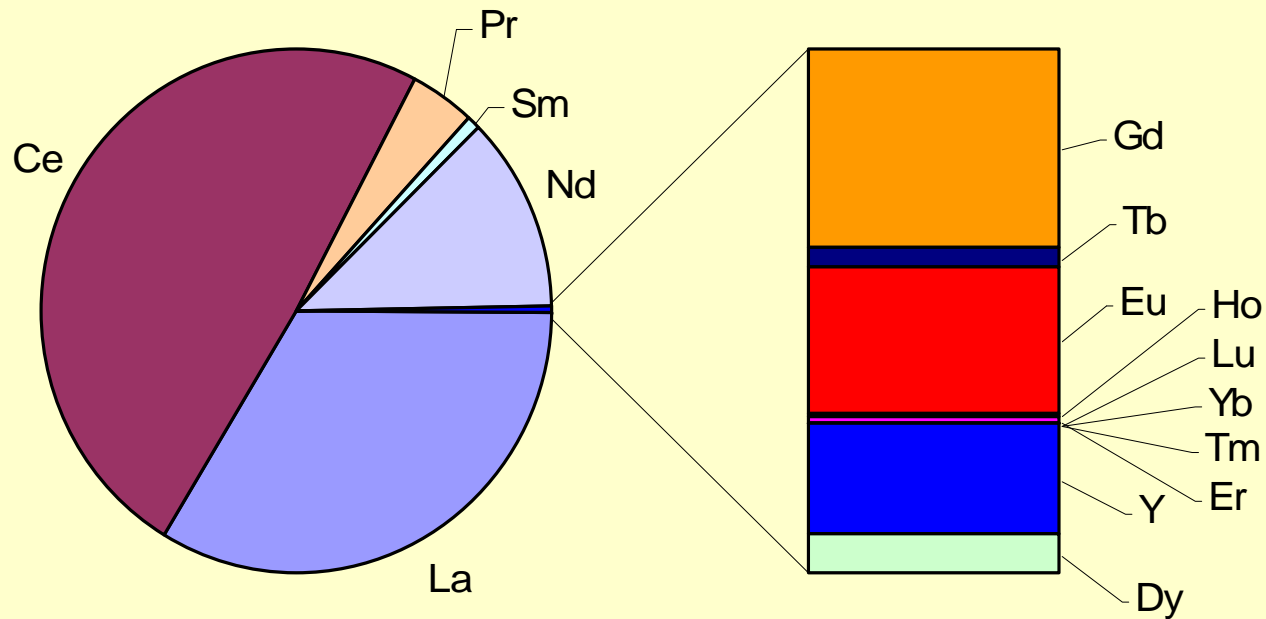
- Xunwu, Jiangxi Province, China
- Longnan, Jiangxi Province, China

■ Loparite

- Lovozero, Kola Peninsula, Russia

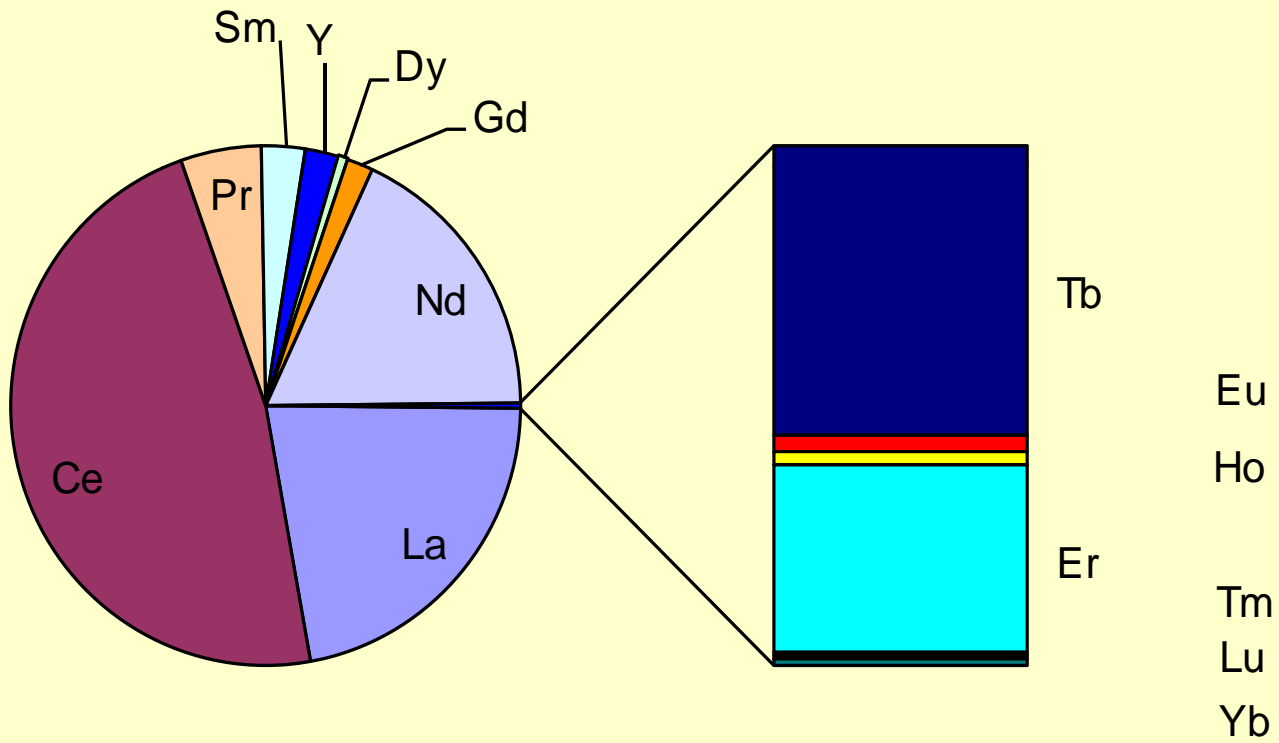
Bastnäsite Mountain Pass, CA

Weight Percent of Total Recovered REE:
Bastnäsite (Mountain Pass, CA)



Monazite Australia

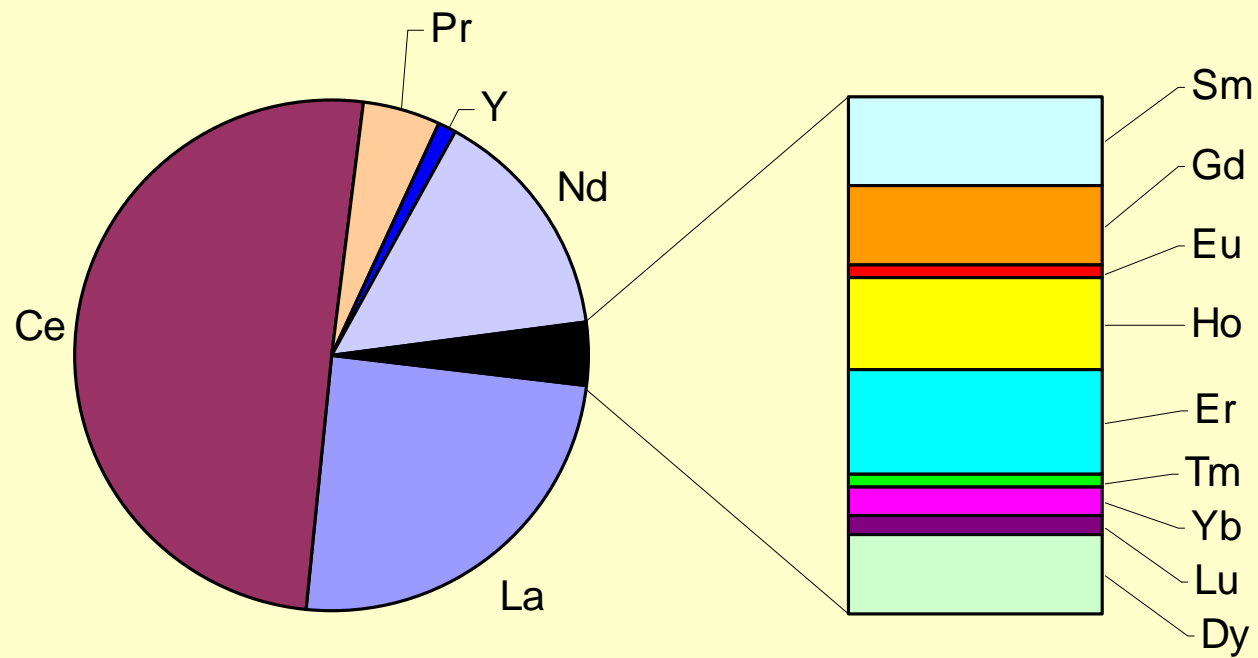
Weight Percent of Total Recovered REE:
Monazite (Australian)



Source: Westralian Sands, Ltd., 1979.

