

Appendix 2 – Fact Sheets

Antimony ($_{51}\text{Sb}$)

MINERAL(S)

Antimonite ($\text{NaSb}(\text{OH})_4$),
Valentinite (Sb_2O_3),
Jamesonite ($\text{Pb}_4\text{FeSb}_6\text{S}_{14}$)



Antimonite

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.

PRODUCTION: 161,948 tonnes/year (2012-2016)

SUPPLY RISK (SR): 2 (2020) ●

ECONOMIC IMPORTANCE (EI): 4.8 (2020) ●

RECYCLING RATIO: 38 %

SUBSTITUTION:

- Manufacture of glass (compounds of chromium, tin, titanium).
- Flame-retardant materials (alumina trihydrate, magnesium hydroxide).

COUNTRY OF ORIGIN: China (74 %),
Tadzhikistan (8%), Russia (4%)



PROPERTIES

- Combined with halogenated flame-retardant compounds constitutes a highly-effective flame retardant.
- (With Pb) Improves tensile strength, corrosion resistance and charging characteristics in Lead-acid batteries.
- Gives resistance to different metal-alloys.
- Antimony trioxide (catalyst).
- In the form of sodium hexahydroxyantimonate becomes a degassing agent.

USES

- Flame-retardant materials (plastics, wire coatings, upholstered furniture, car seats).
- Grid plates, straps and terminals in Lead-acid batteries.
- Manufacturing of Low-load bearings.
- Manufacture of plastic bottles (PET).
- High-quality clear glass.



Catalyst in PET
manufacturing



Flame-retardant plastics



PbSb Batteries

Barium ($_{56}\text{Ba}$)

MINERAL(S)

Baryte (BaSO_4), Witherite (BaCO_3)

PRODUCTION: 9,725,000 tonnes/year (2012-2016)

SUPPLY RISK (SR): 1.3 (2020) ●

ECONOMIC IMPORTANCE (EI): 3.3 (2020) ●

RECYCLING RATIO: 2 %

SUBSTITUTION:

- Weighting agent for oil and gas industry (hematite, Fe_2O_3 ; ilmenite, FeTiO_3).
- Fillers (Calcium carbonate, CaCO_3).

COUNTRY OF ORIGIN: China (38 %), India (12 %), Morocco (10 %)



Baryte

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.



PROPERTIES

- High specific gravity (containing pressure and preventing blowouts).
- Soundproof material, x-ray protection, resistant to abrasion.
- As barium carbonate (BaCO_3) flux and crystallizing agent

USES

- Weighting agent in drilling fluids ("muds") for oil and gas wells prospecting (Oil production).
- Heavy filler in rubber, paint and plastic applications. Automotive industry (moulded components), Concrete with special features, asphalt.
- Chemicals: High-fire glazes, brick and tile industries.



Weighting agent in drilling fluids



Breaks and clutches pads (automotive industry)



High-fire glazes pottery

Aluminium ($_{13}\text{Al}$)

MINERAL(S)

Bauxite ($\text{AlO}_x(\text{OH})_{3-2x}$)
 $x \in [0,1]$



Bauxite

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.

PRODUCTION: 281,124,000 tonnes/year (2012-2016)

SUPPLY RISK (SR): 2.1 (2020) ●

ECONOMIC IMPORTANCE (EI): 2.9 (2020) ●

RECYCLING RATIO: 12 %

SUBSTITUTION:

- For mobility applications carbon-fibre-reinforced plastic, titanium and magnesium are possible substitutes.
- In the construction sector steel, plastics (such as PVC or vinyl) and wood were considered as possible substitutes.
- Glass, plastics and steel are potential substitutes for aluminium for packaging applications,
- Copper can replace aluminium in electrical lines for power transmission and distribution, as well as in heat-exchange applications.

COUNTRY OF ORIGIN: Australia (28 %), India (12 %), Brazil (13 %)



PROPERTIES

- Soft material.
- Low specific gravity.
- It is the principal ore of aluminium.
- Calcined alumina is a very hard material used as an abrasive.

USES

- Aluminium production (metallurgical bauxite).
- Production of refractory materials, chemicals, abrasives or cements (non-metallurgical bauxite).



Cans



Abrasives



Refractory bricks

Beryllium (${}^4\text{Be}$)

MINERAL(S)

Beryl ($\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$)
Bertrandite ($\text{Be}_4\text{Si}_2\text{O}_7(\text{OH})_2$)



Beryl

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.

PRODUCTION: 251 tonnes/year (2012-216)

SUPPLY RISK (SR): 2.3 (2020) ●

ECONOMIC IMPORTANCE (EI): 4.2 (2020) ●

RECYCLING RATIO: 0 %

SUBSTITUTION: Very difficult to substitute (very expensive). Loss of performance (10 %), Cu-Be, Al-Be, pure Be.

- Mechanical properties (titanium alloys, magnesium alloys).
- Thermal properties (carbon reinforced composites).

COUNTRY OF ORIGIN: US (88 %), China (8 %), Madagascar (2%)

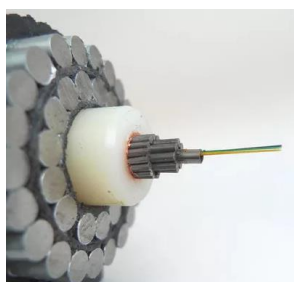


PROPERTIES

- Cu-Be: Improve mechanical properties without impairing the electrical conductivity.
- Low density combined with strength.
- High thermal stability and conductivity and resistance to acids.

USES

- Electronic and telecommunication equipment (connectors, batteries, chips, undersea fibre optic cables).
- Transport and defence (automotive electronics, light metal vehicle components, aerospace components).
- Energy application: Stop leaking during oil spills.



Undersea Fibre Optic Cables



Weather Forecasting Satellites



Landing Gear

Bismuth ($_{83}\text{Bi}$)

MINERAL(S)

Bismuthinite (Bi_2S_3)
Bismutite ($\text{Bi}_2(\text{CO}_3)\text{O}_2$)
Bismite (Bi_2O_3)

Is mainly obtained as a by-product of Pb and W extraction from skarn deposits which contain traces of Bi.



Bismuthinite

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.

PRODUCTION: 10,332 tonnes/year (2012-2016)

SUPPLY RISK (SR): 2.2 (2020) ●

ECONOMIC IMPORTANCE (EI): 4 (2020) ●

RECYCLING RATIO: 0 %

SUBSTITUTION:

- Pharmaceutical applications: Antibiotics.
- Pigments: Titanium dioxide-coated mica flakes.
- Fire-sprinklers: Glycerine-filled glass bulbs.

COUNTRY OF ORIGIN: China (85 %), Laos (7%), Mexico (4 %)



PROPERTIES

- Eco-friendly material (non-toxicity): Bismuth subsalicylate.
- Sn-Bi (low melting point).
- Bismuth vanadate (high temperatures resistant, SO_2 resistance).

USES

- Pharmaceutical and animal-feed industries (anti-ulcer agents, antacid).
- Fusible alloys (replacement of most harmful metals (lead)) in solders.
- Metallurgical additives, coatings, pigments.



Antacid (bismuth subsalicylate)



Pigments (bismuth vanadate)



Fusible alloy (Sn-Bi)

Boron (borates) (${}^5\text{B}$)

MINERAL(S)

Borates (simple form: BO_3)
More than 300 minerals:

Kernite ($\text{Na}_2\text{B}_4\text{O}_6(\text{OH})_2 \cdot 3\text{H}_2\text{O}$)

Borax ($\text{Na}_2\text{B}_4\text{O}_5(\text{OH})_4 \cdot 8\text{H}_2\text{O}$)

Boracite $\text{Mg}_3\text{B}_7\text{O}_{13}\text{Cl}$

PRODUCTION: 918,968 tonnes/year (2012-2016)

SUPPLY RISK (SR): 3.2 (2020) ●

ECONOMIC IMPORTANCE (EI): 3.5 (2020) ●

RECYCLING RATIO: 2 %

SUBSTITUTION:

- Insulation (stone wools, polymers foams).
- Soaps (potassium salts and sodium).
- Detergents (sodium percarbonate).
- Glass insulation, fertilizers (no existing substitute).

COUNTRY OF ORIGIN: Turkey (42 %), US (24 %), Chile (11 %)



Boracite

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.



