RAWMATCARDS

Critical Raw Materials Memory Card Game
Authors:

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SUMMARY
**Summary**

<table>
<thead>
<tr>
<th><strong>BARIUM (Ba)</strong></th>
<th><strong>BISMUTH (Bi)</strong></th>
<th><strong>ANTIMONY (Sb)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Property:</strong></td>
<td><strong>Property:</strong></td>
<td><strong>Property:</strong></td>
</tr>
<tr>
<td>High specific gravity</td>
<td>Stabilizes the process of solidification of composites</td>
<td>aids the development of ignition</td>
</tr>
<tr>
<td>Weighting agent in drilling fluids (oil production)</td>
<td>Fusible alloys in solders (replacement of harmful metals (lead))</td>
<td>Fire-resistant plastic</td>
</tr>
</tbody>
</table>

**Target age**

Age 15 and over

**Level of difficulty**

- [ ] Easy  [x] Medium  [ ] High

**Key words:**

CRMs applications, CRMs properties, Minerals, Substitutes.

**Abstract of the activity:**

Simple card game that can be used with a group of students for them to learn, by playing, the main properties and uses of several critical raw materials, as well as their importance nowadays in our technological society. They will also be introduced to the current worldwide environmental and socioeconomically concerns.

The main aim of the game is to match the cards of the elements properties with their corresponding application. For this purpose, cards will be faced down on the table and students will turn them over by turns.
### Summary

#### Learning Goals
- CRMs economic importance and risk supply.
- CRMs minerals, manufacturing, properties and uses.
- CRMs environmental and social impacts.

#### Specific Abilities - *At the end of the activity the student will be able to:*
- Identify Critical Raw Materials, their origin, properties and applications in real life products.

#### Cross-curricula Links-
- Geology: minerals
- Economy: renewable and digital technologies key sectors, circular economy.
- Environment Sciences: mining and e-waste generation impacts, ecological footprint.
- Social Sciences: mining social concerns, child exploitation and soldiers.
- Politics: European Commission policies about Critical Raw Materials.

#### Prerequisites - *Knowledge and skills necessary for carrying out the activity*
- Basic materials properties knowledge.

#### Time requirement
- ☐ 1 h
- ☐ 15 min
Summary

Learning and Teaching Support Materials - What you can find in the toolkit

1. Teachers’ Card.
2. Awareness-raising, environmental and social impacts.
3. Fact Sheets.
4. Game Instructions.
5. Student’s Play Cards.
6. Access to a prepared Kahoot!

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TEACHER CARD
# Teachers’ Card

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### CRMs Memory Card Game

<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BARIUM (85Ba)</strong></td>
<td>Property: high specific gravity</td>
</tr>
<tr>
<td><strong>BISMUTH (83Bi)</strong></td>
<td>Property: low melting point</td>
</tr>
<tr>
<td><strong>ANTIMONY (51Sb)</strong></td>
<td>Property: slow development of ignition</td>
</tr>
</tbody>
</table>

- **BARIUM**: Weighting agent in drilling fluids (oil production).
- **BISMUTH**: Fusible alloys in solders (replacement of harmful metals (tack!)).
- **ANTIMONY**: Flame-retardant plastics.
Teachers’ Card

General Introduction

This simple memory card game can be used with a group of students for them to learn, the main properties and uses of several critical raw materials, as well as their importance nowadays in our technological society. They will also be introduced to the current worldwide environmental and socioeconomically concerns.

The targeted audience are students from 15 to 18 years old, as it is advisable that they have some scientific and technological background.

This toolkit is organised in a collection of facts sheets for each Critical Raw Material (CRM) with information on the main mineral/minerals from which are extracted, global supply information, properties and uses. It is completed with a set of cards for students to learn by playing.

Keywords:

CRMs applications, CRMs properties, Minerals, Substitutes.

Extended background information

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. There are three properties that these materials must meet to be considered ‘critical’:

- **Significant economic importance for key sectors in the European economy**: such as consumer electronics, environmental technologies, automotive, aerospace, military 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.
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. Then, in 2014, 44 critical materials were revised and a new list with 20 critical raw materials was set. Afterwards, in 2017, the list was increased to 27 CRMs based on a refined methodology. 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. Finally, in 2020, the current Critical Raw Material List was published.

All these lists were (and still are) supposed to help the European trade in various ways:

- 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’.

2020 was the last year that a critical raw materials’ list was set, which was completed up to 30 critical raw materials that appear in Table 1.

### 2020 Critical Raw Materials

<table>
<thead>
<tr>
<th>Antimony</th>
<th>Fluorspar</th>
<th>Magnesium</th>
<th>Silicon Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baryte</td>
<td>Gallium</td>
<td>Natural Graphite</td>
<td>Tantalum</td>
</tr>
<tr>
<td>Bauxite</td>
<td>Germanium</td>
<td>Natural Rubber</td>
<td>Titanium</td>
</tr>
<tr>
<td>Beryllium</td>
<td>Hafnium</td>
<td>Niobium</td>
<td>Vanadium</td>
</tr>
<tr>
<td>Bismuth</td>
<td>HREEs</td>
<td>PGMs</td>
<td>Tungsten</td>
</tr>
<tr>
<td>Borates</td>
<td>Indium</td>
<td>Phosphate rock</td>
<td>Strontium</td>
</tr>
<tr>
<td>Cobalt</td>
<td>Lithium</td>
<td>Phosphorus</td>
<td></td>
</tr>
<tr>
<td>Coking Coal</td>
<td>LREEs</td>
<td>Scandium</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: List of Critical Raw Materials (European Commission, 2019). HRREs: 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, around 90% of all the beryllium produced that supplies the global economy comes from USA or 86% of LREEs and HREEs are produced by China. Meanwhile, Figure 2 contains the same type of percentages referred to the supply of EU raw materials (EU would only be self-sustaining for strontium).