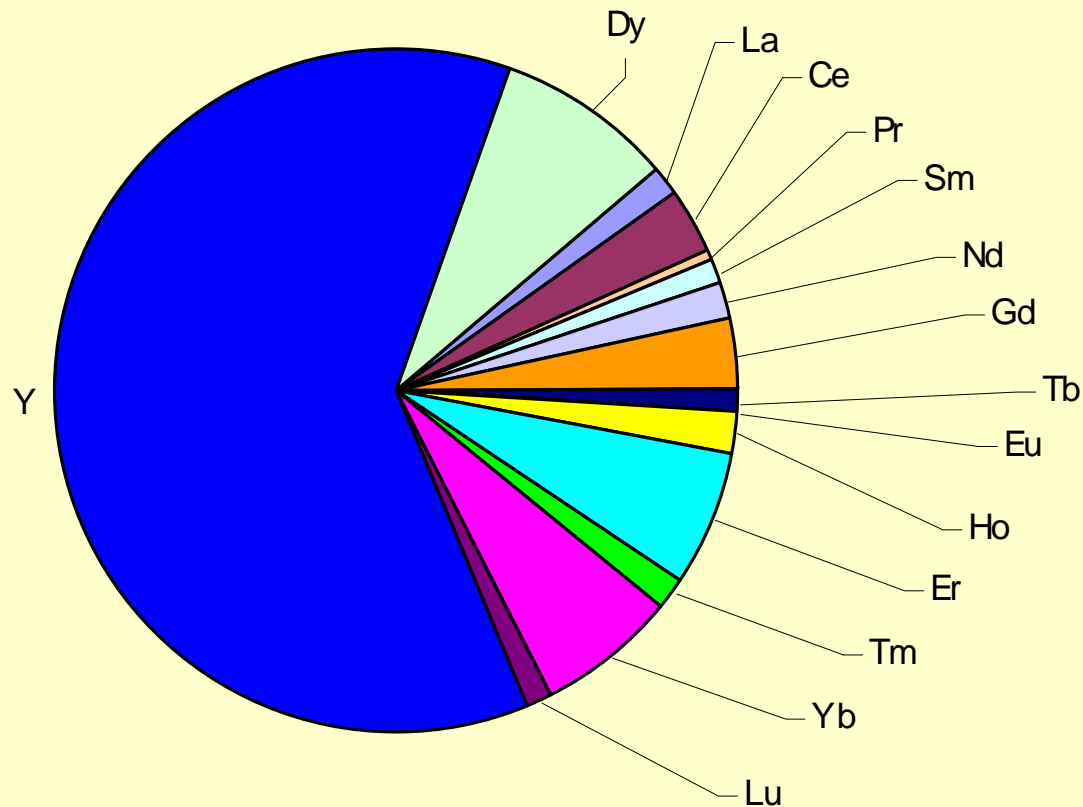
Loparite Russia

Weight Percent of Total Recovered REE:
Loparite (Russia)



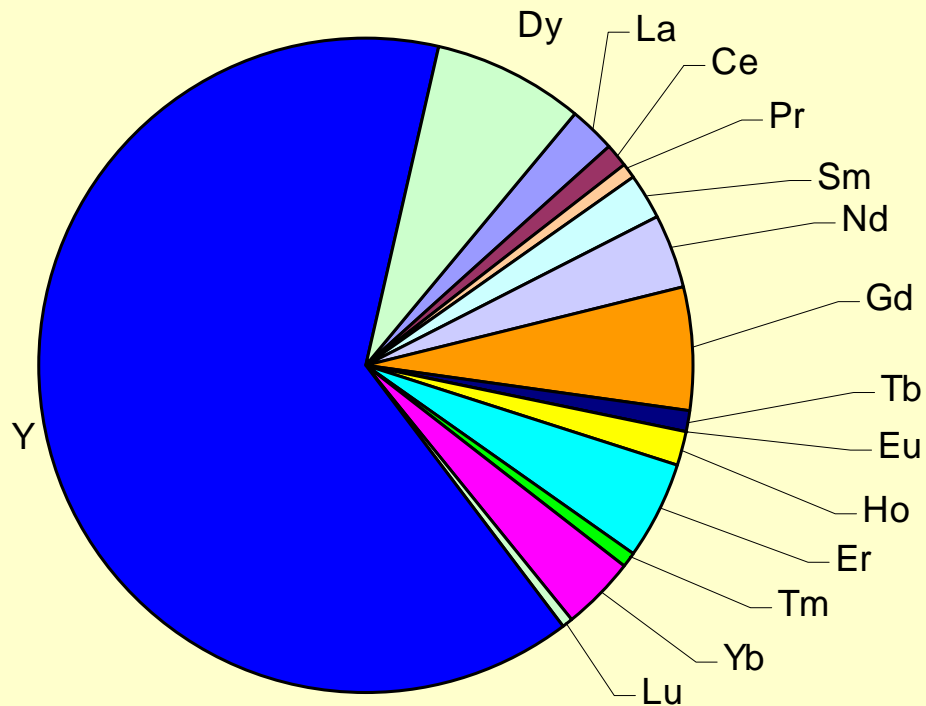
Xenotime Malaysia

Weight Percent Of Total Recovered REE:
Xenotime (Malaysian)



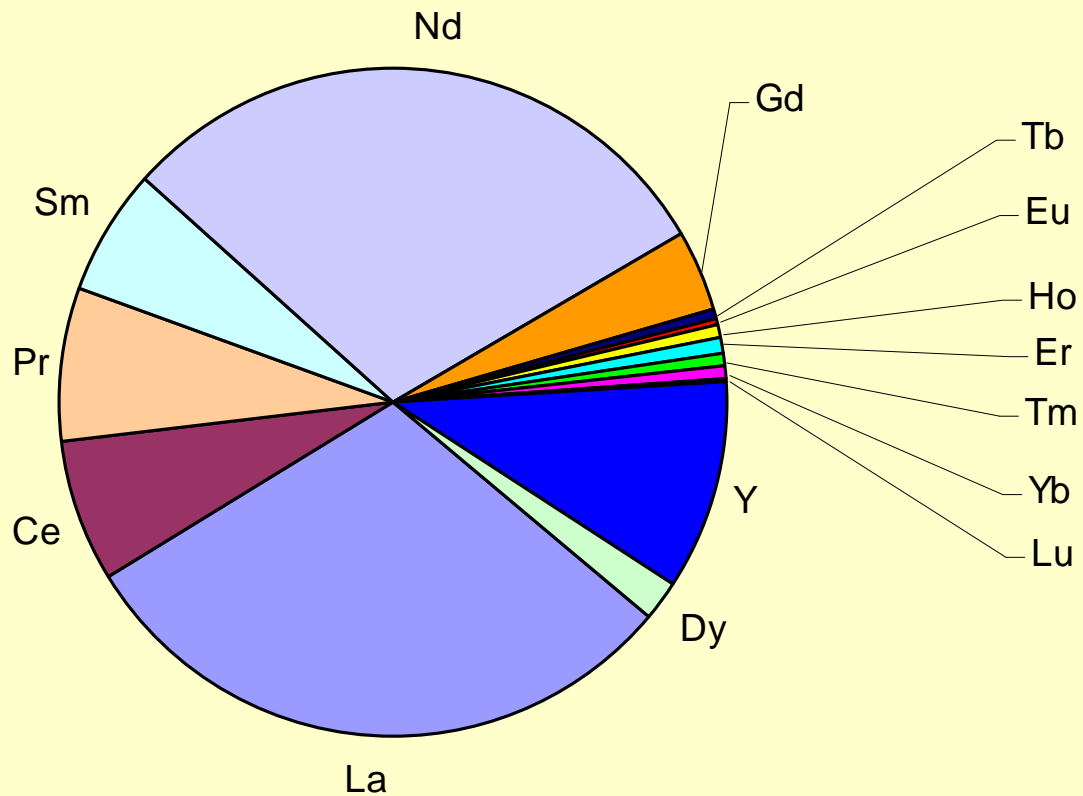
IAT Ore – yttrium rich Longnan, Jiangxi Province, China

Weight Percent of Total Recovered REE:
Longnan Lateritic Ore (China)

