RAWMATCARDS

Critical Raw Materials Cards Game

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ABSTRACT

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Critical Raw Materials (CRMs) are those raw materials which are economically and strategically important for the European economy but have a high-risk associated with their supply. This document describes a card game and provides all the material to play. The goal of the activity is to learn the importance of critical raw materials, their properties and their applications. Teachers can use a detailed description of each of the elements (with information about their mineral source, production, economic importance, properties and main uses) and *Kahoot!* questions to test the knowledge of their students. Students work in groups, matching cards (property and use) to guess which elements made a jet engine, a solar panel, a phone screen and many more items necessary in our everyday life.

TOOLKIT DESCRIPTION

Toolkit's title

RawMatCards: a game with Raw Materials

Content

Content	1
General introduction.....	1
Teacher's Card	1
Student's Card.....	4
Sources.....	7
Appendix. Experimental protocols.....	8

General introduction

It consists of a simple card game that can be used in a group of students to show them the main properties and uses of several critical raw materials. The game is recommended for students groups of 2 to 5 members which have to guess the uses of each of the raw materials shown in the cards in order to fulfill the "application Sheets", that contain different general applications of raw materials (as a bingo). The group that completes all the elements corresponding to the objects represented in the "application sheet" card wins.

- This simple game will allow students to learn general information about "Critical Raw Materials" and its importance nowadays in our society with physical cards.
- They will also be introduced to the current worldwide environmental, economical and social concerns that affect all of us.

Teacher's Card

There are two types of teacher's card. First, a set of sheets that will be the same as the student's cards (described in the next section) but already matched (in order to know the correct answer). Secondly, there is another set of fact sheets that contains general information of each critical "element" and lets the teacher to have a basic knowledge of the production, properties and uses of all these critical materials. Therefore, teachers will be able to complete the knowledge that the students will get through the game.

- Access to teacher cards (virtual cards).
 - A set of sheets with the student's cards already matched.
 - A4 fact-sheets guideline for each critical raw material (in the following page is shown an example of the teachers/professors/organizations fact sheet).
- There is a card with the instructions of the game that the teacher will have to read in order to carry out the game properly.
- Also, there is access to a complete and prepared "Kahoot!" test with three questions for each "element" that the teacher will have to choose for the session with the students (enter with your username, search for "Critical Raw Materials Properties&Uses" questionnaire created by EITRMSchools user and duplicate into your account).

Questions: to check the comprehension of the contents

"Kahoot" example regarding the cobalt (Co) element:

- What mineral does cobalt come from?
 - Bauxite.
 - Cobaltite. ✓
 - Bertrandite.
 - Fluorspar.
- The high temperature stability, which offers cobalt in materials, makes it suitable for:
 - Pigments.
 - Biological roles (Vitamin B12).
 - Refrigeration.
 - Superalloys for aviation. ✓
- Cobalt is used as a blue pigment for ceramic decoration as it ... :
 - ... is an effective cathode as lithium oxide.
 - ... has high hardness .
 - ... is wear and corrosion resistant.
 - ... can form CoAl_2O_4 , which is a coloured compound with chromatic stability. ✓

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

MINERAL(S)

Cobaltite (CoAsS)

PRODUCTION: 135,497 tonnes/year (2010-2014)

SUPPLY RISK (SR): 1.6 (2017) ●

ECONOMIC IMPORTANCE (EI): 5.7 (2017) ●

RECYCLING RATIO: 0 %

SUBSTITUTION:

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

COUNTRY OF ORIGIN: Democratic Republic of Congo (64 %); Canada (5 %); China (5 %)

Cobaltite

PROPERTIES

- High temperature stability.
- High hardness, corrosion and wear resistant.
- Effective cathode as lithium element oxide.
- Oxidizing agent.
- (CoAl_2O_4) Colored metal and chromatic stability.
- Constituent of cobalamin.

USES

- Superalloys for aviation.
- Cutting tools in manufacturing processes.
- Rechargeable batteries.
- Catalysts.
- Pigments.
- Biological role (vitamin B12).

Blue pigment for ceramics decoration

LiCoO_2 Batteries

Corrosion resistant alloys

Student's Card

It consists of three packs of cards. Firstly, there is a group denominated as “application sheets”, which has the name and a picture of general devices, machines or utensils, such as: batteries, mobile devices, telecommunication satellites, aircraft engines, laptop computers, etc. Each of these main cards will have some elements that the players must get in order to complete the game (as if it were a bingo). The secondary cards are organized in two groups. One block (blue stripe) contains basic information of properties and origin of the materials (mineral which the material is obtained from) while the other one (red stripe) contains pictures of the different uses of each material. There will be three cards for every element in these two packs of cards (therefore the properties can be matched with the respective uses). The students will play in teams in a “competition” by turns to complete the elements shown in the “application sheets” by joining the cards of properties with the ones of uses.

- The properties and uses cards (two packs of cards) are a sixth of an A4 sheet size.
- The “application sheets” have an A4 sheet size.
- It is advisable to print the material in poster board or cardboard (a more rigid material) in order to resist all the game handlings (the teacher's cards can be perfectly printed in ordinary paper).
- Students will be checking their choices through a moderator who will be able to check the answers with a simple version of the same cards already matched.
- At the end of the session there will be a short “Kahoot!” quiz just to reinforce the new acquired knowledge.

In the next diagram it can be seen how the “property” and “use” cards from one element (in this case, cobalt) are matched as how they are supposed to be.

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

Cobaltite (CoAsS)

Property:
 **LiCoO_2 as Li-ion
batteries cathode**

Corrosion resistant alloys

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

Cobaltite (CoAsS)

Property:
 **$(\text{CoAl}_2\text{O}_4)$ Coloured metal
and chromatic stability**

LiCoO_2 Batteries

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

Cobaltite (CoAsS)

Property:
**High hardness, corrosion
and wear resistant**

**Blue pigment for ceramics
decoration**

Once there is a correct match of a certain element, it can be placed on the corresponding “application sheet” (as it can be seen in the following example).

BIOLOGICAL ROLES	Cobalt ($_{27}\text{Co}$)	Bismuth ($_{83}\text{Bi}$)
	Boron (borates) ($_5\text{B}$)	Phosphate Rock (phosphorus) ($_{15}\text{P}$)

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Appendix. Experimental protocols

Necessities:

- Toolkit:
 - Access to the prepared and structured “Kahoot!” (Critical Raw Materials Properties&Uses, created by the user EITRMSchools).
 - Student’s cards (properties and uses cards + application-sheets).
 - Teacher’s cards (similar to student’s cards + fact-sheets).
 - Instructions for learning how to play the game.
 - Informative diagrams to show students general information about CRM in a simple illustration.
 - Consciousness-raising paper sheet about ethical, social and environmental general problems in (past and present) mining processes in the world.

Experimental procedure:

0 Teachers/professors/organizations must have prepared previously the questions of an already structured “Kahoot!” that will be played at the end of the game to reinforce the recently acquired knowledge.

1 Two or more groups must be formed in order to play the game and the rules are explained to the students.

2 An application-sheet will be sorted out to each team, along with cards of block 1 and block 2 corresponding to the elements they have to get.

3 For a specific time, students will be playing in teams by turns trying to complete their cards as if it were a bingo game.