PROPERTIES

- Fire retardant material.
- Enhance chemical, thermal and wear resistant.
- Essential macronutrient for plant growth, crop yield and seed development.
- Enhance stain removal and bleaching, provide alkaline buffering, soften water and improve surfactant performance.

USES

- To prevent or delay the ignition of different materials.
- Frits and ceramics (additive).
- Fertilizers (Borax 10 Mol, Etibor 48, Etidot 67).
- Detergents (laundry detergents, household and industrial cleaning products).



Fire retardants



Fertilizer (Borax 10 Mol)



Detergents

Cobalt ($_{27}\text{Co}$)

MINERAL(S)

Cobaltite (CoAsS),
Asbolane ($(\text{Ni}, \text{Co})_2\text{-}$
 $\text{xMn}^{4+}(\text{O}, \text{OH})_4 \cdot n\text{H}_2\text{O}$),
Heterogenite ($\text{Co}^{3+}\text{O}(\text{OH})$),
Skutterudite (CoAs_3)



Skutterudite

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.

PRODUCTION: 1,339,000 tonnes/year (2012-2016)

SUPPLY RISK (SR): 2.5 (2020) ●

ECONOMIC IMPORTANCE (EI): 5.9 (2020) ●

RECYCLING RATIO: 22 %

SUBSTITUTION:

- Batteries (lithium-ion batteries).
- Alloys (titanium-aluminides).

COUNTRY OF ORIGIN: Democratic Republic of Congo (59 %), China (7 %), Canada (5 %)



PROPERTIES

- High temperature stability.
- High hardness, corrosion and wear resistant.
- Lithium cobalt oxide (LiCoO_2) as Li-ion batteries cathode.
- Oxidizing agent.
- (CoAl_2O_4) Coloured metal and chromatic stability.
- Constituent of cobalamin.

USES

- Superalloys for aviation.
- Cutting tools in manufacturing processes.
- Lithium-ion rechargeable batteries (electric cars, mobile devices).
- Catalysts.
- Pigments.
- Biological role (vitamin B12).



Blue pigment for ceramics decoration



LiCoO₂ Batteries



Corrosion resistant alloys

Fluorine ($_9\text{F}$)

MINERAL(S)

Fluorspar (CaF_2)



Fluorspar

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.

PRODUCTION: 6,358,000 tonnes/year (2012-2016)

SUPPLY RISK (SR): 1.2 (2020) ●

ECONOMIC IMPORTANCE (EI): 3.3 (2020) ●

RECYCLING RATIO: 2 %

SUBSTITUTION:

- Air condition and refrigeration sector (hydrocarbons: propane).
- Solid fluoropolymers (plastics, stainless steel, ceramics, aluminium).
- Iron and steel making sector (calcium aluminate, aluminium smelting dross).

COUNTRY OF ORIGIN: China (65 %), Mexico (15 %), Mongolia (5 %)



PROPERTIES

- Solid fluoropolymers: Extreme chemical resistance.
- Fluorochemicals: High heat of vaporization, high critical temperature.
- Low melting point (reduces the melting point of steel/iron).
- Uranium Hexafluoride (UF_6): Its triple point is at temperature 64.05 °C (147 °F) with a pressure slightly higher than atmosphere pressure.

USES

- Cookware coating, cable insulation and membranes (electrical appliances, aeronautics, fuel-cells).
- Refrigeration, air conditioning and heat-pumps (HCFCs, HFCs).
- Steel and iron making (Metspar in Iron & Steel making).
- Nuclear Uranium fuel.



Cookware coating



HCFCs refrigeration



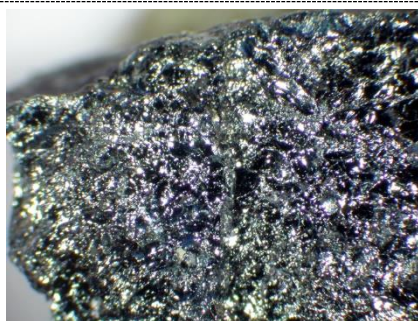
Steel and iron making

Gallium ($_{31}\text{Ga}$)

MINERAL(S)

Gallite (CuGaS_2), Bauxite ($\text{AlO}_x(\text{OH})_{3-2x}$) $x \in [0,1]$

Is mainly obtained as a by-product of Al extraction from bauxite containing traces of Ga.



Gallite

Source: Mindat.org

PRODUCTION: 218 tonnes/year (2012-2016)

SUPPLY RISK (SR): 1.3 (2020) ●

ECONOMIC IMPORTANCE (EI): 3.5 (2020) ●

RECYCLING RATIO: 0 %

SUBSTITUTION:

- Semiconductors, GaAs, GaN (silicon-based substrates, SiGe).
- Solid state LED (organic LED OLED).
- Photovoltaic CIGS (crystalline silicon technologies).

COUNTRY OF ORIGIN: China (80 %), Germany (8 %), Ukraine (5 %)



PROPERTIES

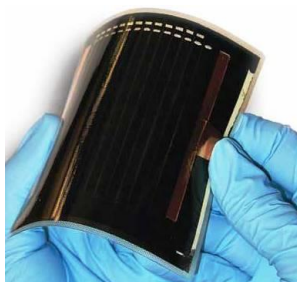
- Semiconductors (GaAs, GaN).
- Cu-In-Se-Ga (CIGS) (semiconductor and flexibility).
- Ga added in small quantities to improve magnetic properties and corrosion resistance.

USES

- Integrated circuits, lightning applications (LED) (cell phones, wireless communication systems, military applications).
- Photovoltaics technology.
- NdFeB magnets.



Cell Phone Power Amplifier
(3G, 4G) - Semiconductor



CIGS photovoltaics
(flexibility)



NdFeB magnets

Germanium ($_{32}\text{Ge}$)

MINERAL(S)

Germanite ($\text{Cu}_{13}\text{Fe}_2\text{Ge}_2\text{S}_{16}$)

Is mainly obtained as a by-product of Zn extraction from Zn ores and coal ashes containing traces of Ge.



Germanite
Source: Mindat.org

PRODUCTION: 122,6 tonnes/year (2012-2016)

SUPPLY RISK (SR): 3.9 (2020) ●

ECONOMIC IMPORTANCE (EI): 3.5 (2020) ●

RECYCLING RATIO: 2 %

SUBSTITUTION: (not optimal, loss of performance)

- Electronic applications (silicon).
- Polymerization catalysts (antimony, titanium).
- Infrared optics (zinc selenide, zinc sulphide).
- No substitute in satellite solar cells.

COUNTRY OF ORIGIN: Refining: China (80 %), Finland (10 %), Russia (5%)



PROPERTIES

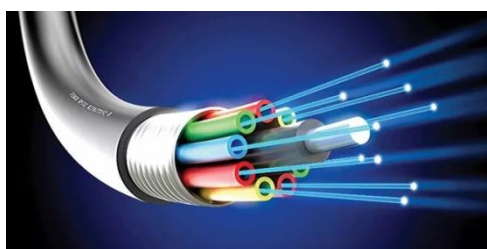
- Transparent to infrared radiation (IR) wavelengths.
- Light weight and high efficiency.
- GeO_2 is a polymerisation catalyst.
- Semiconductor (high switching speed and energy efficiency).
- GeO_2 (dopant in pure silica glass, increases its reflective index, preventing signal loss).

USES

- Infrared optics: lenses and windows (night-vision devices, advanced firefighting equipment, satellite imagery sensors).
- Solar cells (space-based applications).
- PET (plastic bottles, sheet, textile fibres).
- Electronic components (LED, germanium transistors).
- Fibre-optics (high-speed telecommunication).



Night-vision devices



Fibre optics



Space-based solar cells

Hafnium ($_{72}\text{Hf}$)

MINERAL(S)

Hafnon $((\text{Hf}, \text{Zr})\text{SiO}_4)$

Alvite $((\text{Hf}, \text{Th}, \text{Zr})\text{SiO}_4 \cdot \text{H}_2\text{O})$

Is mainly obtained as a by-product of Zr extraction from zircon and baddeleyite containing traces of Hf.



Hafnon

Source: Mindat.org

PRODUCTION: 71 tonnes/year (2012-2016)

SUPPLY RISK (SR): 1.1 (2020) ●

ECONOMIC IMPORTANCE (EI): 3.9 (2020) ●

RECYCLING RATIO: 0 %

SUBSTITUTION:

- Steel alloys (magnesium, niobium, tantalum)
- Nuclear applications (silver-cadmium-indium control rods).
- Zirconium (50% of all hafnium applications).