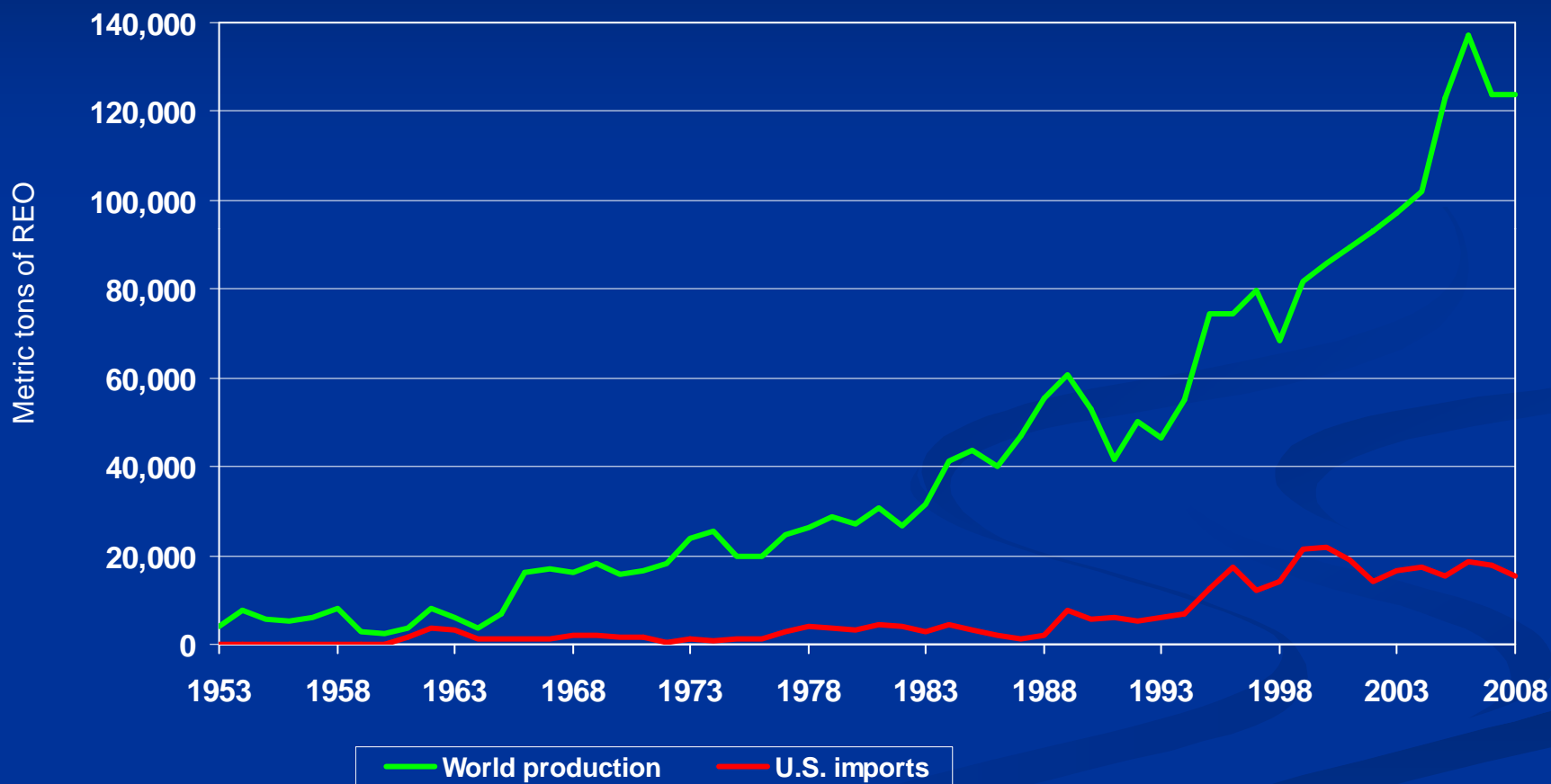


IAT Ore – Nd and La rich Xunwu, Jiangxi Province, China

Weight Percent of Total Recovered REE:
Xunwu Lateritic Ore (China)



Rare Earth World Production and U.S. Imports



Mineral Processing



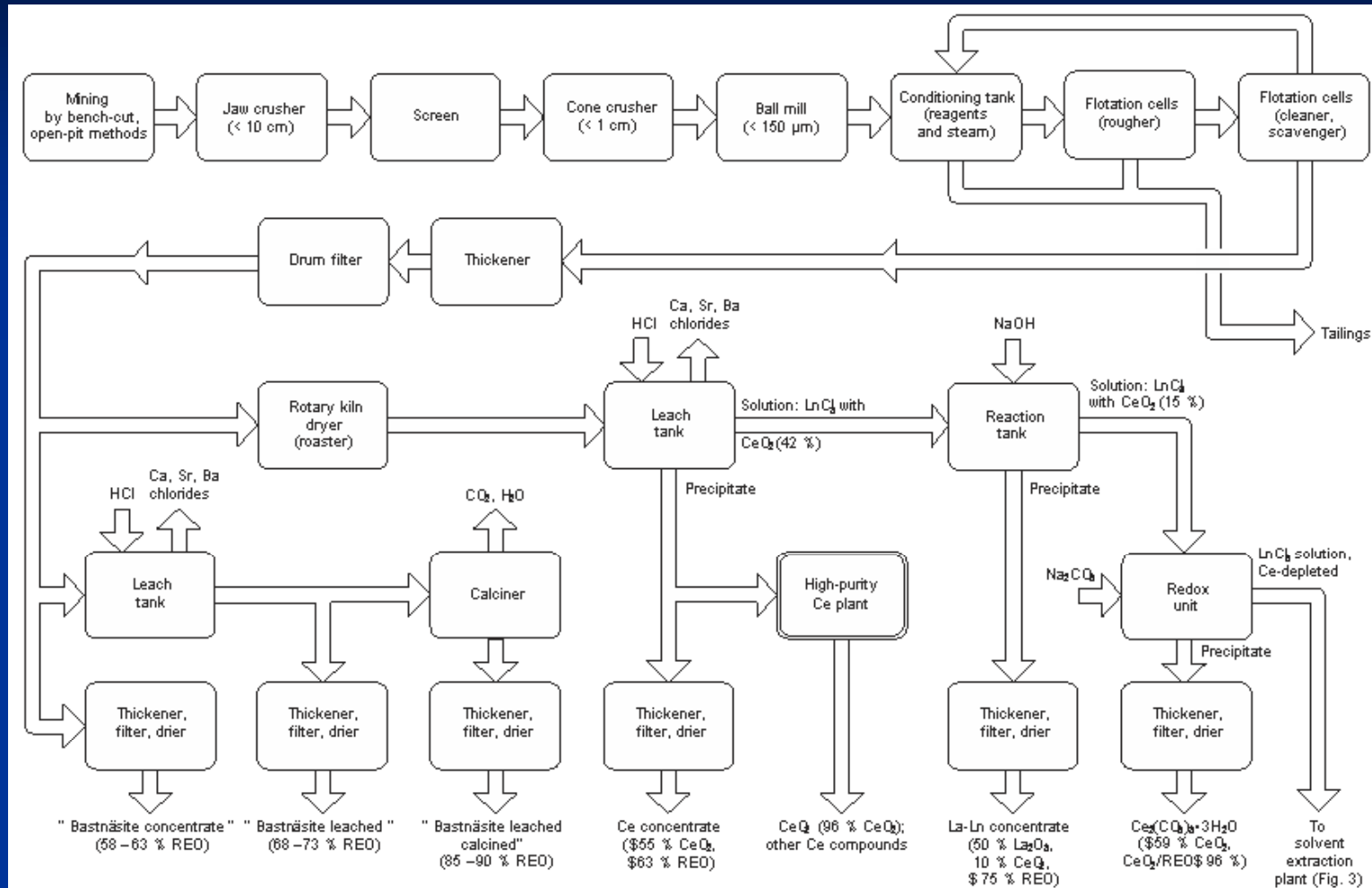
The rare earths perplex us in our researches, baffle us in our speculations, and haunt us in our very dreams. They stretch like an unknown sea before us, mocking, mystifying, and murmuring strange revelations and possibilities.