The European Union needs to ensure a safe and sustainable Critical Raw Material supply, and it is fundamental that companies, authorities and EU institutions work together to achieve this goal. Further investigations about possible substitutes for Critical Raw Materials and residues reprocessing in order to avoid that valuable materials end up in a landfill, are needed. Critical Raw Material supply is a challenge that concerns all of us as they are used in a huge variety of essential devices and technological items of our daily life. That is why it is important for students to get familiar with these materials.
Teachers’ Card

Learning Outcomes

By the end of the lesson the students will be able to know:

- CRMs economic importance and risk supply.
- CRMs minerals, manufacturing, properties and uses.
- CRMs environmental and social impacts.

Key Competence European Framework

<table>
<thead>
<tr>
<th>Literacy competence</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1. Ability to understand and interpret concepts, feelings, facts or opinions in oral and written form.</td>
</tr>
<tr>
<td>S3. Ability to interpret the world and relate to others.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Multilingual competence</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1. Ability to understand and interpret concepts, feelings, facts or opinions in oral and written form.</td>
</tr>
<tr>
<td>S3. Ability to interpret the world and relate to others.</td>
</tr>
<tr>
<td>S5. Knowledge of vocabulary, grammar and language.</td>
</tr>
<tr>
<td>S7. Ability to use technical language accordingly to the field of work.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mathematical competence and competence in science, technology and engineering</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1. Ability to use constructed thinking in order to solve a problem in every situation.</td>
</tr>
<tr>
<td>S4. Readiness to address new problems from new areas.</td>
</tr>
<tr>
<td>S5. Capacity for quantitative thinking.</td>
</tr>
<tr>
<td>S6. Ability to extract qualitative information from quantitative data</td>
</tr>
<tr>
<td>S8. Ability to design experimental and observational studies and analyse data resulting from them.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Personal, social and learning to learn competence</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1. Ability to pursue and persist in different kinds of learning.</td>
</tr>
<tr>
<td>S3. Ability to gain process and assimilate new knowledge, skills and qualification required for career goals.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Citizen competence</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2. Ability to adapt to the changing situation, being flexible and work under pressure</td>
</tr>
<tr>
<td>S3. Ability to work effectively and collaborate with other team members</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Entrepreneurship competence</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1. Awareness of local, national, European culture heritage and their place in the world</td>
</tr>
</tbody>
</table>
United Nations’ Sustainable Development Goals

The Sustainable Development Goals are the blueprint to achieve a better and more sustainable future for all. They address the global challenges we face, including those related to poverty, inequality, climate change, environmental degradation, peace and justice. **Goals linked to this activity:**

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Enable access to basic services</td>
<td></td>
<td>Safe medical devices</td>
<td>Access to education</td>
<td>Less hardship, more opportunities</td>
<td>Safe and affordable water</td>
<td>Energy – the golden thread</td>
<td>Safety of workers and economic growth</td>
<td>Resilient infrastructure and sustainable industrialization</td>
</tr>
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<tr>
<td></td>
<td>Equal access to global expertise</td>
<td>Sustainable urbanization</td>
<td>Responsible consumption and production</td>
<td>Strengthen resilience, reduce disaster impact</td>
<td>Reduce marine pollution</td>
<td>Sustainable use of terrestrial ecosystems</td>
<td>Promote peaceful and inclusive societies</td>
<td>Better access to technology and innovation</td>
</tr>
</tbody>
</table>

**Contents – Theoretical principles**

Appendix 1 – Awareness-raising, environmental and social impacts

Appendix 2 – Fact Sheets
Lab Procedure/Activity

Appendix 3 – Game Instructions
Appendix 4 – Student’s Play Cards

Learning Pathway

Step 1 (15 minutes) – Teachers give a seminar to introduce the concept of CRMs, their challenges and examples of applications and uses.

Step 2 (10 minutes) – Game rules are explained, students are divided into groups and teams, setting up the game (preferably 3 groups of 3-4 teams and 2-3 students per team).

Step 3 (35 minutes) – Students teams, in turns, try to match as many application-use pairs as possible (there are 3 sets of cards, so they can play up to 3 rounds).

Step 4 (15 minutes) – Students play a Kahoot!

Evaluation

Access to a prepared and structured public “Kahoot!” (Critical Raw Materials Properties&Uses, created by the user EITRMSchools). The teacher can save the results of the students' scores for the evaluation.

Description of Student’s Cards

Appendix 4 – Student’s Play Cards
Sources

- Von Stackelberg, Katherine; Amos, Craig; Smith, Thomas; Cropek, Don and MacAllister, Bruce (2004), *Military smokes and obscurants fate and effects*. US Army Corps of Engineers. Engineer Research and Development Center. ERDC/CERL TR-04-29.
Acknowledgement

This document has been prepared by: Miguel Izquierdo Díaz*, David Bolonio, Ignacio Laorga, Andrea Ruiz, LJiljana Medic, Christian Peña, Isabel Ámez, Blanca Castells

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AWARENESS-RAISING, ENVIRONMENTAL AND SOCIAL IMPACTS
AWARENESS-RAISING, ENVIRONMENTAL AND SOCIAL IMPACTS

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 handful of the concerns 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 [1][2]. 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) [3]. Nowadays, it must be said that, despite there is much more control over conflicts and corruption, the petrol still has 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 [4]).

“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 [5]. 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 [6]. 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 [7]. 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, smartphones, game consoles), automotive industry or jewelry [8][9].