COUNTRY OF ORIGIN: France (49 %), US (44 %), Russia (3 %)



PROPERTIES

- Hafnium compounds are very refractory; they will not melt except under the most extreme temperatures.
- High thermal neutron absorption cross section.

USES

- Super alloys (turbine blades and vanes in aerospace industry and industrial gas turbines). Refractory ceramic materials, microchips, nozzles for plasma arc cutting.
- Nuclear control rods (nuclear reactors and nuclear submarines).



Turbine blades



Refractory material



Nuclear reactor control rods

Indium ($_{49}\text{In}$)

MINERAL(S)

Trace element in some zinc, copper, lead and tin minerals. Mostly recovered from zinc-sulphide mineral sphalerite (20-200 ppm of In).

PRODUCTION: 827 tonnes/year (2012-2016)

SUPPLY RISK (SR): 1.8 (2020) ●

ECONOMIC IMPORTANCE (EI): 3.3 (2020) ●

RECYCLING RATIO: <1 %

SUBSTITUTION:

- Transparent conducting oxides (TCOs), flat panels displays, amorphous PV cells (Al doped Zn oxide, F doped Sn oxide).
- Sn-In alloys (Sn-Bi in low T bonding and soldering applications).
- No substitute in semiconductor compounds used in thin-film solar cells (CIGS and CIS).

COUNTRY OF ORIGIN: China (48 %), South Korea (21 %), Japan (8 %)



Sphalerite

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.



PROPERTIES

- Soft, ductile and very malleable silvery metal.
- Reduces melting point in solder alloys and improves fatigue performance.
- Light absorber material (CIGS); Maximizes light transmission into solar cells (ITO).
- Excellent conductivity and ductility.
- Inhibit zinc corrosion.

USES

- ITO thin films (flat-panels displays, FPDs; whether liquid crystal displays; for television, laptops, cell phones, car and aircraft windshields for defogging and deicing).
- Low-T free Hg-solder (electronics industry).
- Film solar cells (CIGS, ITO).
- Thermal interface material (electronic devices).
- Substitute of Hg in alkaline batteries.



Computer screens



Electronics industry



Film solar cells (CIGS)

Lithium (${}^3\text{Li}$)

MINERAL(S)

Brines and pegmatite

PRODUCTION: 31,682 tonnes/year (2012-2016)

SUPPLY RISK (SR): 1.6 (2020) ●

ECONOMIC IMPORTANCE (EI): 3.1 (2020) ●

RECYCLING RATIO: <1 %

SUBSTITUTION:

- In rechargeable batteries: NiCd, NiMH and lead-acid batteries.
- In primary batteries: Zn, Ca, Mg and Hg.
- In electronics: La, and Ga
- In air conditioning: ammonia/water systems.
- In primary aluminium production: Na
- In engineering resins: Composite materials consisting of boron, glass, or polymer fibres.

COUNTRY OF ORIGIN: Chile (44 %), China (39 %), Argentina (13 %)



Pegmatite

Source: Mindat.org



PROPERTIES

- Lightest solid metal.
- High thermic conductivity, high specific heat, low viscosity and very low density.
- It reacts easily with hydrogen, water, carbon and halogens.
- The ions are small enough to pass through a separator between the anode and cathode.

USES

- Glass and ceramics production.
- Lubricating greases.
- Cement production.
- Steel casting.
- Pharmaceutical products.
- Rubber and plastic production.
- Al-Li alloys, improving their strength and making them lighter.
- High-energy density rechargeable batteries.



Lithium batteries



Pharmaceutical products



Light Al-Li alloy bicycle frame

Magnesium ($_{12}\text{Mg}$)

MINERAL(S)

Dolomite ($\text{CaMg}(\text{CO}_3)_2$)
Magnesite (MgCO_3)
Carnallite ($\text{KMgCl}_3 \cdot 6\text{H}_2\text{O}$)
Seawater (Mg^{2+})



Dolomite

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.

PRODUCTION: 927,000 tonnes/year (2012-2016)

SUPPLY RISK (SR): 3.9 (2020) ●

ECONOMIC IMPORTANCE (EI): 6.6 (2020) ●

RECYCLING RATIO: 13 %

SUBSTITUTION:

- Carbon-fibre reinforced plastic, steel and titanium alloys (casting alloys, transportation applications, construction sector).
- Steel desulfurization process reagents (lime (CaO), CaC_2).

COUNTRY OF ORIGIN: China (89 %), US (4%)



PROPERTIES

- Lower overall weight, withstanding exposure to ozone (O_3) and impact of high energy particles and matter.
- High affinity for sulphur.
- Improves aluminium strength without removing the material workability.
- MgCO_3 high tendency to "absorb" water.

USES

- Automotive industry casting alloys, terrestrial and aircraft (gearbox, steering column, seat frames, fuel tank covers).
- Desulphurization of steel.
- Aluminium alloys (packaging applications, construction equipment).
- Improve athletes grip in climbing and for gymnasts and weight-lifters performances.



Seat frames



Aluminium alloys



MgCO_3 (sports)

Carbon (Graphite) ($_6C$)

MINERAL(S)

Natural Graphite (C)

PRODUCTION: 1,137,000 tonnes/year (2012-2016)

SUPPLY RISK (SR): 2.3 (2020) ●

ECONOMIC IMPORTANCE (EI): 3.2 (2020) ●

RECYCLING RATIO: 3 %

SUBSTITUTION:

- Refractories (no substitute).
- Foundry applications (synthetic graphite, calcined petroleum coke).
- Decarburizing (carbon products).
- Lubricants (synthetic graphite, molybdenum disulphide).
- Li-ion batteries anode (spheroidal graphite).

COUNTRY OF ORIGIN: China (69 %), India (12 %), Brazil (8 %)



Graphite

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.



PROPERTIES

- High temperature stability and chemical inertness.
- Loose interlamellar coupling between sheets in the structure (dry powder).
- Amorphous graphite.
- High electrical conductivity (high porosity).

USES

- Refractory materials (steel making and hot metal-forming).
- Solid dry lubricants (brake linings, brake pads, clutch facings).
- Rise carbon content of steel (carbon steel).
- Anode lithium-ion batteries (electric vehicles, portable electronics, energy storages).



Foundry refractory materials



Graphite anodes

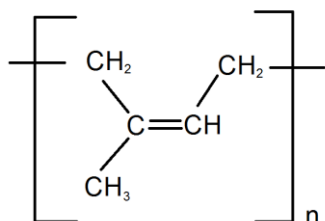


Solid dry lubricant

Natural Rubber

MINERAL(S)

Rubber trees:
Latex (*cis*-1,4-polyisoprene)



PRODUCTION: 13,140,000 tonnes/year (2012-2016)

SUPPLY RISK (SR): 1.0 (2020) ●

ECONOMIC IMPORTANCE (EI): 7.1 (2020) ●

RECYCLING RATIO: 2 %

SUBSTITUTION:

- Latex (under investigation: guayule, Russian dandelion).
- Elastomer and synthetic rubber (polybutadiene, butyl, polyisoprene, styrene butadiene) (packaging, sportswear, furniture, plastics).

COUNTRY OF ORIGIN: Thailand (33 %), Indonesia (24 %), Vietnam (7 %)



Source: Wikipedia
Rubber tree



PROPERTIES

- Flexibility, insulation, resistance to abrasion, elasticity.
- Elasticity, resistance to abrasion, inertness.
- Inertness, elasticity, resistance to most fluid chemicals, electrical resistance.

USES

- Tire industry (cars, heavy trucks, airplanes).
- Industrial products (moulded and extruded products).
- Consumer products (footwear, toys); Latex products (dipped goods, thread, adhesives, gloves, condoms).



Monster Truck tires



Latex toys



Latex gloves

Niobium ($_{41}\text{Nb}$)

MINERAL(S)

Columbite ((Fe, Mn) Nb_2O_6)
Pyrochlore
((Na, Ca) $\text{Nb}_2\text{O}_6(\text{OH}, \text{F})$)



Columbite

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.

PRODUCTION: 42,500 tonnes/year (2012-2016)

SUPPLY RISK (SR): 3.9 (2020) ●

ECONOMIC IMPORTANCE (EI): 6 (2020) ●

RECYCLING RATIO: <1 %

SUBSTITUTION: Any substitution would be associated with a price and /or performance penalty.