Sir William Crookes, 1902

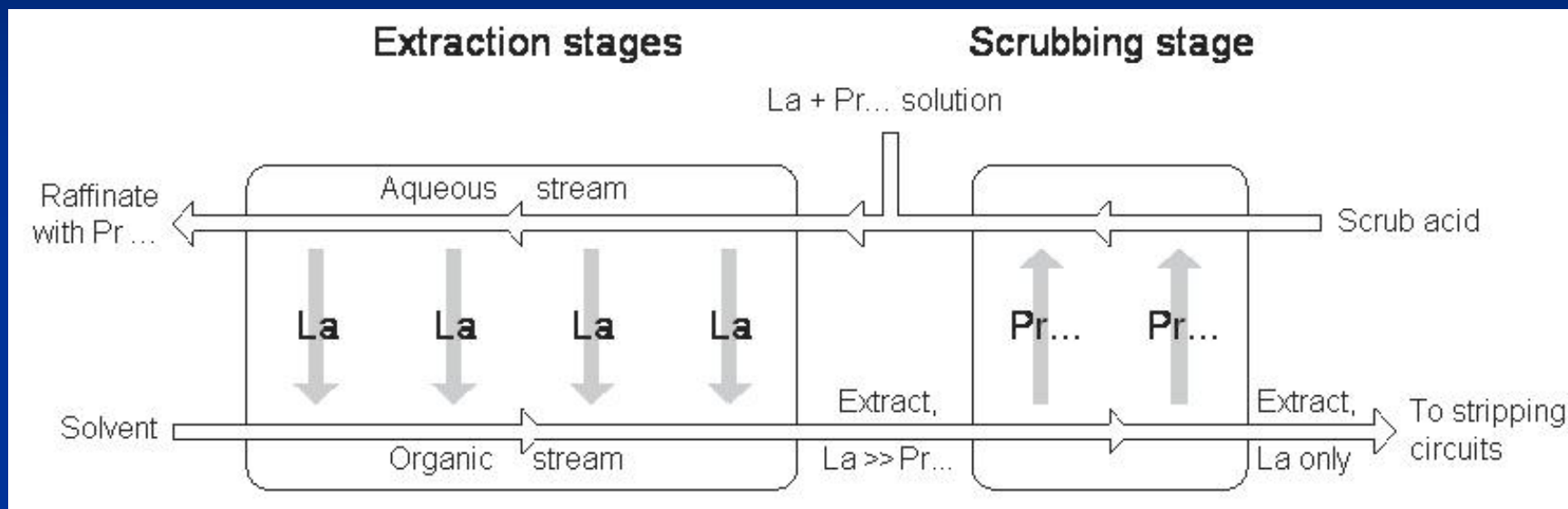
In point of respectability your radium family will be a Sunday school compared with the rare earth elements, whose chemical behavior is simply outrageous. It is absolutely demoralizing to have anything to do with them.

Bertram Boltwood, 1905

Beneficiation of Bastnäsite

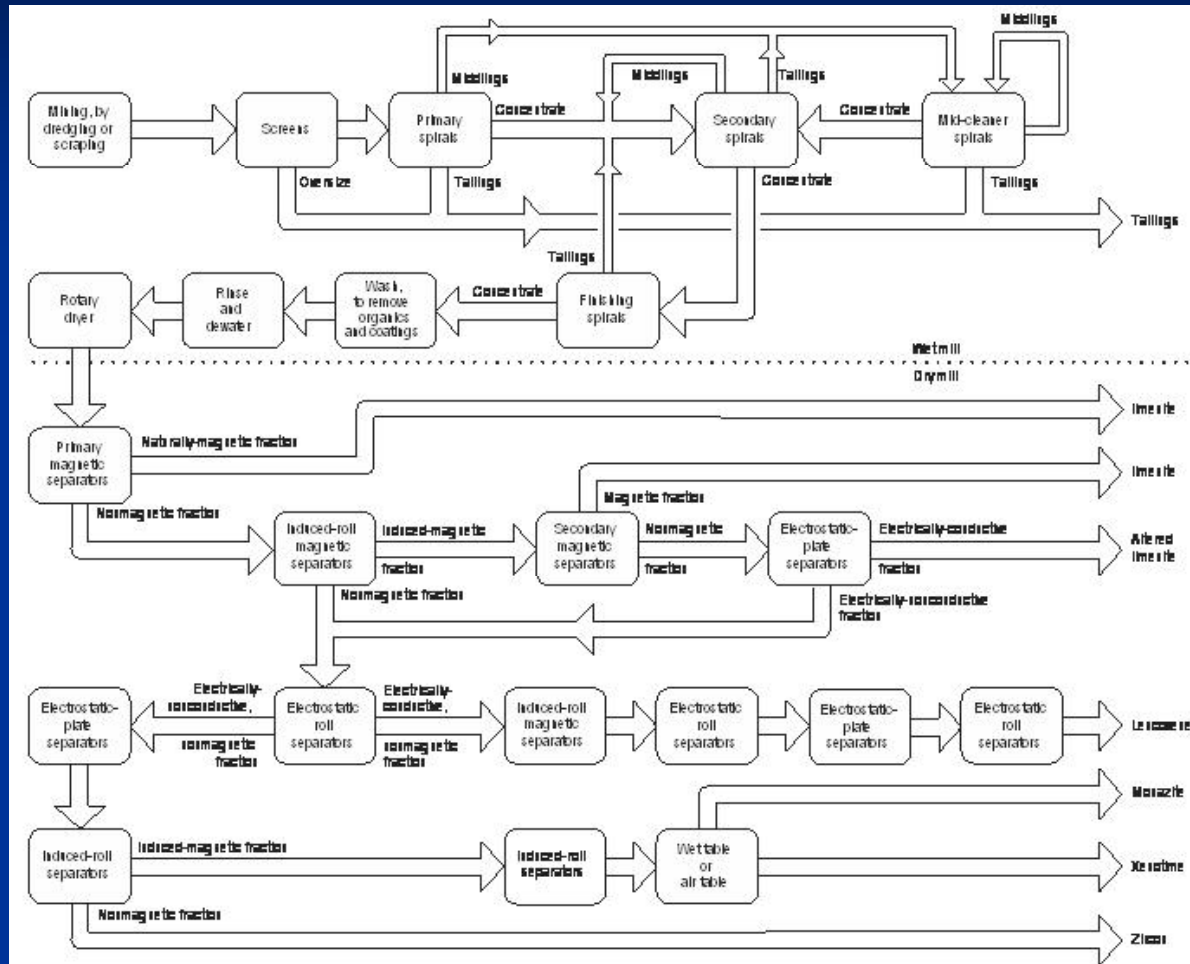


Solvent Extraction (SX) Processing



- Immiscible solutions of an organic solvent and aqueous raffinate are mixed mechanically and then allowed to separate, enriching the solvent in a particular rare earth.
- The longer the solutions are mixed and allowed to separate, the higher the purity.

Beneficiation of Placer Monazite Wet and Dry Mill (Generalized)



Defense Applications



Samarium-cobalt magnets in motors for flight control surfaces

■ AIM-9X Sidewinder



■ AIM-120 AMRAAM



■ AIM-54 Phoenix



AIM-120 AMRAAM Missile

- Sm-Co magnets used by mid-fuselage fins
- Improved Electronic Counter Counter Measures (ECCM) with jamming detection, an upgraded seeker, and a longer range – rare earths in ECCM



BGM-109D Tomahawk Cruise Missile

Tail control fins use direct drive RE magnet actuators



Smart Bombs—Joint Direct Attack Munitions (JDAM)

- Nd-Fe-B magnets control fins of gravity guided bombs linked to a GPS system
- Magnets for JDAM made in China



Nd:YAG Laser

Designator-Rangefinder



Laser Targeting System
on Abrams M1A1 Tank



F-15 With Yttria-Stabilized Zirconia



Coating in hot section of engine to protect metal alloy

F-117 Avionics with REE Phosphors



Sonar Transducers for Submarines

- Terfenol-D® Tb-Fe-Ni alloy with Dy - magnetostrictive alloy
- Magnetic domains in the crystal rotate when a magnetic field is applied which creates a sonar ping.