4 At the end of the game, teachers/professors/organizations will play a “Kahoot!” so students can consolidate what they have learned.

INTRODUCTION

DEFINITION AND DISTRIBUTION

Critical Raw Materials (CRMs) are those raw materials which are economically and strategically important for the European economy, and also have a high-risk associated with their supply. They are not only 'critical' for key industry sectors and future applications, but also for the sustainable functioning of the European economy [1]. There are three properties that these materials must meet to be considered 'critical' [1]:

- **Significant economic importance for key sectors in the European economy:** such as consumer electronics, environmental technologies, automotive, aerospace, defence, health and steel-making.
- **High supply risk:** very-high import dependence and high level of concentration of set critical raw materials in particular countries.
- **Lack of viable substitutes:** very unique and reliable properties (present and future applications).

To address this challenge, the European Commission has created a list of critical raw materials (CRMs) for the EU, which is subject to a regular review and update at least every 3 years to reflect production, market and technological developments [2].

The first analysis for critical raw materials was published in 2011 by the Ad-Hoc Working Group on Defining Critical Raw Materials. Fourteen critical raw materials were identified from a candidate list of forty-one non-energy and non-agricultural materials [2][3]. Then, in 2014, 44 critical materials were revised and a new list with 20 critical raw materials was set. Then, in 2017 the critical raw materials list was increased to 27 CRMs based on a refined methodology. And finally, in January 2018, a report on CRMs including circular economy aspects was published, reviewing relevant EU policies, key initiatives, good practices and indicating possible further actions [2]. All these lists were (and still are) supposed to help the European trade in various ways [2]:

- Strengthening the competitiveness of European industry in line with the renewed industrial strategy for Europe.
- To stimulate the production of CRMs by enhancing new mining and recycling activities in the EU.
- To foster efficient use and recycling of critical raw materials, a priority area in the EU circular economy action plan.
- To increase awareness of potential raw material supply risks and related opportunities among EU countries, companies and investors.
- To negotiate trade agreements, challenging trade distortion measures, developing research and innovation actions and implementing the 2030 'Agenda on sustainable development and its sustainable development goals'.

2017 was the last year that a critical raw materials' list was set, which was completed with 27 critical raw materials that appear in Table 1.

Table 1: Critical raw materials added in 2017 [2] (European Commission, 2019)

2017 CRMs (27)			
Antimony	Fluorspar	LREEs	Phosphorus
Baryte	Gallium	Magnesium	Scandium
Beryllium	Germanium	Natural graphite	Silicon metal
Bismuth	Hafnium	Natural rubber	Tantalum
Borate	Helium	Niobium	Tungsten
Cobalt	HREEs	PGMs	Vanadium
Coking coal	Indium	Phosphate rock	

*HREEs: Heavy Rare Earth Elements; LREEs: Light Rare Earth Elements; PGMs: Platinum Group Metals

Other issue that concerns EU and that has encouraged it to develop the critical raw materials' strategy, is that most of those raw materials are produced and supplied from non-EU countries. The percentages of each element can be seen in the graphics of Figure 1 and Figure 2. Figure 1 contains the percentage of the total production of each element that comes from each marked country (for global economy supply); for example, the 90 % of all the beryllium produced that supplies the global economy comes from USA. Meanwhile, Figure 2 contains the same type of percentages referred to the supply of EU raw materials.

Figure 1: Countries accounting for largest share of global supply of CRMs [2] (European Commission, 2019)

Figure 2: Countries accounting for largest share of EU supply of CRMs [2] (European Commission, 2019)

CONCIOUSNESS-RAISING

This document contains information about ethical, social and environmental (past and present) issues related to countries which have the main minerals reserves of critical raw materials in the world, such as: Democratic Republic of Congo, Rwanda, China, India, Australia or Persian Gulf. Only a few of the problems are going to be highlighted, some that have occurred in the past (to prevent from repeating again) and others that are existing now-a-days; Consequently, in this scientific (and social) field (as in others), there are serious problems that affect all, especially related to the choices we make in our daily lives.

PETROL (“Black Gold”)

The most well-known problem is the oil dispute. This raw material, despite it is not a critical raw material, has been the main cause of the current international geopolitical conflict.

Petroleum is the most widely produced product in the industry worldwide, and also, in industrialized countries, petrol is vital for their well development and also their simply existence now-a-days. Due to this dependency of petrol on most countries (there are important strategies that involve petrol), due to the concentration of petrol resources in few countries and because the corruption, clandestine operations and military operations are sometimes part of “negotiations”; there have been important conflicts (in practically all the continents), between several countries and within some countries their selves, in the past and the present century [4][5]. Some general examples: conflict in the Niger Delta, war in Sudan, South China Sea, Persian Gulf, Egypt and Israel, Iraq or US-Iran-Israel. Also, it must be mentioned that petroleum industry has given rises to severe environmental impacts (soil, water and air pollution, climate change) [6]. Now-a-days, it must be said that, despite there is much more control over conflicts and corruption, the petrol still have this harmful power, as it can be used as a “economical weapon” because it finances military and terrorist activities (for example, ISIS using oil revenue [7]).

“BLOOD DIAMONDS”

Trade of diamonds has involved, in the past, uncontrolled violations of human rights, as well as armed conflicts, wars, etc. It started in the 1990's in Sierra Leone and then it spread to others countries in Africa such as, Angola, Democratic Republic of Congo. Meanwhile the enterprises that bought these diamonds, were selling them in some developed countries [8]. Therefore, the commercial chain was completed. People that bought those diamonds were supporting all that damage and conflicts without knowing it (that was the key; people did not know the real source of what they were buying). The solutions,

although significant, including the Kimberley Process Certification Scheme signed in 2000, have not yet been definitive

COLTAN (Tantalum), CASSITERITE (Tin), WOLFRAMITE (Tungsten), GOLD

Conflict minerals are those, whose systematic exploitation and trade in a context of conflict contribute to, benefit from or result in the commission of serious violations of human rights, violations of international humanitarian law or violations amounting to crimes under international law [9]. The four most commonly mined conflict minerals (known as 3TGs) are cassiterite (for tin), wolframite (for tungsten), coltan (columbite-tantalite, for tantalum) and gold ore, which are extracted, mainly, from the eastern Congo [10]. These minerals go through many intermediates before reaching the consumer from well-known companies. These minerals are used in many fields such as in electronic devices (laptops, smart phones, game consoles), automotive industry or jewellery [11][12].

Due to increasing business process outsourcing and globally dispersed production facilities, social problems and human rights violations are no longer only intraorganizationally rooted, but also occur in companies' supply chains.

Therefore, initiatives like the Dodd-Frank Wall Street Reform and Consumer Protection Act or the OECD (Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas) demand the supply chain managers to verify purchased goods as "conflict-free" or implement measures to better manage any inability to do so [13]. However, the mere transfer of responsibilities upstream in the supply chain apparently will not stop the trade with conflict minerals, notably due to two reasons [9]:

- On one hand, globalization has created governance gaps in a sense that companies are able to infringe human rights without being sanctioned by independent third parties. Consequently, there is a non-allocation of responsibility that makes the problem of human rights abuses and social conflicts within dispersed supply chains very likely to endure.
- On the other hand, conflict minerals usually originate from globally diverse deposits and are difficult to track within components and manufactured products. This is the case because these minerals are mostly mixed with minerals of different origin and added to metal alloys. As a result, although the share of these minerals in single end products is negligible, they are prevalent in numerous products and commodities [9].