- HSLA steel and superalloys production (vanadium, molybdenum, tantalum and titanium).

COUNTRY OF ORIGIN: *Refining:* Brazil (92 %), Canada (8 %)



PROPERTIES

- Ferroniobium: Increases strength and gives alloy weight savings in the final product.
- Corrosion resistance, high-strength at high operating temperatures.
- Nb-Ti or Nb-Sb alloys (superconductivity).

USES

- HSLA steels production (pipelines, ship hulls, railway tracks).
- Niobium-bearing alloys (nuclear reactors, rocket thruster nozzles).
- Superconducting magnets (MRI scanners, particle accelerator).



Rocket thruster nozzels



LHC (Large Hadron Collider)



Gas pipelines

Platinum-Group Metals (Pd, Pt, Rh, Ir, Ru, Os)

MINERAL(S)

Ores of nickel and cooper

Merensky Reef
(5-7 g/t Pt+Pd; Pt/Pd =3)

Chromitite Reef
(4-8 g/t Pt+Pd; Pt/Pd=2.5)



Sulfidic chromitite from Merensky Reef

Source: Wikipedia.

PRODUCTION: 447 tonnes/year (2017)

SUPPLY RISK (SR): 1.8 (2020) ●

ECONOMIC IMPORTANCE (EI): 5.9 (2020) ●

RECYCLING RATIO: 21%

SUBSTITUTION: The best and only available substitution is of one PGM for another.

COUNTRY OF ORIGIN: South Africa (84%) → iridium, platinum, rhodium, ruthenium; Russia (40%) → palladium (see individual PGM factsheets for quantitative information)



PROPERTIES

- Highly chemical attack resistant.
- High temperature resistant and electrical conductors.
- Highly resistant to wear.
- Tarnish resistant; regarded as precious metals.

USES

- Autocatalysts (reduce emissions from petrol and diesel engines, reduce emissions of NOx); Catalysts in industrial sector (petroleum refining, nitric acid and ammonia production).
- Electronics (printed circuit boards, LEDs).
- Others: Glass, medical industry, investments.
- High value jewellery.



Autocatalysts (car catalyst)(Pt)



Fillings in dental application (Pd)



Manufacturing of Organic LEDs (Ir)

Iridium ($_{77}\text{Ir}$)

MINERAL(S)

Ores of nickel and cooper:

Mafic-Ultramafic igneous complexes:

Bushveld Igneous Complex
(South Africa)

Great Dyke (Zimbabwe)



Bushveld igneous complex

Source: Wikipedia.

PRODUCTION: 6.1 tonnes/year (2012-2016)

SUPPLY RISK (SR): 3.2 (2020) ●

ECONOMIC IMPORTANCE (EI): 4.2 (2020) ●

RECYCLING RATIO: 14 %

SUBSTITUTION:

- Substitution with other PGM (limited).
- Electrical industry, growth of large single crystals of sapphire (molybdenum, Tungsten (W)).

COUNTRY OF ORIGIN: South Africa (92 %)



PROPERTIES

- High melting point and resistance to chemical attack.
- Iridium with ruthenium: resistance to chemical attack.
- Iridium-192 radioisotope

USES

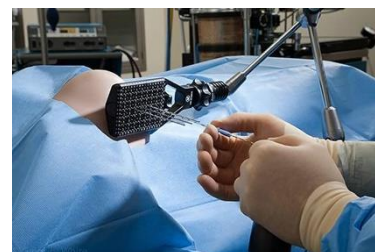
- Electrical industry (crucibles for growing single crystal sapphire, used in blue and green light emitting diodes), flat screen displays in portable electronic equipment.
- Stable anodes for electrochemical production of Cl_2 and NaOH .
- Source of gamma-radiation for the treatment of cancer



Flat screen displays (portable electronic equipment)



Ruthenium-Iridium Anodes



Brachytherapy

Palladium ($_{46}\text{Pd}$)

MINERAL(S)

Ores of nickel and cooper:

Mafic-Ultramafic igneous complexes (South Africa)

Nickel sulphide deposits (Russia, Canada)



Sulfidic serpentinite (Pd and Pt ore)

Source: Wikipedia.

PRODUCTION: 199,4 tonnes/year (2012-2016)

SUPPLY RISK (SR): 1.3 (2020) ●

ECONOMIC IMPORTANCE (EI): 7.0 (2020) ●

RECYCLING RATIO: 28 %

SUBSTITUTION:

- Investment sector (gold or other PGM).

COUNTRY OF ORIGIN: Russia (40 %)



PROPERTIES

- Finely divided on carbon (Pd/C) becomes a catalyst.
- Low melting point.
- It is soft and ductile and it is the least dense compound of the PGM.
- Precious metal (alternative to platinum).

USES

- Autocatalysis (hydrogenation, petroleum cracking): light duty petrol engines.
- Electrical applications (multilayer ceramic capacitors).
- Dentistry (fillings and bridges).
- Jewellery (white gold), investment sector.



Petroleum cracking



Multilayer ceramic capacitor



Dental bridges

Platinum ($_{78}\text{Pt}$)

MINERAL(S)

Ores of nickel and cooper:

Mafic-Ultramafic igneous complexes (South Africa, Zimbabwe)

Nickel sulphide deposits (Russia)



Sulfidic serpentinite (Pd and Pt ore)

Source: Wikipedia.

PRODUCTION: 177,7 tonnes/year (2012-2016)

SUPPLY RISK (SR): 1.8 (2020) ●

ECONOMIC IMPORTANCE (EI): 5.9 (2020) ●

RECYCLING RATIO: 26 %

SUBSTITUTION:

- Other PGM or base materials.
- Palladium for jewellery.
- Investment sector (gold, palladium, and rhodium).

COUNTRY OF ORIGIN: South Africa (71 %)



PROPERTIES

- Platinum Black, resistance to corrosion, chemical stability.
- Platinum black as a catalyst for many reactions.
- Silver-white metal.
- Ductile, electrical conductance.

USES

- Autocatalyst (vehicle emissions control devices).
- Chemical process (petroleum refining, fuel cells, lab instrumental).
- Jewellery.
- Electrical applications (hard disk drives).



Automobile emission control system



Conductivity meter



Platinum jewellery

Rhodium ($_{45}\text{Rh}$)

MINERAL(S)

Ores of nickel and cooper:

Mafic-Ultramafic igneous complexes:

Bushveld Igneous Complex
(South Africa)

Great Dyke (Zimbabwe)



Bushveld igneous complex

Source: Wikipedia.

PRODUCTION: 21,7 tonnes/year (2012-2016)

SUPPLY RISK (SR): 2.1 (2020) ●

ECONOMIC IMPORTANCE (EI): 7.4 (2020) ●

RECYCLING RATIO: 28 %

SUBSTITUTION: Such a high price that leads to considerable interest in finding alternatives:

- Other PGM, gold or a base metal.

COUNTRY OF ORIGIN: South Africa (80 %)



PROPERTIES

- Catalyst, corrosion resistant.
- Silvery-white noble metal.
- Inertness, corrosion resistant, small electrical resistance.
- Rhodium plated by electroplating is extremely hard.
- Characteristic X-rays it produces.

USES

- Catalyst (automobile catalyst converter).
- Jewellery.
- Electrical contacts
- Optical instruments.
- Filters in mammography systems.



Mammography filters



Eye exam equipment



Carbon fibre rhodium plated XLR connectors

Ruthenium ($_{44}\text{Ru}$)

MINERAL(S)

Ores of nickel and cooper:

Mafic-Ultramafic igneous complexes:

Bushveld Igneous Complex (South Africa)
Ural Mountains

Mineral (rare): Laurite (RuS_2)



Laurite (RuS_2)

Source: Mindat.org

PRODUCTION: 27,1 tonnes/year (2012-2016)

SUPPLY RISK (SR): 3.4 (2020) ●

ECONOMIC IMPORTANCE (EI): 4.1 (2020) ●

RECYCLING RATIO: 11 %

SUBSTITUTION:

- Electrical components (other PGM and silver).
- Ammonia synthesis plants (magnetite-based catalyst).

COUNTRY OF ORIGIN: South Africa (93 %)



PROPERTIES

- High electrical conductance.
- High temperature resistant.
- Resistant to wear and to chemical attack.
- Tarnish resistant and is regarded as precious metal as gold or silver.

USES

- Electrical components (thick film pastes, hard drive disks, contacts for thermostats and relays).
- Spark plugs.
- Dentistry, superalloys.
- Jewellery.