Radar Surveillance

- Rare-earth magnet waveguides in travelling wave tubes (TWT) and klystrons
- Yttrium iron garnet (YIG) and yttrium gadolinium garnet (YGG) in phase shifters, tuners, and filters
- Rare earths are used in pulsed and continuous wave radar, satellite communication



Electronic Warfare

- **Electronic Intelligence (ELINT)**
 - **Electronic Countermeasures (ECM)**
 - Support Jamming
 - Self-Protect Jamming
 - **Electronic Surveillance Measures (ESM)**
- **Both ESM and ECM use Yttrium Iron Garnets (YIG) and Yttrium Gadolinium Garnets (YGG)**

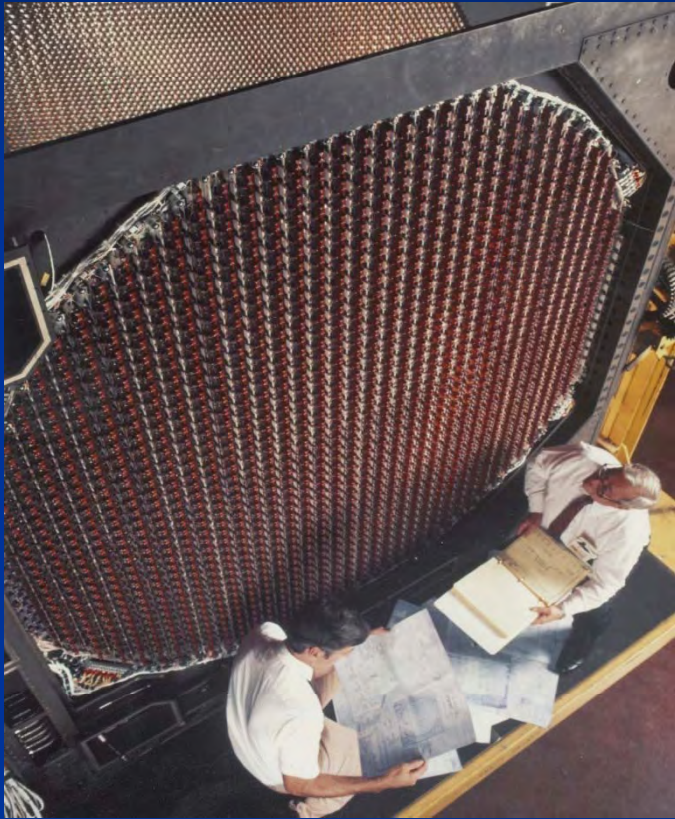
Ferrite-Enabled Defense Systems

Yttrium iron garnet (YIG) – Yttrium gadolinium garnet (YGG)

- **Phased-Array Radars—Patriot, Aegis, B-1B, Joint STARS, SPQ-9B**
- **Communication Satellites—DSCS III, MILSTAR, Advanced EHF, Classified**
- **Communication Systems**
 - F-22 Intra-Flight Data Link, Dark Star and newer UAV Data Links
 - Potential JSF, UCAV, etc.
- **ECM Systems**
 - ALQ-172 (B-52, AC-130), ALQ-178 (F-16)
 - ALQ-211 (AH-64D, MH-47, MH-60, CV-22)

PATRIOT Phased-Array TRacking to Intercept Of Target

solid state phased array radar

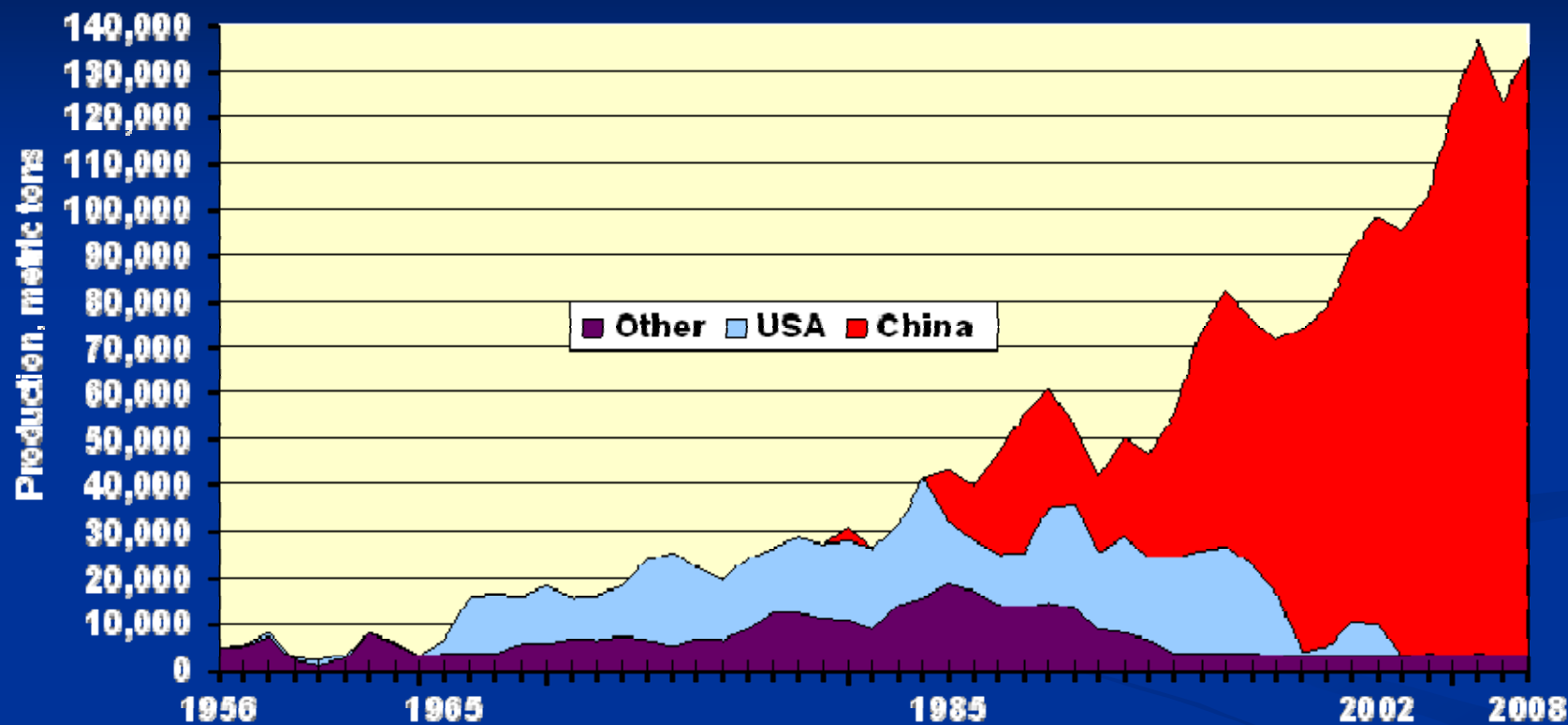


YIG and YGG used in toroids and RF (radio frequency) circulators

BMEWS Ballistic Missile Early Warning System solid state phased array radar



REE Production Trends



Monazite-placer
era

Mountain Pass
era

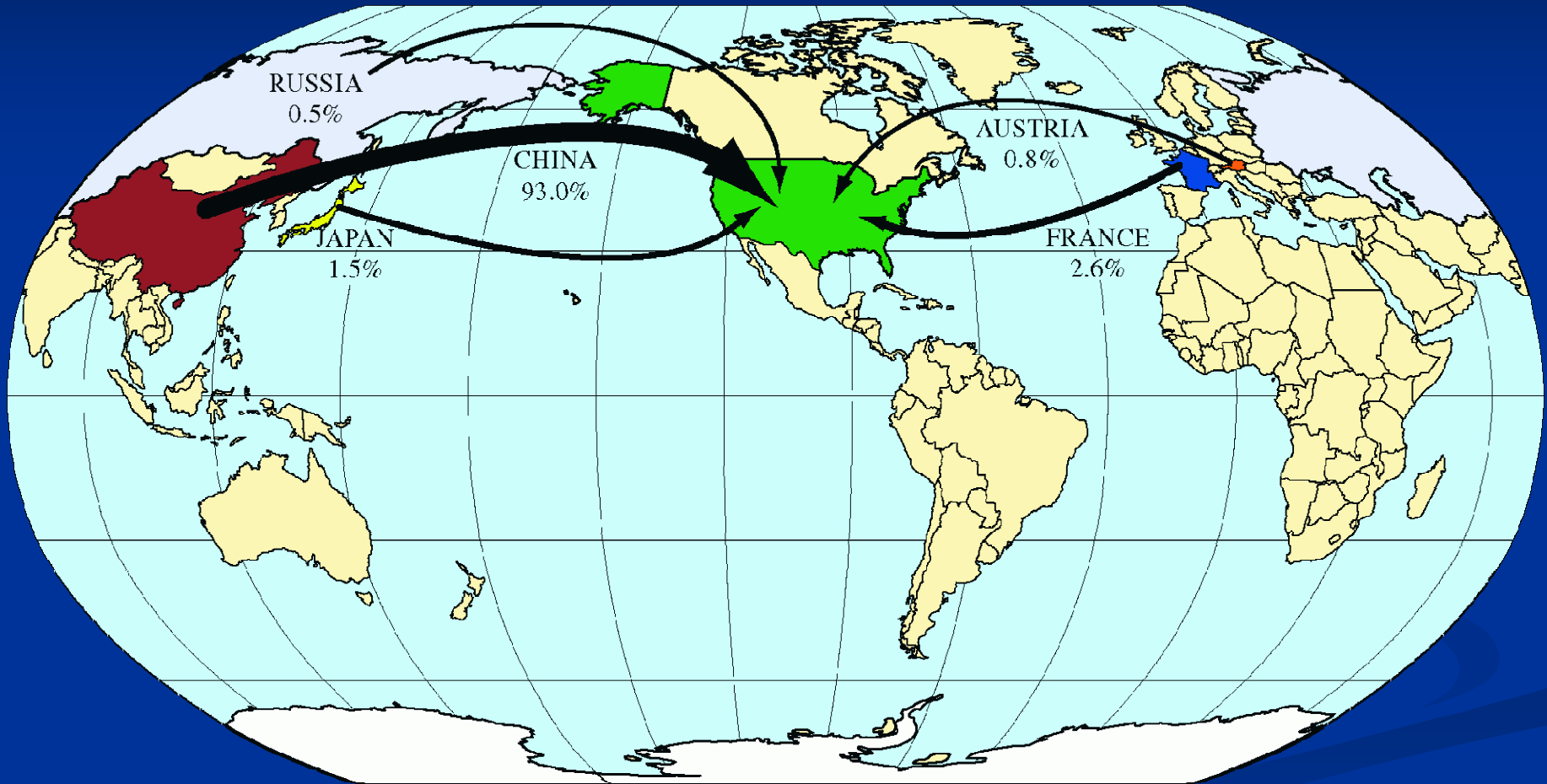
Chinese era → ?