Hence, there are many organizations and celebrities currently working to find solutions and raise awareness of conflict minerals, such as: *Save the Congo*, *The Enough Project*, *Partnership Africa Canada*, *The Conflict Free Tin Initiative*, *Solutions for Hope*, *FairPhone*, and more.

LITHIUM (“White Oil” or “White Gold”)

Lithium has been used as a lubricant in aircraft engines and to produce nuclear weapons, but also in medicine, air purification, in telescope lenses and so. Nowadays, the major use of lithium is found in batteries use in electric vehicles, smart phones, laptop computers and more electric and electronic devices and engines. Therefore, there has been an enormous increase of lithium demand. However, more than half of Li reserves on the planet lay on the “lithium triangle”, formed by Chile, Argentina and Bolivia. In addition, there are other countries which have an important production of lithium, such as Portugal and Australia. But the problem affects to all of them. Less than 5 % of lithium-ion batteries are currently recycled, and therefore, there are millions of tons of lithium batteries disposed of, causing a huge environmental and economical impact [14][15]. There must be researches and investments in this sector to mend the situation, but the impact will still be there until a proper solution is found.

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TEACHER FACT SHEETS

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

MINERAL(S)

Stibnite (Sb_2S_3)

Stibnite

PRODUCTION: 42,833 tonnes/year (2010-2014)

SUPPLY RISK (SR): 4.3 (2017) ●

ECONOMIC IMPORTANCE (EI): 4.3 (2017) ●

RECYCLING RATIO: 28 %

SUBSTITUTION:

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

COUNTRY OF ORIGIN: China (87 %), Vietnam (11 %)

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)

Baryte

PRODUCTION: 9,200,000 tonnes/year (2010-2014)

SUPPLY RISK (SR): 1.6 (2017) ●

ECONOMIC IMPORTANCE (EI): 2.9 (2017) ●

RECYCLING RATIO: 1 %

SUBSTITUTION:

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

COUNTRY OF ORIGIN: China (44 %), India (18 %), Morocco (10 %)

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

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

MINERAL(S)

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

Bertrandite

PRODUCTION: 320 tonnes/year (2012)

SUPPLY RISK (SR): 2.4 (2017) ●

ECONOMIC IMPORTANCE (EI): 3.9 (2017) ●

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: Ores: US (90 %), China (8 %); Refined: US (75 %), Japan (25 %)

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.

PRODUCTION: 8,180 tonnes/year (2010-2014)

SUPPLY RISK (SR): 3.8 (2017) ●

ECONOMIC IMPORTANCE (EI): 3.6 (2017) ●

RECYCLING RATIO: 1 %

SUBSTITUTION:

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

COUNTRY OF ORIGIN: China (82 %), Mexico (11 %), Japan (7 %)

Bismuthinite

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: 1,000,000 tonnes/year (2010-2014)

SUPPLY RISK (SR): 3.0 (2017) ●

ECONOMIC IMPORTANCE (EI): 3.1 (2017) ●

RECYCLING RATIO: 0 %

SUBSTITUTION:

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

COUNTRY OF ORIGIN: Turkey (38 %), US (23 %), Argentina (12 %)

Boracite

PROPERTIES

- Thermal and acoustic insulation.
- 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

- Glass insulation (fibreglass and textile fibreglass).
- Frits and ceramics (additive).
- Fertilizers (Borax 10 Mol, Etibor 48, Etidot 67).
- Detergents (laundry detergents, household and industrial cleaning products).

Fibreglass insulation

Fertilizer (Borax 10 Mol)

Detergents

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

MINERAL(S)

Cobaltite (CoAsS)

Cobaltite

PRODUCTION: 135,497 tonnes/year (2010-2014)

SUPPLY RISK (SR): 1.6 (2017) ●

ECONOMIC IMPORTANCE (EI): 5.7 (2017) ●

RECYCLING RATIO: 0 %

SUBSTITUTION:

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

COUNTRY OF ORIGIN: Democratic Republic of Congo (64 %); Canada (5 %); China (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

LiCoO_2 Batteries

Corrosion resistant alloys

Fluorine (${}^9\text{F}$)

MINERAL(S)

Fluorspar (CaF_2)

Fluorspar

PRODUCTION: 6,615 tonnes/year (2010-2014)

SUPPLY RISK (SR): 1.3 (2017) ●

ECONOMIC IMPORTANCE (EI): 4.2 (2017) ●

RECYCLING RATIO: 1 %

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 (64 %), Mexico (16 %), 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 $64.05\text{ }^\circ\text{C}$ ($147\text{ }^\circ\text{F}$) 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)

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

Gallite

PRODUCTION: 340 tonnes/year (2010-2014)

SUPPLY RISK (SR): 1.4 (2017) ●

ECONOMIC IMPORTANCE (EI): 3.2 (2017) ●

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 (85 %), Germany (7 %), Kazakhstan (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

PRODUCTION: *Extraction:* 760 tonnes/year; *Refining:* 136 tonnes/year (2010-2014)

SUPPLY RISK (SR): 1.9 (2017) ●

ECONOMIC IMPORTANCE (EI): 3.5 (2017) ●

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: *Extraction:* China (56 %), US (16 %), Australia (13 %); *Refining:* China (67 %), Finland (11 %), Canada (9 %), US (9 %)

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.

PRODUCTION: 72 tonnes/year (2010-2014)

SUPPLY RISK (SR): 1.3 (2017) ●

ECONOMIC IMPORTANCE (EI): 4.2 (2017) ●

RECYCLING RATIO: 1 %

SUBSTITUTION:

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

COUNTRY OF ORIGIN: France (43 %), US (41 %), Ukraine (8 %), Russia (8 %)

Hafnon

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

Helium ($_2\text{He}$)

MINERAL(S)

Natural Gas by-product
(average content v/v %: 0,1
%- 0,5 %)

PRODUCTION: 167.1 tonnes/year (2010-2014)

SUPPLY RISK (SR): 1.6 (2017) ●

ECONOMIC IMPORTANCE (EI): 2.8 (2017) ●

RECYCLING RATIO: 1 %

SUBSTITUTION:

- Cryogenics, purge and pressurization (no substitute).
- Welding, semiconductor, optical fibre manufacturing, controlled atmospheres (argon).
- Lifting gas (hydrogen).
- Leak detection, Analysis (H_2 and N_2).

COUNTRY OF ORIGIN: US (73 %), Qatar (12 %), Algeria (10 %)

PROPERTIES

- **Liquid Helium** (lowest boiling point among all the elements).
- **Gas helium:**
- Provides inert gas shield and prevents oxidation.
- Inertness, heat conducting and cooling properties. The second lightest element after H_2 .

USES

- Cryogenics (cool superconductive magnets of MRI scanners and in particle physics research facilities).
- Arc welding.
- Cooling gas (strand spinning operations in optical fibre cables), controlled atmospheres, leak detection, lifting gas.

MRI (Magnetic resonance imaging)

Arc welding (as a shield to prevent oxidation)

Lifting gas (zeppelin)

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).