Due to increasing business process outsourcing and globally dispersed production facilities, social problems and human rights violations are no longer only intra-organizationally 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 [10]. 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 [6]:

- 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 [6].

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, smartphones, 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 economic impact [1][12]. 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.

References


## Antimony (\(51\)Sb)

<table>
<thead>
<tr>
<th><strong>MINERAL(S)</strong></th>
<th><strong>PRODUCTION:</strong> 161,948 tonnes/year (2012-2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antimonite (NaSb(OH)(_4)), Valentinite (Sb(_2)O(_3)), Jamesonite (Pb(_4)FeSb(<em>6)S(</em>{14}))</td>
<td><strong>SUPPLY RISK (SR):</strong> 2 (2020)</td>
</tr>
<tr>
<td><strong>ECONOMIC IMPORTANCE (EI):</strong> 4.8 (2020)</td>
<td><strong>RECYCLING RATIO:</strong> 38 %</td>
</tr>
<tr>
<td><strong>SUBSTITUTION:</strong></td>
<td><strong>COUNTRY OF ORIGIN:</strong> China (74 %), Tadzhikistan (8 %), Russia (4 %)</td>
</tr>
<tr>
<td>- Manufacture of glass (compounds of chromium, tin, titanium).</td>
<td></td>
</tr>
<tr>
<td>- Flame-retardant materials (alumina trihydrate, magnesium hydroxide).</td>
<td></td>
</tr>
</tbody>
</table>

### 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.

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**Antimonite**

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

**Catalyst in PET manufacturing**

**Flame-retardant plastics**

**PbSb Batteries**
# Barium (\(56^{\text{Ba}}\))

## MINERAL(S)

Baryte (BaSO₄), Witherite (BaCO₃)

## PRODUCTION:

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

## SUPPLY RISK (SR):

1.3 (2020)

## ECONOMIC IMPORTANCE (EI):

3.3 (2020)

## RECYCLING RATIO:

2 %

## SUBSTITUTION:

- Weighting agent for oil and gas industry (hematite, Fe₂O₃; ilmenite, FeTiO₃).
- Fillers (Calcium carbonate, CaCO₃).

## COUNTRY OF ORIGIN:

China (38 %), India (12 %), Morocco (10 %)

## PROPERTIES

- High specific gravity (containing pressure and preventing blowouts).
- Soundproof material, x-ray protection, resistant to abrasion.
- As barium carbonate (BaCO₃) 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.

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Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.
# Aluminium (\(^{13}\text{Al}\))

## MINERAL(S)

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

## PRODUCTION

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

## SUPPLY RISK (SR)

- **2.1** (2020)

## ECONOMIC IMPORTANCE (EI)

- **2.9** (2020)

## RECYCLING RATIO

- **12%**

## SUBSTITUTION

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

## COUNTRY OF ORIGIN

- Australia (28%), India (12%), Brazil (13%)

## PROPERTIES

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

## USES

- Aluminium production (metallurgical bauxite).
- Production of refractory materials, chemicals, abrasives or cements (non-metallurgical bauxite).
## Beryllium (\(^{4}\text{Be}\))

<table>
<thead>
<tr>
<th>MINERAL(S)</th>
<th>PRODUCTION: 251 tonnes/year (2012-216)</th>
</tr>
</thead>
</table>
| **Beryl** (\(\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}\))  
**Bertrandite** (\(\text{Be}_4\text{Si}_2\text{O}_7(\text{OH})_2\)) | **SUPPLY RISK (SR): 2.3 (2020)** |
|             | **ECONOMIC IMPORTANCE (EI): 4.2 (2020)** |
|             | **RECYCLING RATIO: 0 %** |
|             | **SUBSTITUTION:** Very difficult to substitute (very expensive). Loss of performance (10 %), Cu-Be, Al-Be, pure Be.  
- Mechanical properties (titanium alloys, magnesium alloys).  
- Thermal properties (carbon reinforced composites). |
|             | **COUNTRY OF ORIGIN:** US (88 %), China (8 %), Madagascar (2%) |

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

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

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**Source:** Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.
**Bismuth (\(^{83}\)Bi)**

### MINERAL(S)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bismuthinite</td>
<td>(\text{Bi}_2\text{S}_3)</td>
<td>(\text{Bi}_2\text{S}_3) is mainly obtained as a by-product of Pb and W extraction from skarn deposits which contain traces of Bi.</td>
</tr>
<tr>
<td>Bismutite</td>
<td>(\text{Bi}_2(\text{CO}_3)\text{O}_2)</td>
<td></td>
</tr>
<tr>
<td>Bismite</td>
<td>(\text{Bi}_2\text{O}_3)</td>
<td></td>
</tr>
</tbody>
</table>

### PRODUCTION

- **10,332 tonnes/year (2012-2016)**

### SUPPLY RISK (SR)

- **2.2 (2020)**

### ECONOMIC IMPORTANCE (EI)

- **4 (2020)**

### RECYCLING RATIO

- 0 %

### SUBSTITUTION

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

### COUNTRY OF ORIGIN

- China (85 %), Laos (7%), Mexico (4 %)

### PROPERTIES

- Eco-friendly material (non-toxicity): Bismuth subsalicylate.
- Sn-Bi (low melting point).
- Bismuth vanadate (high temperatures resistant, SO\(_2\) resistance).