Spark plugs



Hard Drive Disk



Ammonia gas sensor

Phosphorus (PR; WP) ($_{15}\text{P}$)

MINERAL(S)

Phosphate rock (**PR**) (300 minerals); Apatite ($\text{Ca}_5(\text{PO}_4)_3(\text{F}, \text{Cl}, \text{OH})$)

White phosphorus (**WP**) (P_4)

PRODUCTION: PR: 76,719,000 tonnes/year; WP: 1,227,000 tonnes/year (2012-2016)

SUPPLY RISK (SR): PR: 1.1 ● WP: 3.5 (2020) ●

ECONOMIC IMPORTANCE (EI): PR: 5.6 ● WP: 5.3 (2020) ●

RECYCLING RATIO: PR: 17 %; WP: 0 %

SUBSTITUTION:

- **PR:** No substitution options for use in fertilizer.
- **WP:** No substitution options for chemical applications.

COUNTRY OF ORIGIN: PR: China (48 %), Morocco (11 %), US (10 %); WP: China (74 %), Vietnam (9 %), Kazakhstan (9 %)



Fluorapatite

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.



White phosphorus powder

Source: Wikipedia



PROPERTIES

- Phosphorus is a vital part of plant and animal nourishment.
- Highly flammable and pyrophoric upon contact with air, submerged in water is safe from self-igniting, glows in the dark, catalyst, forms of H_3PO_4 and $\text{P}_2\text{O}_5/\text{P}_4\text{O}_{10}$ very useful.

USES

- **PR:** Fertilization of food crops, food additives, fireworks, detergents, flame retardants.
- **WP:** Chemical industry applications (oil additives, lubricant additives, detergents, emulsifying agents, matches and pyrotechnics, luminescent materials, weapon).



Phosphate fertilizer



Flame retardant ($\text{NH}_4)_3\text{PO}_4$



White phosphorus pyrotechnics

Rare Earth Elements (REEs)

MINERAL(S)

Carbonatite-associated deposits (bastnäsite), ion adsorption deposits (clays and xenotime mineralization), alkaline igneous rocks (loparite).

Lanthanides, scandium and yttrium (+actinides); 17 (+15)



Carbonatite
Source: Mindat.org.

PRODUCTION: 115,000 tonnes/year (2012-2016)

SUPPLY RISK (SR): Light REEs: 4.9 ● Heavy REEs: 4.8 (2017) ●

ECONOMIC IMPORTANCE (EI): Light REEs: 3.6 ● Heavy REEs: 3.7 (2017) ●

RECYCLING RATIO: Light REEs: 4%, Heavy REEs: 8%

SUBSTITUTION: See individual factsheets.

COUNTRY OF ORIGIN: Light REEs: China (86 %), Australia (6%), US (2%); Heavy REEs: China (86%), Australia (6 %), US (2%)

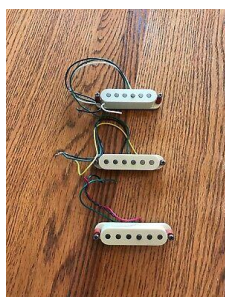


PROPERTIES

- REEs are all silvery-white to grey materials.
- Highly reactive with H₂O and O₂.
- Tarnish easily in air.
- Mostly have high electrical conductivity.
- Magnetic, catalytic and optical properties.

USES

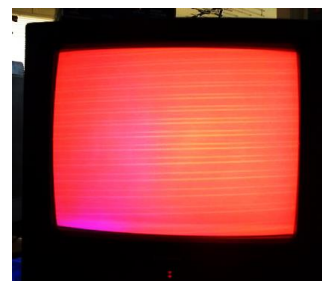
- Main markets for LREEs are in catalysts, metallurgy, glass/polishing, magnets (developed in individual factsheets).
- Main markets for HREEs are in phosphors and ceramics (developed in individual factsheets).



Samarium-Cobalt Electric guitar pickups



Permanent magnet in traction motors in hybrid and electric vehicles (Dysprosium)



Red component of colour TV cathode ray tubes from yttrium, Y₂O₃ (yttria)

Cerium ($_{58}\text{Ce}$)

MINERAL(S)

By-product

Bastnäsite-(Ce)
(Ce, La) CO_3F

Monazite – (Ce)
(Ce, La, Nd, Th) PO_4



Bastnäsite-(Ce)

Source: Mindat.org

PRODUCTION: 51,166 tonnes/year (2012-2016)

SUPPLY RISK (SR): Light REEs: 6.2 (2020) ●

ECONOMIC IMPORTANCE (EI): Light REEs: 3.5 (2020) ●

RECYCLING RATIO: 2 %

SUBSTITUTION:

- Auto-catalyst sector (lanthanum, neodymium, praseodymium).
- Polishing (iron oxide, alumina powder).
- Metallurgical applications (calcium, lanthanum, neodymium, gadolinium).

COUNTRY OF ORIGIN: China (86 %)



PROPERTIES

- CeO_2 (ceria): abrasion resistance.
- CeO_2 (ceria): Catalyst.
- CeO_2 (ceria): Substitute of its radioactive congener thorium (ThO_2).
- Cerium (IV): high refractive index enhances photo stability and makes pigments opaquer.

USES

- Polishing (chemical-mechanical planarization).
- Electrodes in gas tungsten arc welding.
- Auto-catalyst (catalytic converter for emissions in motor vehicles).
- Additive for pigments as it provides pigments with light fastness.



Integrated circuits
(Chemical-mechanical planarization)



Pigments



Gas tungsten arc welding

Dysprosium (${}_{66}\text{Dy}$)

MINERAL(S)

By-product

Monazite sand
(Ce, La, Nd, Th)PO₄

Extraction of Yttrium

PRODUCTION: 1,018 tonnes/year (2012-2016)

SUPPLY RISK (SR): Heavy REEs: 6.2 (2020) ●

ECONOMIC IMPORTANCE (EI): Heavy REEs: 7.2 (2020) ●

RECYCLING RATIO: 0 %

SUBSTITUTION:

- Reduce content of Dy by positioning Dy atoms at the grain boundaries of the NdFeB alloys.
- Design of wind turbines exempt of Dy by adding a cooling system to reduce T.

COUNTRY OF ORIGIN: China (86 %)



Monazite sand
Source: Mindat.org.



PROPERTIES

- Increases the Curie temperature, allows the use of the magnets at up to 200 °C (392 °F).

USES

- Permanent magnets NdFeB (new generation of wing turbines, industrial motors).



Neodymium (NdFeB) magnets



Wind turbines



Industrial motors

Erbium (${}_{68}\text{Er}$)

MINERAL(S)

By-product
Ion adsorption clays
Xenotime (YPO_4)
Euxenite ($\text{Y, Ca, Ce, U, Th}(\text{Nb, Ta, Ti})_2\text{O}_6$)



Xenotime

Source: Mindat.org

PRODUCTION: 483 tonnes/year (2012-2016)

SUPPLY RISK (SR): Heavy REEs: 6.1 (2020) ●

ECONOMIC IMPORTANCE (EI): Heavy REEs: 3.1 (2020) ●

RECYCLING RATIO: 1 %

SUBSTITUTION:

- No substitute in glass colorization (pink color).
- Phosphors or YAG-lasers: Yttrium and Gadolinium (in the 2nd case with a different wavelength).

COUNTRY OF ORIGIN: China (86 %)



PROPERTIES

- Erbium-doped optical silica-glass fibres.
- Co-doping of optical fibre with Er and Yb.
- Erbium-doped laser.
- Er^{3+} ions are pink colour and have optical fluorescent properties useful in laser applications.

USES

- Optical communications: erbium-doped fibre amplifiers (EDFAs).
- High-power Er/Yb fibre laser.
- YAG lasers: dental laser, laser surgery.
- Glass optical applications: Colorant for glass.



Pink colour for glass



YAG laser, dental laser



Erbium-doped fibre link amplifier

Europium (${}_{63}\text{Eu}$)

MINERAL(S)

By-product

Carbonatite-associated deposits (bastnäsite), ion adsorption deposits (clays and xenotime mineralization), alkaline igneous rocks (loparite)



Bastnäsite

Source: Mindat.org

PRODUCTION: 422 tonnes/year (2012-2016)

SUPPLY RISK (SR): Light REEs: 3.7 (2020) ●

ECONOMIC IMPORTANCE (EI): Light REEs: 3.3 (2020) ●

RECYCLING RATIO: 38 %

SUBSTITUTION:

- No substitution in fluorescent lamps → Alternative lightning technology (LED) (which the amounts of Eu 1,000 lower than LFL).