Sphalerite

PRODUCTION: 689 tonnes/year (2010-2014)

SUPPLY RISK (SR): 2.4 (2017) ●

ECONOMIC IMPORTANCE (EI): 3.1 (2017) ●

RECYCLING RATIO: 0 %

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 (57 %), South Korea (15 %), Japan (10 %)

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

Fil solar cells (CIGS)

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+})

PRODUCTION: 846 tonnes/year (2010-2014)

SUPPLY RISK (SR): 4.0 (2017) ●

ECONOMIC IMPORTANCE (EI): 7.1 (2017) ●

RECYCLING RATIO: 9 %

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 (87 %)

Dolomite

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) ($_6\text{C}$)

MINERAL(S)

Natural Graphite (C)

PRODUCTION: 1,100,000 tonnes/year (2010-2014)

SUPPLY RISK (SR): 2.9 (2017) ●

ECONOMIC IMPORTANCE (EI): 2.9 (2017) ●

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

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: 11,965,000 tonnes/year (2010-2014)

SUPPLY RISK (SR): 1.0 (2017) ●

ECONOMIC IMPORTANCE (EI): 5.4 (2017) ●

RECYCLING RATIO: 1 %

SUBSTITUTION:

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

COUNTRY OF ORIGIN: Thailand (32 %), Indonesia (26 %), Vietnam (8 %), India (8 %)

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

PRODUCTION: 113,000 tonnes/year (2010-2014)

SUPPLY RISK (SR): 3.1 (2017) ●

ECONOMIC IMPORTANCE (EI): 4.8 (2017) ●

RECYCLING RATIO: 0.3 %

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: *Extraction:* Brazil (95 %), Canada (4 %); *Refining:* Brazil (90 %), Canada (10 %)

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 nozzles

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

PRODUCTION: 452 tonnes/year (2010-2014)

SUPPLY RISK (SR): 2.5 (2017) ●

ECONOMIC IMPORTANCE (EI): 5.0 (2017) ●

RECYCLING RATIO: See individual PGM factsheets

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

COUNTRY OF ORIGIN: South Africa, Russia, Zimbabwe, Canada (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 NO_x); 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

PRODUCTION: 7.1 tonnes/year (2016)

SUPPLY RISK (SR): 2.8 (2017) ●

ECONOMIC IMPORTANCE (EI): 4.3 (2017) ●

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 (85 %), Zimbabwe (9 %)

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)

Nickel sulphide (Pd and Pt ore)

PRODUCTION: 209 tonnes/year (2010-2014)

SUPPLY RISK (SR): 1.7 (2017) ●

ECONOMIC IMPORTANCE (EI): 5.6 (2017) ●

RECICLYING RATIO: 10 %

SUBSTITUTION:

- Investment sector (gold or other PGM).

COUNTRY OF ORIGIN: Russia (46 %), South Africa (36 %), Canada (7 %)

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 copper:

Mafic-Ultramafic igneous complexes (South Africa, Zimbabwe)

Nickel sulphide deposits (Russia)

Sulphidic Bronzite (Pd-Pt ore)

PRODUCTION: 187 tonnes/year (2010-2014)

SUPPLY RISK (SR): 2.2 (2017) ●

ECONOMIC IMPORTANCE (EI): 4.9 (2017) ●

RECYCLING RATIO: 11 %

SUBSTITUTION:

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

COUNTRY OF ORIGIN: South Africa (71 %), Russia (16 %), Zimbabwe (6 %)

PROPERTIES

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

USES

- Autocatalysts (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

PRODUCTION: 21.5 tonnes/year (2010-2014)

SUPPLY RISK (SR): 2.5 (2017) ●

ECONOMIC IMPORTANCE (EI): 6.6 (2017) ●

RECYCLING RATIO: 24 %

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 (83 %), Russia (10 %), Zimbabwe (4 %)

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)

PRODUCTION: 27.7 tonnes/year (2016)

SUPPLY RISK (SR): 3.4 (2017) ●

ECONOMIC IMPORTANCE (EI): 3.5 (2017) ●

RECYCLING RATIO: 11 %

SUBSTITUTION:

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

COUNTRY OF ORIGIN: South Africa (93 %), Zimbabwe (3 %), Russia (2 %)

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)

(¹⁵P)

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: 217,627,419 tonnes/year; WP: 915,000 tonnes/year (2010-2014)

SUPPLY RISK (SR): PR: 1.0 ● WP: 4.1 (2017) ●

ECONOMIC IMPORTANCE (EI): PR: 5.1 ● WP: 4.4 (2017) ●

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 (44 %), Morocco (13 %), US (13 %); WP: China (58 %), Vietnam (19 %), Kazakhstan (13 %)

Apatite

White phosphorus powder

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 (NH_4PO_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

PRODUCTION: 135,650 tonnes/year (2010-2014)

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: See individual factsheets

SUBSTITUTION: See individual factsheets.

COUNTRY OF ORIGIN: China (95 %), USA (1.7 %), Russia (1.3 %), Australia (1.2 %)

PROPERTIES

- REEs are all silvery-white to grey materials.
- Highly reactive with H_2O and O_2 .
- 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, Y_2O_3 (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)

PRODUCTION: 51,382 tonnes/year (2010-2014)

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

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

RECYCLING RATIO: 1 %

SUBSTITUTION:

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

COUNTRY OF ORIGIN: China (95 %)

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 more opaque.

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: 1,357 tonnes/year (2010-2014)

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

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

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 (95 %)

Monazite sand

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

PRODUCTION: 950 tonnes/year (2010-2014)

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

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

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 (95 %)

Xenotime (YPO_4)

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)

Loparite-(Ce)
(Ce, Na, Ca)(Ti, Nb)O₃

PRODUCTION: 407 tonnes/year (2010-2014)

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

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

RECYCLING RATIO: 38 %

SUBSTITUTION:

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

COUNTRY OF ORIGIN: China (95 %)

PROPERTIES

- Eu₂O₃ phosphorescence.

USES

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

Leppersonite-(Gd) (unique mineral with essential Gd)
 $\text{Ca}(\text{Gd,Dy})_2(\text{UO}_2)_{24}(\text{SiO}_4)_4(\text{CO}_3)_8(\text{OH})_2 \cdot 48\text{H}_2\text{O}$

Gadolinite

Leppersonite-(Gd)

PRODUCTION: 2,307 tonnes/year (2010-2014)

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

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

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 (95 %)

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

Euxenite

PRODUCTION: 1,764 tonnes/year (2010-2014)

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

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

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 (95 %)

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)

PRODUCTION: 35,146 tonnes/year (2010-2014)

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

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

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 (95 %)

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

Nd dominant minerals:

Monazite-(Nd) (Nd,La,Ce) PO_4
Kozoite-(Nd) (Nd,La,Sm,Pr) CO_3OH

PRODUCTION: 22,391 tonnes/year (2010-2014)

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

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

RECYCLING RATIO: 1 %

SUBSTITUTION:

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

COUNTRY OF ORIGIN: China (95 %)

Kozoite-(Nd)

Monazite-(Nd)

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

PRODUCTION: 6,514 tonnes/year (2010-2014)

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

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

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 color in ceramics.