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

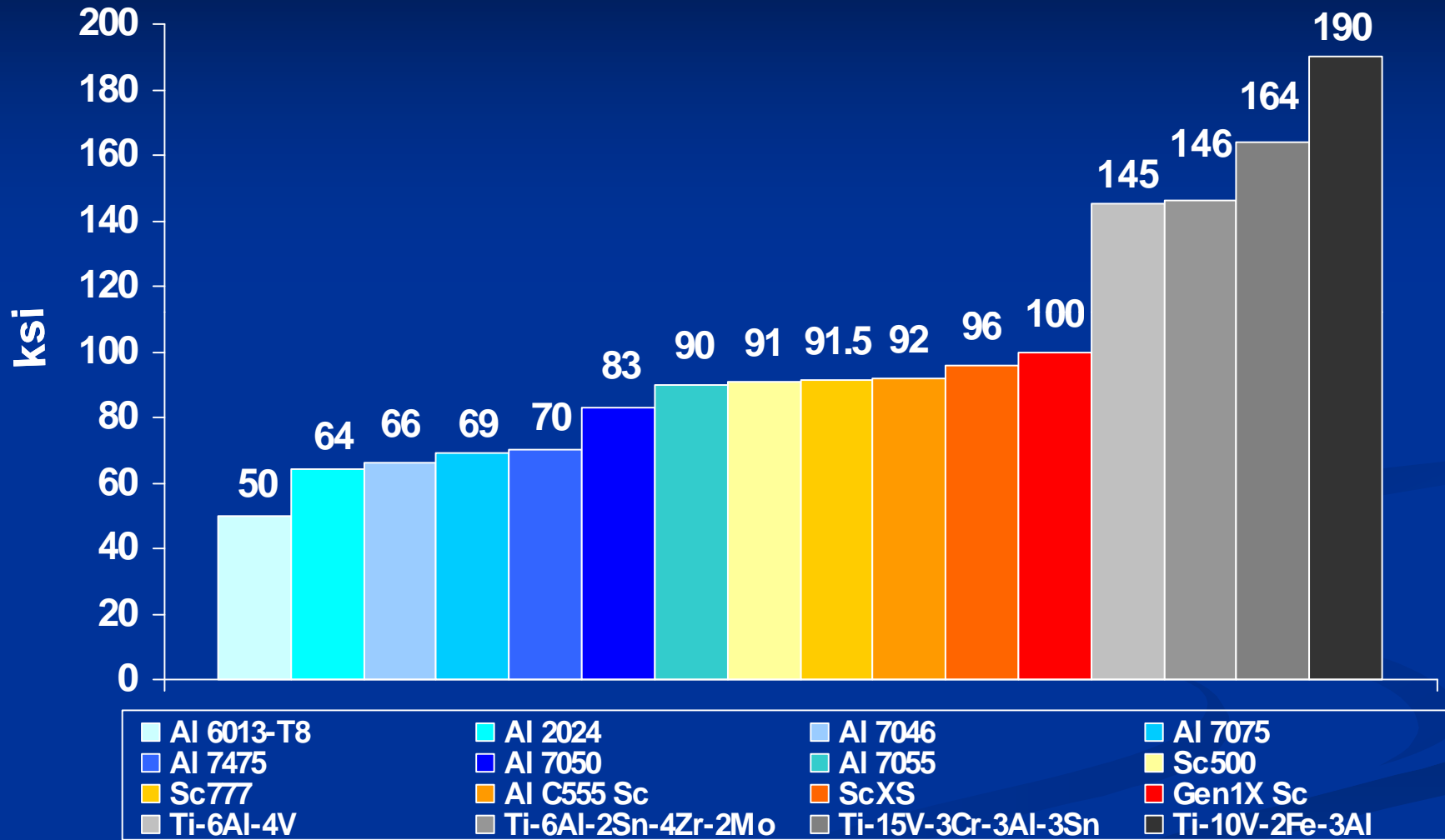
Rare Earth Imports

Principal sources by weight in 2008



Tensile Strength (ksi = 1,000 pounds/square inch)

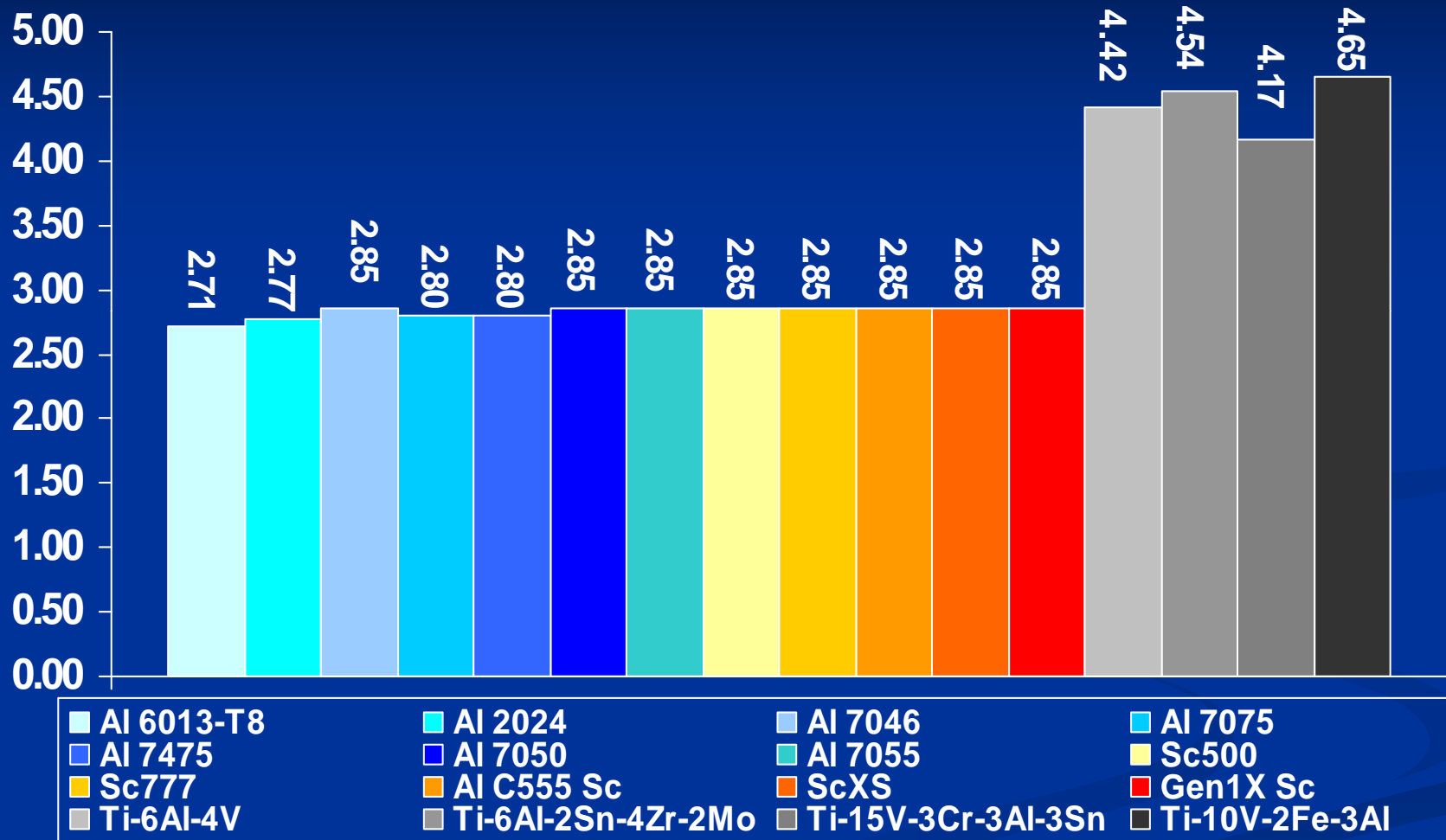
Al, Sc-Al, and Ti Alloys



Source: Company alloy data, ASTM, MatWeb Material Property Data

Density (g/cm³)