COUNTRY OF ORIGIN: China (86 %)



PROPERTIES

- Eu_2O_3 phosphorescence.

USES

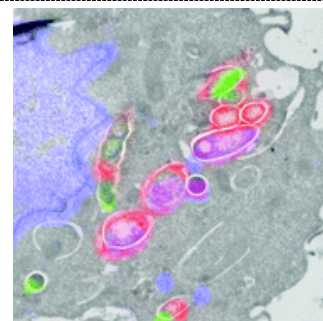
- Lightning applications (red phosphor in TV sets, fluorescent lamps, protection for fraud of Euro banknotes, interrogation of biomolecular interactions in drug-discovery screens).



Helical fluorescent light bulbs



Anti-counterfeiting phosphors in a 50€ banknote



Interrogation (signal transmission) of biomolecular interactions in drug-delivery screens

Gadolinium (${}_{64}\text{Gd}$)

MINERAL(S)

By-product

(bastnäsite, monazite)

Gadolinite $(\text{Ce}, \text{La}, \text{Nd}, \text{Y})_2\text{FeBe}_2\text{Si}_2\text{O}_{10}$
(enough traces of Gd to show a spectrum)

Leppersonite-(Gd) (unique mineral with
essential Gd)

$\text{Ca}(\text{Gd}, \text{Dy})_2(\text{UO}_2)_{24}(\text{SiO}_4)_4(\text{CO}_3)_8(\text{OH})_2$
 $4 \cdot 48\text{H}_2\text{O}$



Gadolinite

Source: Mindat.org

PRODUCTION: 1,596 tonnes/year (2012-2016)

SUPPLY RISK (SR): Heavy REEs: 6.1 (2020) ●

ECONOMIC IMPORTANCE (EI): Heavy REEs:
4.6 (2020) ●

RECYCLING RATIO: 1 %

SUBSTITUTION:

- No substitution (medical imagery uses, television tubes).
- NdFeB magnets (dysprosium, terbium).
- Improving the mechanical characteristics of alloyed steel (praseodymium).

COUNTRY OF ORIGIN: China (86 %)

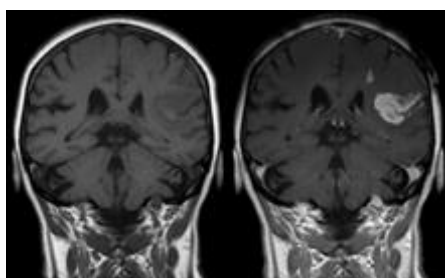


PROPERTIES

- Paramagnetic at room temperature with a ferromagnetic Curie T of 20°C, enhances nuclear relaxation rates. (MRI: Solutions of organic gadolinium complexes).
- Gd_2O_3 , luminescent.
- Improves workability and resistance to high temperature oxidation of iron, chromium, and related alloys.

USES

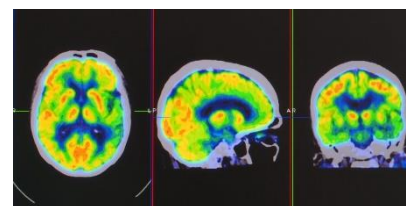
- NdFeB alloys (permanent magnets); Medical contrasting agent for MRIs (intravenous MRI contrast agent to enhance images).
- Green colour in TV, X-ray systems.
- Metallurgical applications (improving mechanical characteristics of alloyed steel, desulphurization, binding trace elements in stainless steel).



MRI contrast agent



Loudspeakers
(NdFeB)



X-ray systems (positron
emission tomography)

Holmium, Lutetium, Ytterbium, Thulium ($_{67}\text{Ho}$, $_{71}\text{Lu}$, $_{70}\text{Yb}$, $_{69}\text{Tm}$)

MINERAL(S)

By-product

Monazite sand $(\text{Ce}, \text{La}, \text{Nd}, \text{Th})\text{PO}_4$
Gadolinite $(\text{Ce}, \text{La}, \text{Nd}, \text{Y})_2\text{FeBe}_2\text{Si}_2\text{O}_{10}$
Euxenite
 $(\text{Y}, \text{Ca}, \text{Ce}, \text{U}, \text{Th})(\text{Nb}, \text{Ta}, \text{Ti})_2\text{O}_6$
Xenotime YPO_4



Monazite



Gadolinite

Source: Mindat.org

PRODUCTION: 660 tonnes/year (2012-2016)

SUPPLY RISK (SR): Heavy REEs: 6.1 (2020) ●

ECONOMIC IMPORTANCE (EI): Heavy REEs: 3.4 (2020) ●

RECYCLING RATIO: 1 %

SUBSTITUTION: Most applications have possible substitutes, given the large market surplus and the relative lack of commercial applications for these metals.

COUNTRY OF ORIGIN: China (86 %)



PROPERTIES

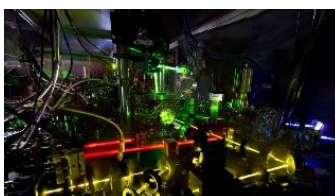
- Ho_2O_3 : colour changes depending on the lighting. Highest magnetic strength of elements.
- Wavelength of Th lasers makes it very efficient for superficial ablation of tissue.
- Source of gamma rays, large number of atoms.
- $\text{Al}_5\text{Lu}_3\text{O}_{12}$, high refractive index immersion lithography, LSO, LuAG.

USES

- Holmium: pigments, magnets, lasers and nuclear reactors.
- Thulium: Lasers (Tm: YAG), portable X-ray devices as radiation sources.
- Ytterbium: nuclear reactors, radiography, high-stability atomic clocks.
- Lutetium: phosphors, PET detectors, glass.



Ho: Cubic zirconia colorants



Yb: High-stability atomic clock



Positron Emission Tomography (PET) detectors

Lanthanum ($_{57}\text{La}$)

MINERAL(S)

Bastnäsite-(La)
(La, Ce) CO_3F



Bastnäsite-(La)

Source: Mindat.org.

PRODUCTION: 29,328 tonnes/year (2012-2016)

SUPPLY RISK (SR): Light REEs: 6.0 (2020) ●

ECONOMIC IMPORTANCE (EI): Light REEs: 1.5 (2020) ●

RECYCLING RATIO: 1 %

SUBSTITUTION:

- Fluid Cracking Catalyst (FCC) (cerium).
- Polishing (cerium, iron oxide, alumina powders).
- Fluorescent lamps replaced by LED technology.
- Metallurgical applications (Ce, Nd, Gd, Ca).

COUNTRY OF ORIGIN: China (86 %)



PROPERTIES

- Catalyst.
- Anodic material, mischmetal (>50 % of La, intermetallic of the AB_5 type).
- La_2O_3 improves alkali resistance of glass, high refractive index and low dispersion.
- Mischmetal, pyrophoric alloy (25 % - 45 % of La).

USES

- Fluid Cracking Catalyst (FCC).
- Nickel-metal hydride batteries (hybrid automobile batteries).
- Glass and ceramics (infrared-absorbing glass, camera and telescope lenses).
- Lighter flints.



Hybrid car batteries



Telescope lenses



Lighter flints

Neodymium ($_{60}\text{Nd}$)

MINERAL(S)

By-product

Bastnäsite $(\text{La, Ce})\text{CO}_3\text{F}$

Monazite-(Ce) $(\text{Ce, La, Nd, Th})\text{PO}_4$

Nd dominant minerals:

Monazite-(Nd) $(\text{Nd, La, Ce})\text{PO}_4$

Kozoite-(Nd) $(\text{Nd, La, Sm, Pr})\text{CO}_3\text{OH}$



Monazite-(Nd)

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.

PRODUCTION: 18,214 tonnes/year (2012-2016)

SUPPLY RISK (SR): Light REEs: 6.1 (2020) ●

ECONOMIC IMPORTANCE (EI): Light REEs: 4.8 (2020) ●

RECYCLING RATIO: 2 %

SUBSTITUTION:

- NdFeB magnets (praseodymium, ferrite magnets).
- NiMH batteries (Li-ion batteries).