COUNTRY OF ORIGIN: China (95 %)

PROPERTIES

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

USES

- High power magnets (motors, printers, watches, headphones, loudspeakers).
- Yellow color (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 $(\text{La}, \text{Ce})\text{CO}_3\text{F}$

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

Other minerals:

Samarskite-(Y)

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

Smarskite-(Y)

PRODUCTION: 2,714 tonnes/year (2010-2014)

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

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

RECYCLING RATIO: 1 %

SUBSTITUTION:

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

COUNTRY OF ORIGIN: China (95 %)

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

PRODUCTION: 407 tonnes/year (2010-2014)

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

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

RECYCLING RATIO: 6 %

SUBSTITUTION:

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

COUNTRY OF ORIGIN: China (95 %)

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)

PRODUCTION: 10,313 tonnes/year (2010-2014)

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

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

RECYCLING RATIO: 31 %

SUBSTITUTION:

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

COUNTRY OF ORIGIN: China (95 %)

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

PRODUCTION: *Refining:* 15 tonnes (Sc_2O_3)/year (2010-2014)

SUPPLY RISK (SR): 2.9 (2017) ●

ECONOMIC IMPORTANCE (EI): 3.7 (2017) ●

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

PRODUCTION: 2,288 tonnes/year (2010-2014)

SUPPLY RISK (SR): 1.0 (2017) ●

ECONOMIC IMPORTANCE (EI): 3.8 (2017) ●

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 (61 %), Brazil (9 %), Norway (7 %), US (6 %)

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: 1,800 tonnes of Ta_2O_5 /year (2010-2014)

SUPPLY RISK (SR): 1.0 (2017) ●

ECONOMIC IMPORTANCE (EI): 3.9 (2017) ●

RECYCLING RATIO: 1 %

SUBSTITUTION:

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

COUNTRY OF ORIGIN: Rwanda (31 %), Dem. Rep. of Congo (19 %), Brazil (14 %)

Tantalite-columbite (Coltan)

PROPERTIES

- Tantalum pentoxide 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)

Tungsten (Wolfram)

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

MINERAL(S)

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

Scheelite

PRODUCTION: 82,000 tonnes/year (2010-2014)

SUPPLY RISK (SR): 1.8 (2017) ●

ECONOMIC IMPORTANCE (EI): 7.3 (2017) ●

RECYCLING RATIO: 42 %

SUBSTITUTION:

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

COUNTRY OF ORIGIN: China (84 %), Russia (4 %)

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 tunneling 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
 $\text{K}_2(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 3\text{H}_2\text{O}$

Vanadinite

PRODUCTION: 71,026 tonnes/year (2010-2014)

SUPPLY RISK (SR): 1.6 (2017) ●

ECONOMIC IMPORTANCE (EI): 3.7 (2017) ●

RECYCLING RATIO: 44 %

SUBSTITUTION:

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

COUNTRY OF ORIGIN: *Refined:* China (53 %), South Africa (25 %), Russia (20 %)

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

- Ferrovanadium / 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

APPLICATION SHEETS

TURBINES

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

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

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

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

EMISSIONS CONTROL CATALYSTS

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

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

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

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

BIOLOGICAL ROLES

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

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

Boron (borates) ($_5\text{B}$)

**Phosphate Rock
(phosphorus) ($_{15}\text{P}$)**

SOLAR PANELS (PHOTOVOLTAIC CELLS)

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

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

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

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

SPORTS

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

Natural Rubber

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

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

SPACECRAFT

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

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

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

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

NUCLEAR REACTORS

Holmium ($_{67}\text{Ho}$)

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

Fluorine ($_{9}\text{F}$)

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

MEDICINE DEVICES

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

Helium (${}_{2}\text{He}$)

Thulium (${}_{69}\text{Tm}$)

Ytterbium (${}_{70}\text{Yb}$)

ELECTRONIC DEVICES (INTEGRATED CIRCUIT)

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

Lutetium ($_{71}\text{Lu}$)

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

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

SCREENS

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

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

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

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

MUSIC (ELECTRONICS)

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

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

Samarium ($_{26}\text{Sm}$)

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

BATTERIES

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

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

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

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

CANCER TREATMENTS

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

Samarium($_{26}\text{Sm}$)

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

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

PYROTECHNICS

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

Carbon (Grafite) ($_6\text{C}$)

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

**White phosphorus
($_{15}\text{P}$)**

STUDENTS PLAY CARDS

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

Stibnite (Sb_2S_3)

Property:

(Halogenated) Highly-effective flame retardant

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

Stibnite (Sb_2S_3)

Property:

PbSb-Corrosion resistant, Charging characteristics

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

Stibnite (Sb_2S_3)

Property:

Gives resistance to different metal-alloys

Flame-retardant plastics

PbSb batteries

Low-load bearing in the automotive sector

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

Baryte (BaSO_4)

Property:

**Soundproof material;
Resistant to abrasion**

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

Baryte (BaSO_4)

Property:

High specific gravity

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

Baryte (BaSO_4)

Property:

**BaSO_4 High density and
opacity to X-rays**

**Break and clutch pads
(automotive industry)**

**Weighting agent in drilling
fluids (Oil production)**

**Radiocontrast agent in X-ray
imaging of the digestive
system**

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

Bertrandite ($\text{Be}_4\text{Si}_2\text{O}_7(\text{OH})_2$)

Property:

Improves mechanical properties without impairing electrical conductivity

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

Bertrandite ($\text{Be}_4\text{Si}_2\text{O}_7(\text{OH})_2$)

Property:

Stiffness, light weight and dimensional stability over a wide temperature range

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

Bertrandite ($\text{Be}_4\text{Si}_2\text{O}_7(\text{OH})_2$)

Property:

Low density combined with strength

Undersea fibre optic cables

Satellites and spacecrafts

Landing Gear (Aircraft)

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

Bismuthinite (Bi_2S_3)

{By-product of Pb and W extraction}

Property:

Antiacid and anti-ulcer agent

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

Bismuthinite (Bi_2S_3)

{By-product of Pb and W extraction}

Property:

BiVO_4 High temperatures resistant, SO_2 resistance

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

Bismuthinite (Bi_2S_3)

{By-product of Pb and W extraction}

Property:

Sn-Bi Low melting point

Antacid (bismuth subsalicylate)

Metallurgical additives, coatings, pigments

Fusible alloys in solders(replacement of harmful metals (lead))

Boron (borates) (${}_5\text{B}$)

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

Property:

Thermal and acoustic insulation

Boron (borates) (${}_5\text{B}$)

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

Property:

Essential macronutrient for plant growth

Boron (borates) (${}_5\text{B}$)

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

Property:

Enhance stain removal and bleaching

Fibreglass and textile insulation

Fertilizer (Borax 10 Mol)

Laundry detergents and industrial cleaning products

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

Cobaltite (CoAsS)

Property:

LiCoO_2 as Li-ion
batteries cathode

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

Cobaltite (CoAsS)

Property:

High hardness, corrosion
and wear resistant

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

Cobaltite (CoAsS)

Property:

$(\text{CoAl}_2\text{O}_4)$ Coloured metal
and chromatic stability

LiCoO_2 Batteries

Corrosion resistant alloys

Blue pigment for ceramics
decoration

Fluorine ($_9\text{F}$)

Fluorspar (CaF_2)

Property:

**Solid fluoropolymers-
Extreme chemical resistance**

Fluorine ($_9\text{F}$)

Fluorspar (CaF_2)

Property:

**Fluorochemicals-High
heat of vaporization**

Fluorine ($_9\text{F}$)