### USES

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

**Antacid (bismuth subsalicylate)**

**Pigments (bismuth vanadate)**

**Fusible alloy (Sn-Bi)**
# Boron (borates) (\(^5\text{B}\))

## MINERAL(S)

Borates (simply form: \(\text{BO}_3\))

More than 300 minerals:

- **Kernite** \((\text{Na}_2\text{B}_4\text{O}_6\text{(OH)}_2\cdot3\text{H}_2\text{O}\)\)
- **Borax** \((\text{Na}_2\text{B}_4\text{O}_5\text{(OH)}_4\cdot8\text{H}_2\text{O}\)\)
- **Boracite** \(\text{Mg}_3\text{B}_7\text{O}_{13}\text{Cl}\)

## PRODUCTION

918,968 tonnes/year (2012-2016)

## SUPPLY RISK (SR):

3.2 (2020)

## ECONOMIC IMPORTANCE (EI):

3.5 (2020)

## RECYCLING RATIO:

2 %

## SUBSTITUTION:

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

## COUNTRY OF ORIGIN:

- Turkey (42 %), US (24 %), Chile (11 %)

## 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).

![Boracite](https://example.com/boracite.jpg)  
*Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.*
**Cobalt (\textsuperscript{27}Co)**

<table>
<thead>
<tr>
<th>MINERAL(S)</th>
<th>PRODUCTION: 1,339,000 tonnes/year (2012-2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobaltite (CoAsS), Asbolane ((Ni,Co)\textsubscript{2-x}Mn\textsuperscript{4+}(O,OH)\textsubscript{4} \cdot nH\textsubscript{2}O), Heterogenite (Co\textsuperscript{3+}O(OH)), Skutterudite (CoAs\textsubscript{3})</td>
<td>SUPPLY RISK (SR): 2.5 (2020)</td>
</tr>
</tbody>
</table>

**SUPPLY RISK (SR):** 2.5 (2020)

**ECONOMIC IMPORTANCE (EI):** 5.9 (2020)

**RECYCLING RATIO:** 22%

**SUBSTITUTION:**
- Batteries (lithium-ion batteries).
- Alloys (titanium-aluminides).

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

**PROPERTIES**
- High temperature stability.
- High hardness, corrosion and wear resistant.
- Lithium cobalt oxide (LiCoO\textsubscript{2}) as Li-ion batteries cathode.
- Oxidizing agent.
- (CoAl\textsubscript{2}O\textsubscript{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 (vita
- min B12).

**Source:** Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.
## Fluorine ($F_2$)

### MINERAL(S)

<table>
<thead>
<tr>
<th>Fluorspar ($CaF_2$)</th>
</tr>
</thead>
</table>

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

**SUPPLY RISK (SR):** 1.2 (2020)

**ECONOMIC IMPORTANCE (EI):** 3.3 (2020)

**RECYCLING RATIO:** 2%

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

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

### PROPERTIES

- Solid fluoropolymers: Extreme chemical resistance.
- Fluorochemicals: High heat of vaporization, high critical temperature.
- Low melting point (reduces the melting point of steel/iron).
- Uranium Hexafluoride ($UF_6$): Its triple point is at temperature 64.05 ºC (147 ºF) 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.

---

*Fluorspar*

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

*World map showing countries of origin.*
### Gallium ($^{31}\text{Ga}$)

<table>
<thead>
<tr>
<th>MINERAL(S)</th>
<th>PRODUCTION: 218 tonnes/year (2012-2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gallite ($\text{CuGaS}_2$), Bauxite ($\text{AlO}<em>x\text{(OH)}</em>{3-2x}) \times \in [0,1]$</td>
<td>SUPPLY RISK (SR): 1.3 (2020)</td>
</tr>
<tr>
<td>Is mainly obtained as a by-product of Al extraction from bauxite containing traces of Ga.</td>
<td>ECONOMIC IMPORTANCE (EI): 3.5 (2020)</td>
</tr>
<tr>
<td></td>
<td>RECYCLING RATIO: 0 %</td>
</tr>
<tr>
<td></td>
<td>SUBSTITUTION:</td>
</tr>
<tr>
<td></td>
<td>- Semiconductors, GaAs, GaN (silicon-based substrates, SiGe).</td>
</tr>
<tr>
<td></td>
<td>- Solid state LED (organic LED OLED).</td>
</tr>
<tr>
<td></td>
<td>- Photovoltaic CIGS (crystalline silicon technologies).</td>
</tr>
<tr>
<td>COUNTRY OF ORIGIN: China (80 %), Germany (8 %), Ukraine (5 %)</td>
<td></td>
</tr>
</tbody>
</table>

**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**

Gallite Source: Mindat.org

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

### PRODUCTION

122.6 tonnes/year (2012-2016)

### SUPPLY RISK (SR)

3.9 (2020)

### ECONOMIC IMPORTANCE (EI)

3.5 (2020)

### RECYCLING RATIO

2%

### SUBSTITUTION

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

### COUNTRY OF ORIGIN

- Refining: China (80%), Finland (10%), Russia (5%)

### PROPERTIES

- Transparent to infrared radiation (IR) wavelengths.
- Light weight and high efficiency.
- $\text{GeO}_2$ is a polymerisation catalyst.
- Semiconductor (high switching speed and energy efficiency).
- $\text{GeO}_2$ (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).
## Hafnium (\textit{72Hf})

<table>
<thead>
<tr>
<th><strong>MINERAL(S)</strong></th>
<th><strong>PRODUCTION:</strong> 71 tonnes/year (2012-2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hafnon ((\text{Hf,Zr})\text{SiO}_4)</td>
<td><strong>SUPPLY RISK (SR):</strong> 1.1 (2020)</td>
</tr>
<tr>
<td>Alvite ((\text{Hf,Th,Zr})\text{SiO}_4\cdot\text{H}_2\text{O})</td>
<td><strong>ECONOMIC IMPORTANCE (EI):</strong> 3.9 (2020)</td>
</tr>
<tr>
<td>Is mainly obtained as a by-product of Zr extraction from zircon and baddeleyite containing traces of Hf.</td>
<td><strong>RECYCLING RATIO:</strong> 0 %</td>
</tr>
</tbody>
</table>