COUNTRY OF ORIGIN: China (86 %)



PROPERTIES

- Unusually large specific heat capacity at liquid-helium temperatures.
- Strongest permanent magnets (a few grams can lift a thousand times its own weight).
- Neodymium-doped crystals (Nd: YVO_4).
- Inclusions of Nd_2O_3 in the glass melt.

USES

- Cryocoolers (heat exchangers and regenerators).
- Neodymium magnets ($\text{Nd}_2\text{Fe}_{14}\text{B}$) (Microphones, loudspeakers, bass and guitar pick-ups, hard disks).
- Used in lasers as a gain media for infrared wavelengths (1054-1064 nm).
- Neodymium glass (blue pigment in glass and ceramic tiles).



Blue pigment in glass



Microphones



DPSS hand-held lasers

Praseodymium ($_{59}\text{Pr}$)

MINERAL(S)

By-product

Monazite $(\text{Ce}, \text{La}, \text{Nd}, \text{Th})\text{PO}_4$



Monzanite

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.

PRODUCTION: 5,413 tonnes/year (2012-2016)

SUPPLY RISK (SR): Light REEs: 5.5 (2020) ●

ECONOMIC IMPORTANCE (EI): Light REEs: 4.3 (2020) ●

RECYCLING RATIO: 10 %

SUBSTITUTION:

- NdFeB permanent magnets (neodymium, ferrite magnets, SmCo).
- NiMH Batteries (Li-ion batteries, NiCd, lead-acid batteries).
- Metallurgy (gadolinium).
- No substitution for yellow colour in ceramics.

COUNTRY OF ORIGIN: China (86 %)



PROPERTIES

- Offers strength and durability in extremely stable magnets.
- Praseodymium compounds yellow colour.
- Alloyed with Mg forms high-strength materials.
- PrNi_5 strong magnetocaloric effect.

USES

- High power magnets (motors, printers, watches, headphones, loudspeakers).
- Yellow colour (ceramics, glass, enamels).
- Aircraft engines.
- Approach within one thousandth of a degree of absolute zero.



Digital watches



Yellow glazing in ceramics



Aircraft engines

Samarium ($_{62}\text{Sm}$)

MINERAL(S)

By-product

Bastnäsite (La, Ce) CO_3F
Monazite-(Ce) (Ce, La, Nd, Th) PO_4

Other minerals:

Samarskite-(Y)
($\text{YFe}^{3+}\text{Fe}^{2+}\text{U, Th, Ca}$) $_2(\text{Nb, Ta})_2\text{O}_8$



Smarskite-(Y)

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.

PRODUCTION: 2,498 tonnes/year (2012-2016)

SUPPLY RISK (SR): Heavy REEs: 6.1 (2020) ●

ECONOMIC IMPORTANCE (EI): Heavy REEs: 7.3 (2020) ●

RECYCLING RATIO: 1 %

SUBSTITUTION:

- Magnets (NdFeB magnets, ferrite magnets, AlNiCo magnets).

COUNTRY OF ORIGIN: China (86 %)



PROPERTIES

- High permanent magnetization.
- Catalyst and reagent.
- Radioactive samarium-153 is beta emitter with a half-life of 46.3 hours (chelated with EDTMP and injected intravenously).

USES

- Sm-Co permanent magnets (small motors, headphones, high-end magnetic pickups for guitars and related musical instruments).
- Assists decomposition of plastics, dechlorination of pollutants (PCBs).
- Used to kill cancer cells in the treatment of lung cancer, prostate cancer, breast cancer.



Headphones



Decomposition of plastics



Used in treatments of cancer

Terbium (${}_{65}\text{Tb}$)

MINERAL(S)

By-product

Monazite $(\text{Ce}, \text{La}, \text{Nd}, \text{Th})\text{PO}_4$

Euxenite

$(\text{Y}, \text{Ca}, \text{Ce}, \text{U}, \text{Th})(\text{Nb}, \text{Ta}, \text{Ti})_2\text{O}_6$

Xenotime YPO_4



Xenotime

Source: Mindat.org

PRODUCTION: 206 tonnes/year (2012-2016)

SUPPLY RISK (SR): Heavy REEs: 5.5 (2020) ●

ECONOMIC IMPORTANCE (EI): Heavy REEs: 4.1 (2020) ●

RECYCLING RATIO: 6 %

SUBSTITUTION:

- NdFeB magnets (dysprosium, gadolinium).
- No substitute in fluorescent lamps. LED is an alternative lighting technology.

COUNTRY OF ORIGIN: China (86 %)

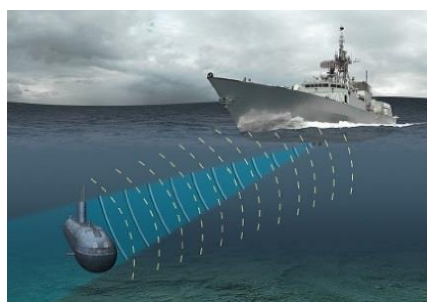


PROPERTIES

- Increase the Curie temperature and thus enable the use of those magnets at high T.
- Terfenol-D (Tb alloy) expands or contracts in the presence of a magnetic field. It is the highest magnetostriction of any alloy.
- Terbium oxide, brilliant fluorescence.
- Acts as an assay of dipicolinic acid based on photoluminescence.

USES

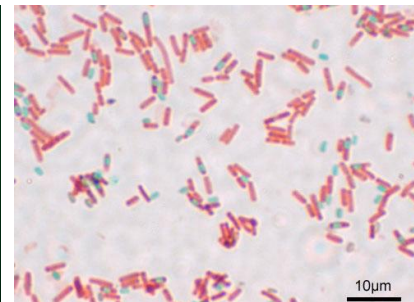
- NdFeB magnets.
- Actuators, naval sonar systems, sensors, SoundBag device.
- Green phosphors in fluorescent lamps and colour TV tubes.
- Biochemistry, to detect endospores.



Naval sonar systems



Green fluorescent lamps



Detecting endospores

Yttrium ($_{39}\text{Y}$)

MINERAL(S)

Bastnäsite-(Y)
(Y, Ce) CO_3F



Bastnäsite-(Y)
Source: Mindat.org.

PRODUCTION: 5,413 tonnes/year (2012-2016)

SUPPLY RISK (SR): Heavy REEs: 4.2 (2020) ●

ECONOMIC IMPORTANCE (EI): Heavy REEs: 3.5 (2020) ●

RECYCLING RATIO: 31 %

SUBSTITUTION:

- No substitution in fluorescent and LED lamps neither in ceramics applications.

COUNTRY OF ORIGIN: China (86 %)

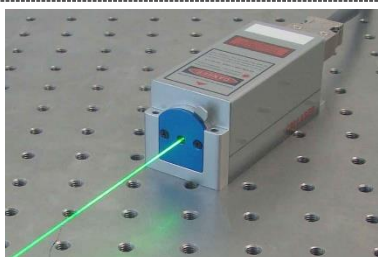


PROPERTIES

- Y-compounds doped with other REEs.
- Yttria (Y_2O_3)-stabilised-zirconia, (YSZ), hard ceramic used as a strong base material.
- Yttria, shock resistance, low thermal expansion properties.
- Isotope Y-90, adds to monoclonal antibodies, killing cancer cells via intense β -radiation.

USES

- Luminophores (fluorescent and LED lamps).
- Refractory uses (full ceramic restorations, dentistry).
- Glass and ceramics (camera lenses).
- Treatment of various cancers (lymphoma, leukemia, liver, ovarian, colorectal cancers).



Nd:YAG rods, used as a crystal laser medium for solid-state lasers



Yttria in YSZ as a base material in full dental ceramic restorations



Monoclonal antibody radioimmunotherapy (Ibritumomab tiuxetan), Zevalin

Scandium ($_{21}\text{Sc}$)

MINERAL(S)

Trace constituent of igneous rocks ferromagnesian minerals, Ni and Co lateritic deposits

Amphibole-hornblende

Pyroxene

Biotite $\text{K}(\text{Mg},\text{Fe})_3\text{AlSi}_3\text{O}_{10}(\text{F},\text{OH})_2$



Biotite

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.

PRODUCTION: Refining: 15,2 tonnes (Sc_2O_3)/year (2012-2016)

SUPPLY RISK (SR): 3.1 (2020) ●

ECONOMIC IMPORTANCE (EI): 4.4 (2020) ●

RECYCLING RATIO: 0 %

SUBSTITUTION:

- High-performance alloys, aerospace and automotive structures (titanium, lithium, carbon fibre materials).
- SOFCs stabilizing the zirconia-based electrolyte (yttrium, scandium).