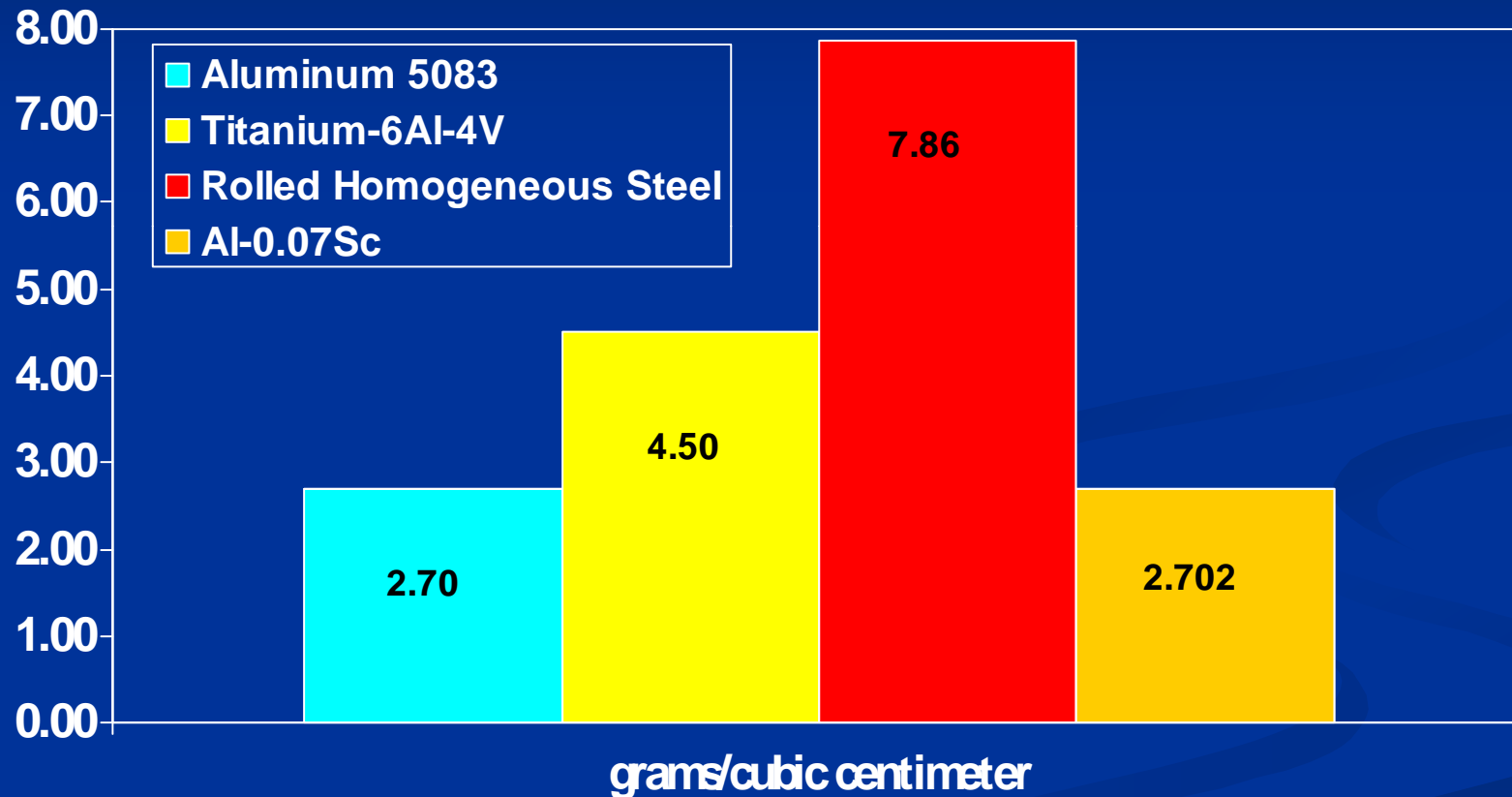
Al, Sc-Al, and Ti Alloys



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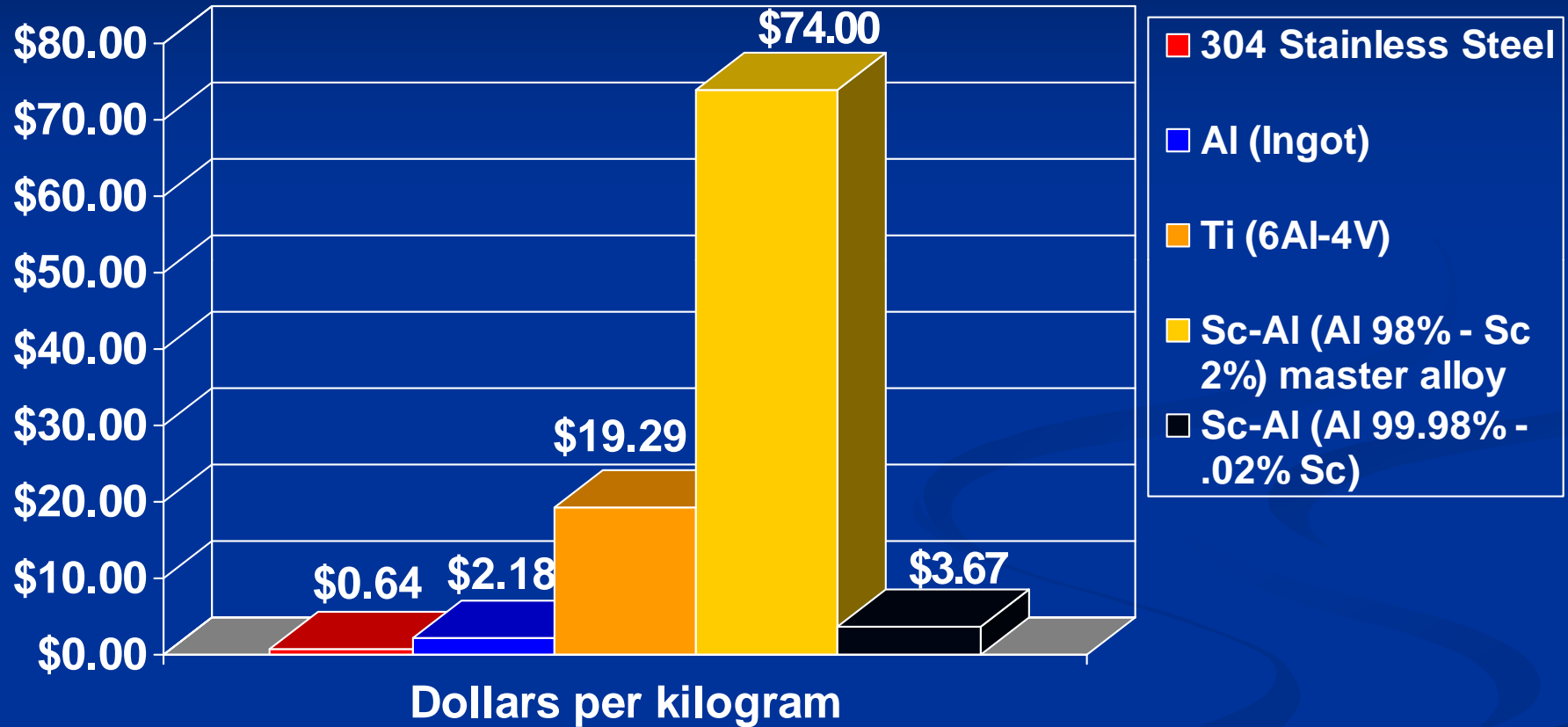
Density

Al, Ti, Steel, and Sc-Al Alloys



Price Comparison at yearend 2009

Stainless Steel, Aluminum, Titanium alloy, and Sc-Al alloys



Source: American Metal Market, London Metal Exchange, and Stanford Materials

Unmanned Aerial Vehicle (UAV) – Predator and the Reaper

MQ-1B Predator



MQ-9 Reaper



UAV – Multi-Spectral Targeting System

AN/AAS-52 by Raytheon has rare earths in:

- Infrared and CCDTV sensors - focal plane arrays (FPA) polished with cerium oxide
- Nd-YAG laser rangefinder, designator, and illuminator
- Optional laser spot tracker sensor with FPA and integrated circuits polished with cerium oxide and yttrium-containing ferrite electronics
- Lenses are polished with cerium oxide

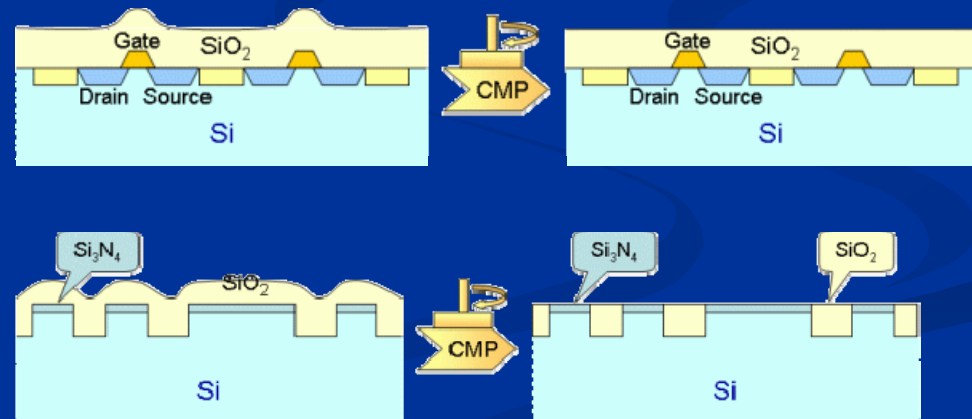
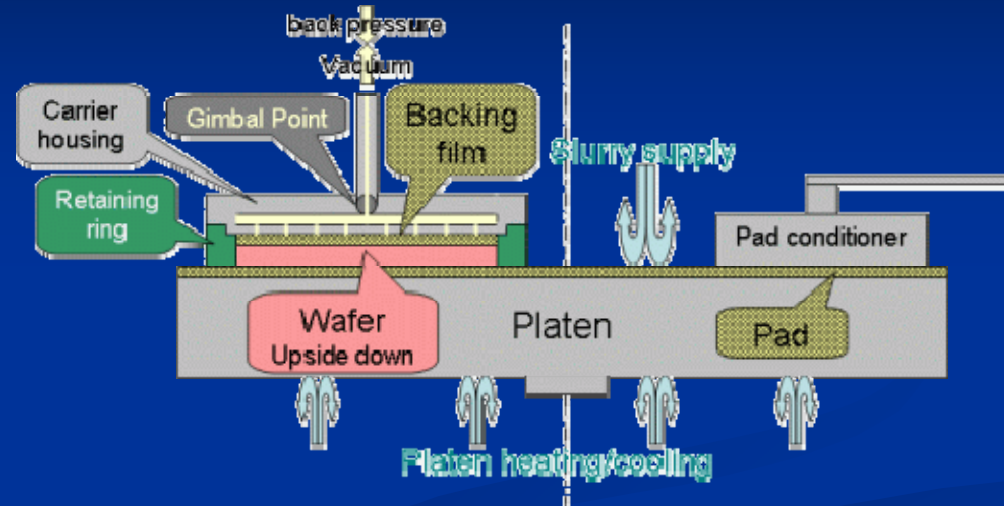


Chemical Mechanical Polishing (CMP)

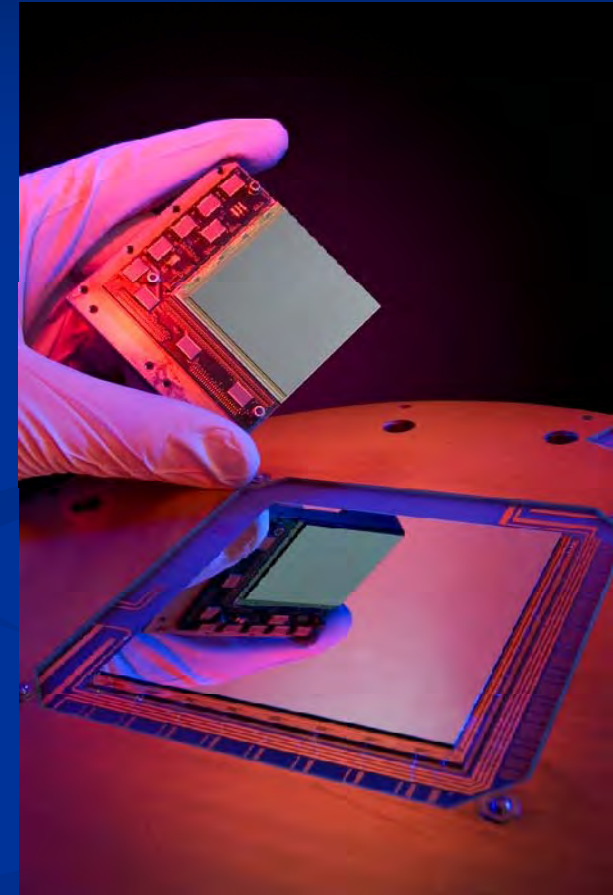
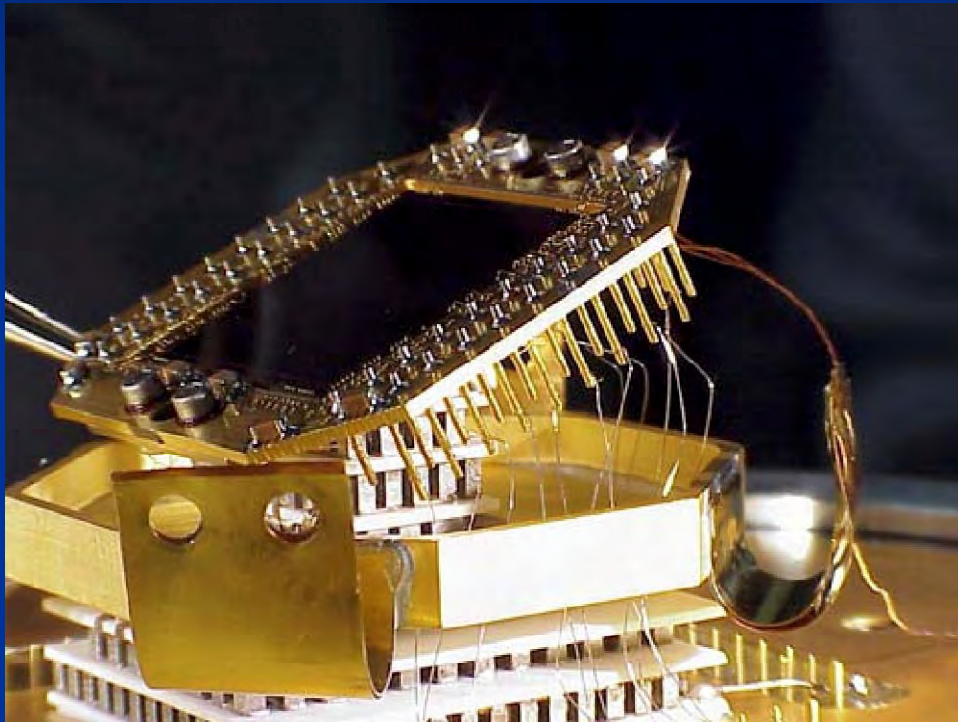
also known as Chemical Mechanical Planarization

■ Cerium oxide is used in polishing:

- Semiconductors – *Logic and Memory Storage*
- Dielectrics
- STI or Shallow Trench Isolation - *Transistors*



Focal Plane Arrays (FPA) HgCdTe or InSb polished with cerium oxide



CMP – Chemical Mechanical Polishing Equipment

- Silicon wafer polishing equipment
- Cerium oxide polishing slurries



Future designs with rare earths



F-35 Joint Strike Fighter design

- F-35A (CTOL) / F-35B (STOVL) / F-35C (CV)



SM-36 Stalma™ design

- Short Take-off Advanced Light Multi-role Attack Jet
- Designed to replace F-16
- 11% Sc-Al in frame decreases frame weight while maintaining strength allowing shorter take off.
- Sc-Al in internal wing, canard and empennage internal structure, fuselage geodetic substructure, air intake ducts, and landing gear structure.
- Planned for 2020-2025 multi-role fighter market.

Rare Earths Are Used in Defense

Every Second...24/7



Credit: U.S. Air Force