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

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

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

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

### Hafnium Sources
- Hafnon \((\text{Hf,Zr})\text{SiO}_4\)
- Alvite \((\text{Hf,Th,Zr})\text{SiO}_4\cdot\text{H}_2\text{O}\)

Source: Mindat.org

Turbine blades | Refractory material | Nuclear reactor control rods
### Indium (49In)

#### MINERAL(S)

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

#### PRODUCTION:
827 tonnes/year (2012-2016)

#### SUPPLY RISK (SR):
1.8 (2020)

#### ECONOMIC IMPORTANCE (EI):
3.3 (2020)

#### RECYCLING RATIO:
<1%

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

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

---

#### 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-pannels 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.

---

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.
# Lithium \((3\text{Li})\)

### Mineral(s)

| PRODUCTION: 31,682 tonnes/year (2012-2016) |
| SUPPLY RISK (SR): 1.6 (2020) |
| ECONOMIC IMPORTANCE (EI): 3.1 (2020) |
| RECYCLING RATIO: <1 % |

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

| Country of Origin: |
| Chile (44 %), China (39 %), Argentina (13 %) |

- Brines and pegmatite

### Properties
- Lightest solid metal.
- High thermic conductivity, high specific heat, low viscosity and very low density.
- It reacts easily with hydrogen, water, carbon and halogens.

### Uses
- Glass and ceramics production.
- Lubricating greases.
- Cement production.
- Steel casting.
- Pharmaceutical products.
- Rubber and plastic production.
- Al-Li alloys, improving their strength and making them lighter.
- Rechargeable batteries.
### Magnesium ($^{12}\text{Mg}$)

**MINERAL(S)**

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

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

**SUPPLY RISK (SR):** 3.9 (2020)

**ECONOMIC IMPORTANCE (EI):** 6.6 (2020)

**RECYCLING RATIO:** 13%

**SUBSTITUTION:**
- Carbon-fibre reinforced plastic, steel and titanium alloys (casting alloys, transportation applications, construction sector).
- Steel desulfurization process reagents (lime (CaO), CaC$_2$).

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

### PROPERTIES

- Lower overall weight, withstanding exposure to ozone (O$_3$) and impact of high energy particles and matter.
- High affinity for sulphur.
- Improves aluminium strength without removing the material workability.
- MgCO$_3$ high tendency to “absorb” water.

### USES

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

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.
## Carbon (Graphite) \((6C)\)

### MINERAL(S)

**Natural Graphite** (C)

### PRODUCTION:

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

### SUPPLY RISK (SR):

2.3 (2020)

### ECONOMIC IMPORTANCE (EI):

3.2 (2020)

### RECYCLING RATIO:

3%

### SUBSTITUTION:

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

### COUNTRY OF ORIGIN:

- China (69 %), India (12 %), Brazil (8 %)

### 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).
# Natural Rubber

## MINERAL(S)
Rubber trees: Latex \((cis-1,4\text{-polyisoprene})\)

![Rubber tree](Source: Wikipedia)

- **PRODUCTION:** 13,140,000 tonnes/year (2012-2016)
- **SUPPLY RISK (SR):** 1.0 (2020)
- **ECONOMIC IMPORTANCE (EI):** 7.1 (2020)
- **RECYCLING RATIO:** 2%
- **SUBSTITUTION:**
  - Latex (under investigation: guayule, Russian dandelion).
  - Elastomer and synthetic rubber (polybutadiene, butyl, polyisoprene, styrene butadiene) (packaging, sportswear, furniture, plastics).

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

## 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).
# Niobium (\(41\)Nb)

## MINERAL(S)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Columbite (((Fe, Mn)Nb_2O_6))</td>
<td>Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.</td>
</tr>
<tr>
<td>Pyrochlore (((Na, Ca)_2Nb_2O_6(OH, F)))</td>
<td></td>
</tr>
</tbody>
</table>

## PRODUCTION

- **42,500 tonnes/year (2012-2016)**

## SUPPLY RISK (SR)

- **3.9 (2020)**

## ECONOMIC IMPORTANCE (EI)

- **6 (2020)**

## RECYCLING RATIO

- **<1 %**

## SUBSTITUTION

- Any substitution would be associated with a price and/or performance penalty.
  - HSLA steel and superalloys production (vanadium, molybdenum, tantalum and titanium).

## COUNTRY OF ORIGIN

- **Refining:** Brazil (92 %), Canada (8 %)

## PROPERTIES

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

## USES

- HSLA steels production (pipelines, ship hulls, railway tracks).
- Niobium-bearing alloys (nuclear reactors, rocket thruster nozzles).
- Superconducting magnets (MRI scanners, particle accelerator).
- Rocket thruster nozzels
- LHC (Large Hadron Collider)
- Gas pipelines
# Platinum-Group Metals (Pd, Pt, Rh, Ir, Ru, Os)

<table>
<thead>
<tr>
<th>MINERAL(S)</th>
<th>PRODUCTION: 447 tonnes/year (2017)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ores of nickel and cooper</td>
<td>SUPPLY RISK (SR): 1.8 (2020)</td>
</tr>
<tr>
<td><strong>Merensky Reef</strong></td>
<td>ECONOMIC IMPORTANCE (EI): 5.9 (2020)</td>
</tr>
<tr>
<td>(5-7 g/t Pt+Pd; Pt/Pd =3)</td>
<td>RECYCLING RATIO: 21%</td>
</tr>
<tr>
<td><strong>Chromitite Reef</strong></td>
<td>SUBSTITUTION: The best and only available substitution is of one PGM for another.</td>
</tr>
<tr>
<td>(4-8 g/t Pt+Pd; Pt/Pd=2.5)</td>
<td>COUNTRY OF ORIGIN: South Africa (84%) → iridium, platinum, rhodium, ruthenium; Russia (40%) → palladium (see individual PGM factsheets for quantitative information)</td>
</tr>
</tbody>
</table>

![Sulfidic chromitite from Merensky Reef](Source: Wikipedia.)