Fluorspar (CaF_2)

Property:

**Reduces the melting
point of steel/iron**

Cookware coating

HCFCs refrigeration

**Steel and iron making
(Metspar in Iron & Steel
making)**

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

Gallite (CuGaS_2)

{By-product of Al extraction from Bauxite}

Property:

**GaAs, GaN-
Semiconductors**

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

Gallite (CuGaS_2)

{By-product of Al extraction from Bauxite}

Property:

**Cu-In-Se-Ga (CIGS)-
Semiconductor and flexibility**

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

Gallite (CuGaS_2)

{By-product of Al extraction from Bauxite}

Property:

**Improves magnetic properties
and corrosion resistance**

**Integrated circuits, LED –
smartphones, wireless
communication systems**

CIGS photovoltaics

NdFeB magnets

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

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

{By-product of Zn extraction from Zn ores and coal ashes}

Property:

Transparent to infrared (IR) wavelengths

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

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

{By-product of Zn extraction from Zn ores and coal ashes}

Property:

Transparent to IR with high efficiency as lightweight

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

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

{By-product of Zn extraction from Zn ores and coal ashes}

Property:

GeO_2 -increases reflective index preventing signal loss

Night-vision devices

Space-based solar cells

Fibre optics

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

Hafnon ((Hf, Zr)SiO₄)

{By-product of Zr extraction from zircon and baddeleyite}

Property:

Super-alloys High temperature resistant

Turbine blades and vanes (aerospace industry)

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

Hafnon ((Hf, Zr)SiO₄)

{By-product of Zr extraction from zircon and baddeleyite}

Property:

Hafnium compounds are very refractory

Refractory ceramic materials

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

Hafnon ((Hf, Zr)SiO₄)

{By-product of Zr extraction from zircon and baddeleyite}

Property:

High thermal neutron absorption cross section

Nuclear control rods in nuclear reactors

Helium (${}^2\text{He}$)

By-product from natural gas
(average content v/v%: 0.1 - 0.5)

Property:

Liquid He: lowest boiling point of all elements

Helium (${}^2\text{He}$)

By-product from natural gas
(average content v/v%: 0.1 - 0.5)

Property:

Gas He: Provides inert gas shield preventing oxidation

Helium (${}^2\text{He}$)

By-product from natural gas
(average content v/v%: 0.1 - 0.5)

Property:

Gas He: Inertness and the 2nd lightest element after H₂

Cryogenics-MRI scanners
(Magnetic Resonance Imaging)

Arc welding (as a shield to prevent oxidation)

Lifting gas - Zeppelin

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

Sphalerite ($(\text{Zn}, \text{Fe})\text{S}$)

{Trace element in sphalerite (20-200 ppm of In)}

Property:

Soft, ductile and very malleable silvery material

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

Sphalerite ($(\text{Zn}, \text{Fe})\text{S}$)

{Trace element in sphalerite (20-200 ppm of In)}

Property:

Reduces melting point in solder alloys and improves fatigue performance

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

Sphalerite ($(\text{Zn}, \text{Fe})\text{S}$)

{Trace element in sphalerite (20-200 ppm of In)}

Property:

Light absorber material and maximizes light transmission into solar cells

ITO thin films-Computer screens

Electronics industry (Low temperature free Hg-solder)

Film solar cells (CIGS, ITO)

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

Dollomite ($\text{CaMg}(\text{CO}_3)_2$)

Property:

Lightweight and high energy impacts resistance

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

Dollomite ($\text{CaMg}(\text{CO}_3)_2$)

Property:

Improves aluminium strength without removing its workability

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

Dollomite ($\text{CaMg}(\text{CO}_3)_2$)

Property:

MgCO_3 -High tendency to “absorb” water

Seat frames (automotive industry casting alloys)

Aluminium alloys (packaging applications, construction equipment)

(MgCO_3) Improves athlete grip in climbing and gymnasts and weight-lifters performances

Carbon (Grafite) ($_6\text{C}$)

Natural Graphite (C)

Property:

**High temperature stability
and chemical inertness**

Carbon (Grafite) ($_6\text{C}$)

Natural Graphite (C)

Property:

**Loose interlamellar coupling
between sheets in the
structure**

Carbon (Grafite) ($_6\text{C}$)

Natural Graphite (C)

Property:

**High electrical
conductivity and porosity**

**Foundry refractory materials
(steel making and hot metal-
forming)**

Solid dry lubricants

Anode ion-lithium batteries

Natural Rubber

Rubber tree

Property:

**Resistance to abrasion,
elasticity**

Natural Rubber

Rubber tree

Property:

**Chemical attacks
resistant, elasticity**

Natural Rubber

Rubber tree

Property:

Inertness, elasticity

Monster Truck tires

Latex toys

Latex gloves

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

Columbite ($(\text{Fe}, \text{Mn})\text{Nb}_2\text{O}_6$)

Property:

FeNb-Increase of strength and lightweight

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

Columbite ($(\text{Fe}, \text{Mn})\text{Nb}_2\text{O}_6$)

Property:

Corrosion resistance and high strength at high temperatures

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

Columbite ($(\text{Fe}, \text{Mn})\text{Nb}_2\text{O}_6$)

Property:

Superconductor (Nb-Ti or Nb-Sb alloys)

Gas pipelines

Rocket thruster nozzles

LHC (Large Hadron Collider)

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

Ores of nickel and copper

Property:

**High melting point and
chemical attack resistant**

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

Ores of nickel and copper

Property:

Iridium-192 radioisotope

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

Ores of nickel and copper

Property:

**Ru-Ir: resistance to
chemical attack**

**Flat screen displays
(portable electronic
resistance)**

**Source of gamma radiation
for the treatment of cancer
(brachytherapy)**

**Ru-Ir anodes for
electrochemical preduction
of NaOH and Cl_2**

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

Ores of nickel and cooper

Property:

Finely divided on carbon (Pd/C) becomes a catalyst

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

Ores of nickel and cooper

Property:

Low melting point

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

Ores of nickel and cooper

Property:

Soft, ductile and with low density

Petroleum cracking

Multilayer ceramic capacitor

Dental fillings and bridges

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

Ores of nickel and cooper

Property:

Platinum black - Catalyst

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

Ores of nickel and cooper

Property:

Platinum black - Corrosion resistance and chemical stability

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

Ores of nickel and cooper

Property:

Silvery-white metal

Automobile emissions control system

Conductivity meter

Platinum jewellery

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

Ores of nickel and cooper

Property:

Inertness, corrosion resistant
and small electrical resistance

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

Ores of nickel and cooper

Property:

Rhodium plated by
electroplating is extremely hard

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

Ores of nickel and cooper

Property:

Characteristic X-rays

Carbon fibre rhodium plated
XLR connectors

Eye exam equipment

Mammography filters

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

Ores of nickel and cooper

Property:

High temperature resistant

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

Ores of nickel and cooper

Property:

High electrical conductance

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

Ores of nickel and cooper

Property:

Resistant to wear and chemical attack

Spark plugs

Hard Drive Disk

Ammonia gas sensor

Phosphate Rock (phosphorus) ($_{15}\text{P}$)

Apatite ($\text{Ca}_5(\text{PO}_4)_3(\text{F}, \text{Cl}, \text{OH})$)
{more than 300 minerals}