COUNTRY OF ORIGIN: China (66 %), Russia (26 %), Ukraine (7 %)



PROPERTIES

- Stabilizing zirconia to withstand high temperatures.
- Alloying element with aluminium or magnesium, light alloys which increase efficiency.
- Sc in the form of metal or oxide.

USES

- Solid Oxide Fuel Cells (SOFCs).
- Aerospace and automotive transportation. High quality sports equipment (bikes, baseball bats).
- Ti-Sc carbides, GSGG laser rods, glazes and ceramic products.



Scalmalloys (Sc-Mg-Al alloy family)



SOFCs in fuel cell vehicles



GSGG laser rods

Silicon metal ($_{14}\text{Si}$)

MINERAL(S)

Quartz (SiO_2)



Quartz

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.

PRODUCTION: 2,541,000 tonnes/year (2012-2016)

SUPPLY RISK (SR): 1.2 (2020) ●

ECONOMIC IMPORTANCE (EI): 4.2 (2020) ●

RECYCLING RATIO: 0 %

SUBSTITUTION:

- Metallurgical (serious loss of end performance or increase of cost).
- No substitutes of silicon in silicones and silanes.
- Si based technology for solar applications (CdTe, CIGS technology).
- Micro-electronics industry (GaAs).

COUNTRY OF ORIGIN: China (66 %), US (8%), Norway (6 %), France (4 %)



PROPERTIES

- Silicones (abrasion resistant material, inertness) synthetic silica (high melting temperature, light-diffusing properties, natural absorbency) and silanes (strong reducing agents).
- Silicon dissolved in molten improves viscosity of Al and the mechanical properties.
- Ultra-high purity grade silicon (efficiencies ranging from 18-24 %).
- Intrinsic semiconductor material (increase its electrical conductivity with higher temperatures).

USES

- Silicones, synthetic silica (surfactants, lubricants, cements, sealants, adhesives, cosmetics), silanes (glass fibres, ceramic, foundry, painting industries).
- Al alloys (castings, automotive industry).
- Solar panels (silicon solar cells).
- Electronics (semiconductors, transistors, printed circuit boards, integrated circuits).



"Portland" cement



Fibreglass



Solar Panels (Silicon solar cells)

Tantalum ($_{73}\text{Ta}$)

MINERAL(S)

Tantalite-columbite (Coltan)
(Fe, Mn)(Ta, Nb) $_2\text{O}_6$

Microlite (Na, Ca) $_2\text{Ta}_2\text{O}_6(\text{O}, \text{OH}, \text{F})$

Wodginite $\text{Mn}^{2+}(\text{Sn}, \text{Ta})\text{Ta}_2\text{O}_8$

Struverite (Ti, Ta, Fe^{3+}) O_2

PRODUCTION: 1,191 tonnes of Ta_2O_5 /year (2012-2016)

SUPPLY RISK (SR): 1.4 (2020) ●

ECONOMIC IMPORTANCE (EI): 4.0 (2020) ●

RECYCLING RATIO: <1 %

SUBSTITUTION:

- Capacitors (niobium, ceramic or Al capacitors).
- Cutting tools (carbides (W, Nb, Ti, Mo)
- Superalloys (substitution unlikely).

COUNTRY OF ORIGIN: Dem. Rep. of Congo (33 %), Rwanda (28 %), Brazil (9 %)



Tantalite-columbite (Coltan)

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.



PROPERTIES

- Tantalum pentaoxide film naturally formed on Ta metal that prevents corrosion (dielectric).
- Refractory material.
- Highly corrosive resistant (chemical inertness).
- Tantalum mill products (chemical inertness).
- Tantalum carbides (wear resistant).

USES

- Capacitors with high capacitance, small size and high performance (video game systems, computers, mobile phones).
- Superalloys (aerospace sector, jet engines, land-base gas turbines).
- Sputtering targets (manufacture of storage media, inkjet printer heads, electronic circuitry).
- Chemical processing equipment, ballistics, surgical implants.
- Cutting tools.



Cell phones (tantalum capacitors)



Jet engines



Mining of Coltan has involved severe problems (economy in detriment of war, human rights, environmental issues)

Titanium ($_{22}\text{Ti}$)

MINERAL(S)

Rutile (TiO_2) and Ilmenite ($\text{Fe}^{2+}\text{Ti}^{4+}\text{O}_3$)



Rutile

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.

PRODUCTION: 187,000 tonnes/year (2012-2016)

SUPPLY RISK (SR): 1.3 (2020) ●

ECONOMIC IMPORTANCE (EI): 4.7 (2020) ●

RECYCLING RATIO: 19 %

SUBSTITUTION:

- Aluminium, nickel, specialty steels or zirconium alloys also have good corrosion resistance.
- Superalloys, steel, composites, aluminium and intermetallics have high strength.
- Calcium carbonate, kaolin or talc can substitute titanium as a white pigment.

COUNTRY OF ORIGIN: China (45 %), Russia (22 %), Japan (22 %)



PROPERTIES

- Titanium is a lightweight, high-strength, low-corrosion structural metal.
- Ductile.
- Good heat transfer properties.
- Titanium is nontoxic and biologically compatible with human tissues and bones.
- Good corrosion resistance.

USES

- Titanium dioxide is frequently used as a white pigment in paint.
- Polymers production.
- Aerospace applications.
- Medical equipment.
- Automotive parts.
- Hand held objects.
- Alloys.



Titanium dioxide white pigment



Jet turbines blades



Titanium knee and hip replacement implants

Tungsten (Wolfram) ($_{74}\text{W}$)

MINERAL(S)

Wolframite $(\text{Fe}, \text{Mn})\text{WO}_4$
Scheelite CaWO_4



Wolframite

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.

PRODUCTION: 85,300 tonnes/year (2012-2016)

SUPPLY RISK (SR): 1.6 (2020) ●

ECONOMIC IMPORTANCE (EI): 8.1 (2020) ●

RECYCLING RATIO: 42 %

SUBSTITUTION:

- Cemented carbides (molybdenum carbides, cermets).
- Ceramics (zirconium, aluminium).
- Lighting applications (phosphorescent lamps and LEDs).

COUNTRY OF ORIGIN: *Refined:* China (69 %), Vietnam (7%), US (6%), Austria (1%), Germany (1 %)



PROPERTIES

- High hardness and strength combined with toughness and plasticity.
- Metal tungsten retains its strength at high temperatures and also has a high melting point (3422 °C; 6192 °F).

USES

- Cemented carbides, hard metals (cutting and drilling tools); Alloys and super-alloys (High speed steels) (Rocket nozzles, radiation shielding, turbine blades).
- Lighting industry (incandescent bulb filament, compact fluorescent lamp, high intensity discharge lamp HID); Electronic industry (integrated circuits, X-ray tubes).



Button bits (mining and tunnelling cutting tool)



Rocket nozzles



Incandescent bulb filament

Vanadium ($_{23}\text{V}$)

MINERAL(S)

Patronite VS_4
Vanadinite $\text{Pb}_5(\text{VO}_4)_3\text{Cl}$
Carnotite
 $\text{K}_2(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 3\text{H}_2\text{O}$

PRODUCTION: 61,371 tonnes/year (2012-2016)

SUPPLY RISK (SR): 1.7 (2020) ●

ECONOMIC IMPORTANCE (EI): 4.4 (2020) ●

RECYCLING RATIO: 3%

SUBSTITUTION:

- Steel alloy (Mg, Mo, Nb, Ti and W) (tubes and pipes, turbines, automotive parts).
- Ferrovandium (FeNb).
- Catalyst (platinum, nickel).
- Paints, varnishes (titanium).

COUNTRY OF ORIGIN: *Refined:* China (55 %), South Africa (22 %), Russia (19 %)



Vanadinite

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.



PROPERTIES

- Considerable increase of strength with small amounts of vanadium.
- Low-neutron-adsorption abilities and it does not deform in creeping under high T.
- V_2O_5 catalyst.

USES

- Ferrovandium / HSLA additive (mixed with Al or Ti alloys) is used in jet engines, high speed air-frames, axles, crankshafts, gears.
- Nuclear reactors.
- Catalyst (manufacturing of sulphuric acid and maleic anhydride and in making ceramics); added to glass produces green or blue tint.



Jet engines



V_2O_5 catalyst



Nuclear reactor