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

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

![Autocatalysts (car catalyst)(Pt)](Image)
![Fillings in dental application (Pd)](Image)
![Manufacturing of Organic LEDs (Ir)](Image)
# Iridium (\textit{77}Ir)

## MINERAL(S)

Ores of nickel and cooper:  

**Mafic-Ultramafic igneous complexes:**  
Bushveld Igneous Complex (South Africa)  
Great Dyke (Zimbabwe)

## PRODUCTION

6.1 tonnes/year (2012-2016)

## SUPPLY RISK (SR)

3.2 (2020)

## ECONOMIC IMPORTANCE (EI)

4.2 (2020)

## RECYCLING RATIO

14%

## SUBSTITUTION

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

## COUNTRY OF ORIGIN

South Africa (92 %)

## PROPERTIES

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

## USES

- Electrical industry (crucibles for growing single crystal sapphire, used in blue and green light emitting diodes), flat screen displays in portable electronic equipment.
- Stable anodes for electrochemical production of Cl\textsubscript{2} and NaOH.
- Source of gamma-radiation for the treatment of cancer

---

**Sources:**  
Wikipedia.
# Palladium (\textsuperscript{46}Pd)

## MINERAL(S)

<table>
<thead>
<tr>
<th>ores of nickel and cooper:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mafic-Ultramafic igneous complexes</strong> (South Africa)</td>
</tr>
<tr>
<td><strong>Nickel sulphide deposits</strong> (Russia, Canada)</td>
</tr>
</tbody>
</table>

## PRODUCTION

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

## SUPPLY RISK (SR)

- 1.3 (2020)

## ECONOMIC IMPORTANCE (EI)

- 7.0 (2020)

## RECYCLING RATIO

- 28%

## SUBSTITUTION

- Investment sector (gold or other PGM).

## COUNTRY OF ORIGIN

- Russia (40%)

---

## PROPERTIES

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

## USES

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

---

**Source:** Wikipedia.

---

**Image Sources:**

- Sulfidic serpentintite (Pd and Pt ore)
- Petroleum cracking
- Multilayer ceramic capacitor
- Dental bridges
# Platinum (\(^{78}\text{Pt}\))

## MINERAL(S)

**Ores of nickel and cooper:**

- **Mafic-Ultramafic igneous complexes** (South Africa, Zimbabwe)
- **Nickel sulphide deposits** (Russia)

![Sulfidic serpentintite (Pd and Pt ore)](Source: Wikipedia.)

## PRODUCTION

- **177.7 tonnes/year (2012-2016)**

## SUPPLY RISK (SR)

- **1.8 (2020) ▼**

## ECONOMIC IMPORTANCE (EI)

- **5.9 (2020) ▶**

## RECYCLING RATIO

- **26%**

## SUBSTITUTION

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

## COUNTRY OF ORIGIN

- **South Africa (71%)**

## PROPERTIES

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

## USES

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

![Automobile emission control system](Automobile emission control system)

![Conductivity meter](Conductivity meter)

![Platinum jewellery](Platinum jewellery)
## Rhodium (\(^{45}\text{Rh}\))

<table>
<thead>
<tr>
<th>MINERAL(S)</th>
<th>PRODUCTION: 21,7 tonnes/year (2012-2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bushveld Igneous Complex (South Africa)</td>
<td>RECYCLING RATIO: 28 %</td>
</tr>
<tr>
<td>Great Dyke (Zimbabwe)</td>
<td>SUBSTITUTION: Such a high price that leads to considerable interest in finding alternatives:</td>
</tr>
<tr>
<td></td>
<td>- Other PGM, gold or a base metal.</td>
</tr>
<tr>
<td>COUNTRY OF ORIGIN: South Africa (80 %)</td>
<td></td>
</tr>
</tbody>
</table>

### 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.

### Ores of nickel and cooper:

**Mafic-Ultramafic igneous complexes:**
- Bushveld Igneous Complex (South Africa)
- Great Dyke (Zimbabwe)

### COUNTRY OF ORIGIN:
- South Africa (80 %)

### PROPERTIES

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

### USES

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

### COUNTRY OF ORIGIN:
- South Africa (80 %)

### PROPERTIES

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

### USES

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

### COUNTRY OF ORIGIN:
- South Africa (80 %)
**Ruthenium (44Ru)**

| **MINERAL(S)** | **PRODUCTION**: 27.1 tonnes/year (2012-2016)  
**SUPPLY RISK (SR)**: 3.4 (2020)  
**ECONOMIC IMPORTANCE (EI)**: 4.1 (2020)  
**RECYCLING RATIO**: 11 %  
**SUBSTITUTION**:  
- Electrical components (other PGM and silver).  
- Ammonia synthesis plants (magnetite-based catalyst).  
**COUNTRY OF ORIGIN**: South Africa (93 %) |
| --- | --- |
| Ores of nickel and cooper:  
Mafic-Ultramafic igneous complexes:  
Bushveld Igneous Complex (South Africa)  
Ural Mountains  
Mineral (rare): Laurite (RuS$_2$) | ...