Property:

**Vital part of plant and
animal nourishment**

Phosphate Rock (phosphorus) ($_{15}\text{P}$)

Apatite ($\text{Ca}_5(\text{PO}_4)_3(\text{F}, \text{Cl}, \text{OH})$)
{more than 300 minerals}

Property:

**$\text{Na}_5\text{P}_3\text{O}_{10}$ is a water
softener**

Phosphate Rock (phosphorus) ($_{15}\text{P}$)

Apatite ($\text{Ca}_5(\text{PO}_4)_3(\text{F}, \text{Cl}, \text{OH})$)
{more than 300 minerals}

Property:

**$(\text{NH}_4)_3\text{PO}_4$ melts and flows at
 $177\text{ }^\circ\text{C}$ (351°F) (smoothing fire)**

Phosphate fertilizer

Detergent

Fire extinguishers

White phosphorus ($_{15}\text{P}$)

White phosphorus powder (P_4)

Property:

**Highly pyrophoric upon
contact with air**

White phosphorus ($_{15}\text{P}$)

White phosphorus powder (P_4)

Property:

Systemic toxicity

White phosphorus ($_{15}\text{P}$)

White phosphorus powder (P_4)

Property:

Produces smoke

White phosphorus weapon

Rodenticide

Military obscurant

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

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

Property:

CeO_2 - Abrasion resistance
→ Chemical-mechanical
planarization

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

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

Property:

CeO_2 -Catalyst

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

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

Property:

Ce (IV) High refractive index
that enhances photostability
(pigments more opaque)

Integrated circuits

Electrodes in gas tungsten
arc welding

Pigments

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

Monzanite sand ($(\text{Ce, La, Nd, Th})\text{PO}_4$)
{By-product}

Property:

**Increase Curie temperature
allowing the use of permanent
magnets at up to 200°C (392°F)**

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

Monzanite sand ($(\text{Ce, La, Nd, Th})\text{PO}_4$)
{By-product}

Property:

**Increase Curie temperature
allowing the use of permanent
magnets at up to 200°C (392°F)**

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

Monzanite sand ($(\text{Ce, La, Nd, Th})\text{PO}_4$)
{By-product}

Property:

**Increase Curie temperature
allowing the use of permanent
magnets at up to 200°C (392°F)**

**Neodymium (NdFeB)
magnets**

Wind turbines

Industrial motors

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

Xenotime (YPO_4)
{By-product}

Property:

Erbium-doped silica-glass fibres has optical properties

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

Xenotime (YPO_4)
{By-product}

Property:

Er^{3+} doped with silica substrate gives a fast multi-phonon transition

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

Xenotime (YPO_4)
{By-product}

Property:

Er^{3+} ions have pink colour

Erbium-doped fibre link amplifier (EDFAs)

YAG laser, dental laser

Pink colour glass

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

Loparite-(Ce) $((\text{Ce}, \text{Na}, \text{Ca})(\text{Ti}, \text{Nb})\text{O}_3)$
{By-product}

Property:

Eu_2O_3 phosphorescence

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

Loparite-(Ce) $((\text{Ce}, \text{Na}, \text{Ca})(\text{Ti}, \text{Nb})\text{O}_3)$
{By-product}

Property:

Eu_2O_3 phosphorescence

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

Loparite-(Ce) $((\text{Ce}, \text{Na}, \text{Ca})(\text{Ti}, \text{Nb})\text{O}_3)$
{By-product}

Property:

Eu_2O_3 phosphorescence

Helical fluorescent light
bulbs

Anti-counterfeiting
phosphors in a 50 €
banknote

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

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

Leppersonite-(Gd)

{Bastnäsite / Monazite sand by-product}

Property:

Enhances nuclear relaxation rates in NdFeB alloys

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

Leppersonite-(Gd)

{Bastnäsite / Monazite sand by-product}

Property:

Solutions of organic gadolinium complexes

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

Leppersonite-(Gd)

{Bastnäsite / Monazite sand by-product}

Property:

Gd_2O_3 luminescence

NdFeB alloys permanent magnets

Intravenous MRI contrast agent to enhance images

X-ray systems (positron emission tomography)

Holmium ($_{67}\text{Ho}$)

Euxenite

$((\text{Y}, \text{Ca}, \text{Ce}, \text{U}, \text{Th})(\text{Nb}, \text{Ta}, \text{Ti})_2\text{O}_6)$
{Monazite sand by-product}

Property:

**Ho_2O_3 -Colour changes
depending on the lighting**

Holmium ($_{67}\text{Ho}$)

Euxenite

$((\text{Y}, \text{Ca}, \text{Ce}, \text{U}, \text{Th})(\text{Nb}, \text{Ta}, \text{Ti})_2\text{O}_6)$
{Monazite sand by-product}

Property:

**Highest magnetic
strength of elements**

Holmium ($_{67}\text{Ho}$)

Euxenite

$((\text{Y}, \text{Ca}, \text{Ce}, \text{U}, \text{Th})(\text{Nb}, \text{Ta}, \text{Ti})_2\text{O}_6)$
{Monazite sand by-product}

Property:

**Highest magnetic
strength of elements**

Cubic zirconia colorants

Nuclear reactors

Lasers

Thulium ($_{69}\text{Tm}$)

Euxenite

$((\text{Y}, \text{Ca}, \text{Ce}, \text{U}, \text{Th})(\text{Nb}, \text{Ta}, \text{Ti})_2\text{O}_6)$
{Monazite sand by-product}

Property:

Wavelength of Th lasers makes it very useful for superficial ablation of tissue

Thulium ($_{69}\text{Tm}$)

Euxenite

$((\text{Y}, \text{Ca}, \text{Ce}, \text{U}, \text{Th})(\text{Nb}, \text{Ta}, \text{Ti})_2\text{O}_6)$
{Monazite sand by-product}

Property:

Radiation source

Thulium ($_{69}\text{Tm}$)

Euxenite

$((\text{Y}, \text{Ca}, \text{Ce}, \text{U}, \text{Th})(\text{Nb}, \text{Ta}, \text{Ti})_2\text{O}_6)$
{Monazite sand by-product}

Property:

Fluorescence (blue colour exposed to ultraviolet light)

Tm:YAG laser capsulotomy (surgery)

Portable X-ray devices

Anti-counterfeiting phosphors in a 50 € banknote

Lutetium ($_{71}\text{Lu}$)

Monazite ((Ce,La,Nd,Th)PO₄)
{Monazite sand by-product}

Property:

Al₅Lu₃O₁₂ high refractive index

Lutetium ($_{71}\text{Lu}$)

Monazite ((Ce,La,Nd,Th)PO₄)
{Monazite sand by-product}

Property:

Lutetium-176 (radioactive isotope), pure beta emitter

Lutetium ($_{71}\text{Lu}$)

Monazite ((Ce,La,Nd,Th)PO₄)
{Monazite sand by-product}

Property:

LuTaO₄ is the densest known stable white material (non radioactive)

Manufacturing integrated circuits by immersion lithography

Neutron activation analysis (most accurate trace elements analysis)

Host for X-ray phosphors

Ytterbium ($_{70}\text{Yb}$)

Euxenite

$((\text{Y}, \text{Ca}, \text{Ce}, \text{U}, \text{Th})(\text{Nb}, \text{Ta}, \text{Ti})_2\text{O}_6)$
{Monazite sand by-product}