**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.
### Phosphorus (PR; WP) (${}_{15}^{31}P$)

#### MINERAL(S)

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

**White phosphorus (WP)** (P$_4$)

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

#### SUPPLY RISK (SR):
- **PR**: 1.1
- **WP**: 3.5 (2020)

#### ECONOMIC IMPORTANCE (EI):
- **PR**: 5.6
- **WP**: 5.3 (2020)

#### RECYCLING RATIO:
- **PR**: 17 %
- **WP**: 0 %

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

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

---

#### 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$_3$PO$_4$ and P$_2$O$_5$/P$_4$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).

---

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

**White phosphorus powder**


**Fluorapatite**

**Phosphate fertilizer**

**Flame retardant (NH$_4$)$_3$PO$_4$**

**White phosphorus pyrotechnics**
# Rare Earth Elements (REEs)

## MINERAL(S)
Carbonatite-associated deposits (bastnäsite), ion adsorption deposits (clays and xenotine mineralization), alkaline igneous rocks (loparite).

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

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

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

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

## RECYCLING RATIO
- Light REEs: 4%
- Heavy REEs: 8%

## SUBSTITUTION
See individual factsheets.

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

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

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

## Images
- **Carbonatite**
  Source: Mindat.org.
- **Samarium-Cobalt Electric guitar pickups**
- **Permanent magnet in traction motors in hybrid and electric vehicles (Dysprosium)**
- **Red component of colour TV cathode ray tubes from yttrium, Y₂O₃ (yttria)**
### Cerium ($^{58}\text{Ce}$)

#### MINERAL(S)

**By-product**

- **Bastnäsite-(Ce)**
  - (Ce, La)CO$_3$F

- **Monazite – (Ce)**
  - (Ce, La, Nd, Th)PO$_4$

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

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

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

#### RECYCLING RATIO:
2 %

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

#### COUNTRY OF ORIGIN:
China (86 %)

#### PROPERTIES

- CeO$_2$ (ceria): abrasion resistance.
- CeO$_2$ (ceria): Catalyst.
- CeO$_2$ (ceria): Substitute of its radioactive congener thoria (ThO$_2$).
- Cerium (IV): high refractive index enhances photo stability and makes pigments opaquer.

#### USES

- Polishing (chemical-mechanical planarization).
- Electrodes in gas tungsten arc welding.
- Auto-catalyst (catalytic converter for emissions in motor vehicles).
- Additive for pigments as it provides pigments with light fastness.
# Dysprosium \((\text{\textit{66}}\text{Dy})\)

## MINERAL(S)

By-product

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

Extraction of Yttrium

## PRODUCTION

1,018 tonnes/year (2012-2016)

## SUPPLY RISK (SR)

Heavy REEs: 6.2 (2020)

## ECONOMIC IMPORTANCE (EI)

Heavy REEs: 7.2 (2020)

## RECYCLING RATIO

0 %

## SUBSTITUTION

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

## COUNTRY OF ORIGIN

China (86 %)

## PROPERTIES

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

## USES

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

---

**Monazite sand**
Source: Mindat.org.
# Erbium (\textit{68}Er)

## Mineral(s)

**By-product**
- Ion adsorption clays
- Xenotime (YPO$_4$)
- Euxenite(Y, Ca, Ce, U, Th)(Nb, Ta, Ti)$_2$O$_6$

## Production

**Supply Risk (SR):** Heavy REEs: 6.1 (2020)

**Economic Importance (EI):** Heavy REEs: 3.1 (2020)

**Recycling Ratio:** 1%

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

## Country of Origin

- China (86%)

## Properties

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

## Uses

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

---

**Pink colour for glass**

**YAG laser, dental laser**

**Erbium-doped fibre link amplifier**

---

*Source: Mindat.org*
**Europium (\(_{63}\)Eu)**

**MINERAL(S)**

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

**PRODUCTION:** 422 tonnes/year (2012-2016)

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

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

**RECYCLING RATIO:** 38%

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

**COUNTRY OF ORIGIN:** China (86%)

---

**PROPERTIES**

- Eu\(_2\)O\(_3\) phosphorescence.

**USES**

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

---

**Bastnäsite**
Source: Mindat.org

---

Helical fluorescent light bulbs

Anti-counterfeiting phosphors in a 50€ banknote

Interrogation (signal transmission) of biomolecular interactions in drug-delivery screens
# Gadolinium (\textsuperscript{64}Gd)

## MINERAL(S)

### By-product
(bastnäsite, monazite)

- **Gadolinite** (Ce,La,Nd,Y)\textsubscript{2}FeBe\textsubscript{2}Si\textsubscript{2}O\textsubscript{10} (enough traces of Gd to show a spectrum)
- **Leppersonite-(Gd)** (unique mineral with essential Gd)

\[
\text{Ca(Gd,Dy)}\textsubscript{2}(\text{UO}_2)\textsubscript{24}(\text{SiO}_4)\textsubscript{4}(\text{CO}_3)\textsubscript{8}(\text{OH})\textsubscript{2}4\cdot48\text{H}_2\text{O}
\]

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

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

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

**RECYCLING RATIO:** 1%

**COUNTRY OF ORIGIN:** China (86%)

### PROPERTIES
- Paramagnetic at room temperature with a ferromagnetic Curie T of 20ºC, enhances nuclear relaxation rates. (MRI: Solutions of organic gadolinium complexes).
- \(\text{Gd}_2\text{O}_3\), 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)**

---

Source: Mindat.org
Holmium, Lutetium, Ytterbium, Thulium (\(\text{Ho}^\text{67}, \text{Lu}^\text{71}, \text{Yb}^\text{70}, \text{Tm}^\text{69}\))