Property:

Yb-169 emits gamma rays

Ytterbium ($_{70}\text{Yb}$)

Euxenite

$((\text{Y}, \text{Ca}, \text{Ce}, \text{U}, \text{Th})(\text{Nb}, \text{Ta}, \text{Ti})_2\text{O}_6)$
{Monazite sand by-product}

Property:

Large number of atoms

Ytterbium ($_{70}\text{Yb}$)

Euxenite

$((\text{Y}, \text{Ca}, \text{Ce}, \text{U}, \text{Th})(\text{Nb}, \text{Ta}, \text{Ti})_2\text{O}_6)$
{Monazite sand by-product}

Property:

Yb^{3+} used as a doping material enhances lifetimes and efficiency

Radiography of small objects

High-stability atomic clock

Solid state lasers

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

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

Property:

Anodic material, mischmetal
($>50\%$ La, intermetallic of
the AB_5 type)

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

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

Property:

La_2O_3 improves alkali resistance
of glass, high refraction index
and low dispersion

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

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

Property:

Mischmetal, pyrophoric
alloy (25% - 45% of La)

Nickel-metal hybrid batteries

Telescope lenses

Lighter flints

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

Monazite-(Nd) (Nd,La,Ce) PO_4
{By-product of Bastnäsite}

Property:

**Blue inclusions of Nd_2O_3
in the glass melt**

Blue pigment in glass

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

Monazite-(Nd) (Nd,La,Ce) PO_4
{By-product of Bastnäsite}

Property:

**Nd-doped crystals (Nd:YVO_4)
serve as a gain media for
infrared wavelengths**

**DPSS hand-held lasers and
laser pointers**

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

Monazite-(Nd) (Nd,La,Ce) PO_4
{By-product of Bastnäsite}

Property:

**Strong permanent magnets (a
few grams can lift a thousand
times its own weight)**

Microphones

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

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

Property:

**Alloyed with Mg forms
high-strength materials**

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

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

Property:

**Praseodymium compounds
have yellow colour**

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

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

Property:

^x
**Offers strength and durability in
extremely stable magnets**

Aircraft engines

Yellow glazing in ceramics

Digital watches

Samarium ($_{26}\text{Sm}$)

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

Property:

High permanent magnetization

Samarium ($_{26}\text{Sm}$)

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

Property:

Catalyst and reagent

Samarium ($_{26}\text{Sm}$)

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

Property

Radioactive Sm-153 is β -emitter with half life of 46.3 hours (injected intravenously)

Headphones

Assists decomposition of plastics, dechlorination of pollutants (PCBs)

Used in treatments of cancer (lung cancer, prostate cancer, breast cancer)

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

Xenotime (YPO_4)
{By-product}

Property:

Terfenol-D (Tb alloy) Highest magnetostriction of any alloy (expands or contracts in a magnetic field)

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

Xenotime (YPO_4)
{By-product}

Property:

Terbium oxide is bright fluorescence

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

Xenotime (YPO_4)
{By-product}

Property:

Acts as an assay of dipicolinic acid based on photoluminescence

Naval sonar system

Green phosphors in fluorescent lamps and colour in TV tubes

Detecting endospores

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

Bastnäsite-(Y) $((\text{Y,Ce})\text{CO}_3\text{F})$
{By-product}

Property:

Yttria (Y_2O_3) stabilized-zirconia, (YSZ) hard ceramic used as a strong base material

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

Bastnäsite-(Y) $((\text{Y,Ce})\text{CO}_3\text{F})$
{By-product}

Property:

Y_2O_5 is shock-resistance and has low thermal expansion properties

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

Bastnäsite-(Y) $((\text{Y,Ce})\text{CO}_3\text{F})$
{By-product}

Property:

Isotope Y-90 has intense β -radiation

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

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

Added to monoclonal antibodies, is used for the treatment of cancer with radio immunotherapy (lymphoma, leukaemia, liver, ovarian cancers)

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

Biotite ($\text{K}(\text{Mg},\text{Fe})_3\text{AlSi}_3\text{O}_{10}(\text{F},\text{OH})_2$)
{Trace constituent of igneous ferromagnesian minerals and in Ni and Co lateritic deposits}

Property:
Stabilizes zirconia to withstand high temperatures

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

Biotite ($\text{K}(\text{Mg},\text{Fe})_3\text{AlSi}_3\text{O}_{10}(\text{F},\text{OH})_2$)
{Trace constituent of igneous ferromagnesian minerals and in Ni and Co lateritic deposits}

Property:
Alloying Sc with Al and Mg forms light alloys with high strength and hardness

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

Biotite ($\text{K}(\text{Mg},\text{Fe})_3\text{AlSi}_3\text{O}_{10}(\text{F},\text{OH})_2$)
{Trace constituent of igneous ferromagnesian minerals and in Ni and Co lateritic deposits}

Property:
Sc in the form of metal or oxide has a high colour rendering index

Solid Oxygen Fuel Cells (SOFCs) in fuel cells vehicles

Scalmalloys (Sc-Mg-Al alloy family), used in aerospace, automotive transportation

GSGG laser rods

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

Quartz (SiO_2)

Property:

Synthetic silica has high melting temperature, inertness, abrasion-resistance and natural absorbency

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

Quartz (SiO_2)

Property:

Silanes are strong reducing agents

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

Quartz (SiO_2)

Property:

Ultra-high purity grade silicon (efficiencies ranging from 18-24 %)

“Portland” cement

Fibreglass

Solar panels (Silicon solar cells)

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

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

Property:

Ta_2O_5 filmed naturally on Ta metal prevents corrosion

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

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

Property:

Refractory material and corrosion resistant

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

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

Property:

Conflict resources (natural resources extracted in a conflict zone and sold to perpetuate the fighting)

Cell phones (tantalum capacitors with high performance)

Jet engines (superalloys, aerospace sector, gas turbines)

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

Tungsten (Wolfram)
(₇₄W)

Wolframite ((Fe,Mn)WO₄)

Property:

**Hardness and strength
combined with toughness and
plasticity (cemented carbides,
hard metals)**

Tungsten (Wolfram)
(₇₄W)

Wolframite ((Fe,Mn)WO₄)

Property:

**Hardness and strength
combined with toughness
and plasticity (superalloys)**

Tungsten (Wolfram)
(₇₄W)

Wolframite ((Fe,Mn)WO₄)

Property:

**Metal tungsten retains its
strength at high
temperatures**

**Button bits (mining and
tunnelling cutting tools)**

Rocket nozzles

Incandescent bulb filaments

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

Vanadinite ($\text{Pb}_5(\text{VO}_4)_3\text{Cl}$)

Property:

Considerable increase of strength with small amounts of V

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

Vanadinite ($\text{Pb}_5(\text{VO}_4)_3\text{Cl}$)

Property:

Low-neutron-adsorption abilities without deforming in creeping under high temperatures

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

Vanadinite ($\text{Pb}_5(\text{VO}_4)_3\text{Cl}$)

Property:

V_2O_5 has catalytic properties

Jet engines (Ferrovanadium / HSLA additive mixed with Al or Ti alloys)

Nuclear reactors

V_2O_5 catalyst (manufacturing of H_2SO_4 or maleic anhydride)