<table>
<thead>
<tr>
<th>MINERAL(S)</th>
<th>PRODUCTION: 660 tonnes/year (2012-2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>By-product</td>
<td>SUPPLY RISK (SR): Heavy REEs: 6.1 (2020)</td>
</tr>
<tr>
<td></td>
<td>ECONOMIC IMPORTANCE (EI): Heavy REEs: 3.4 (2020)</td>
</tr>
<tr>
<td></td>
<td>RECYCLING RATIO: 1 %</td>
</tr>
<tr>
<td></td>
<td>SUBSTITUTION: Most applications have possible substitutes, given the large market surplus and the relative lack of commercial applications for these metals.</td>
</tr>
<tr>
<td></td>
<td>COUNTRY OF ORIGIN: China (86 %)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PROPERTIES</th>
<th>USES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- Holmium: pigments, magnets, lasers and nuclear reactors.</td>
</tr>
<tr>
<td></td>
<td>- Thulium: Lasers (Tm: YAG), portable X-ray devices as radiation sources.</td>
</tr>
<tr>
<td></td>
<td>- Ytterbium: nuclear reactors, radiography, high-stability atomic clocks.</td>
</tr>
<tr>
<td></td>
<td>- Lutetium: phosphors, PET detectors, glass.</td>
</tr>
<tr>
<td></td>
<td>- Ho(_2)O(_3): colour changes depending on the lighting. Highest magnetic strength of elements.</td>
</tr>
<tr>
<td></td>
<td>- Wavelength of Th lasers makes it very efficient for superficial ablation of tissue.</td>
</tr>
<tr>
<td></td>
<td>- Source of gamma rays, large number of atoms.</td>
</tr>
<tr>
<td></td>
<td>- Al(_5)Lu(<em>3)O(</em>{12}), high refractive index immersion lithography, LSO, LuAG.</td>
</tr>
<tr>
<td></td>
<td>- Yb: High-stability atomic clock</td>
</tr>
<tr>
<td></td>
<td>- Ho: Cubic zirconia colorants</td>
</tr>
<tr>
<td></td>
<td>- Positron Emission Tomography (PET) detectors</td>
</tr>
</tbody>
</table>

| MONAZITE (Ce,La,Nd,Th)PO\(_4\) | Source: Mindat.org |
| GADOLINITE (Ce,La,Nd,Y)\(_2\)Fe\(_2\)Be\(_2\)Si\(_2\)O\(_{10}\) |
| EUXENITE (Y,Ca,Ce,U,Th)(Nb,Ta,Ti)\(_2\)O\(_6\) | |
| XENOTIME YPO\(_4\) |
# Lanthanum (\(57\text{La}\))

## MINERAL(S)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Source: Mindat.org.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bastnäsite-(La)</td>
<td></td>
</tr>
<tr>
<td>(La, Ce)CO(_3)F</td>
<td></td>
</tr>
</tbody>
</table>

## PRODUCTION

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

## SUPPLY RISK (SR)

- Light REEs: 6.0 (2020)

## ECONOMIC IMPORTANCE (EI)

- Light REEs: 1.5 (2020)

## RECYCLING RATIO

- 1 %

## COUNTRY OF ORIGIN

- China (86 %)

## SUBSTITUTION

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

## PROPERTIES

- Catalyst.
- Anodic material, mischmetal (>50 % of La, intermetallic of the AB\(_5\) type).
- La\(_2\)O\(_3\) 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.
# Neodymium (\(\text{Nd}^{60}\))

## MINERAL(S)

**By-product**  
Bastnäsite (La, Ce)\(\text{CO}_3\text{F}\)  
Monazite-(Ce) (Ce,La,Nd,Th)\(\text{PO}_4\)

**Nd dominant minerals:**  
Monazite-(Nd) (Nd,La,Ce)\(\text{PO}_4\)  
Kozoite-(Nd) (Nd,La,Sm,Pr)\(\text{CO}_3\text{OH}\)

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

## SUPPLY RISK (SR):
Light REEs: \(6.1\) (2020)

## ECONOMIC IMPORTANCE (EI):
Light REEs: \(4.8\) (2020)

## RECYCLING RATIO:
2 %

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

## COUNTRY OF ORIGIN:
China (86 %)

---

## PROPERTIES
- Unusually large specific heat capacity at liquid-helium temperatures.
- Strongest permanent magnets (a few grams can lift a thousand times its own weight).
- Neodymium-doped crystals (Nd: \(\text{YVO}_4\)).
- Inclusions of \(\text{Nd}_2\text{O}_3\) 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).

---

**Source:** Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.
**Praseodymium (\(_{59}Pr\))**

**MINERAL(S)**

By-product

Monazite \((Ce,La,Nd,Th)PO_4\)

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

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

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

**RECYCLING RATIO:** 10%

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

**COUNTRY OF ORIGIN:** China (86 %)

**PROPERTIES**

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

**USES**

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

**Digital watches**

**Yellow glazing in ceramics**

**Aircraft engines**
# Samarium (\(\text{^{62}Sm}\))

<table>
<thead>
<tr>
<th><strong>MINERAL(S)</strong></th>
<th><strong>PRODUCTION:</strong> 2,498 tonnes/year (2012-2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>By-product</td>
<td><strong>SUPPLY RISK (SR):</strong> Heavy REEs: 6.1 (2020)</td>
</tr>
<tr>
<td>Bastnäsite (La, Ce)(\text{CO}_3\text{F}) Monazite-(Ce) (Ce,La,Nd,Th)(\text{PO}_4)</td>
<td><strong>ECONOMIC IMPORTANCE (EI):</strong> Heavy REEs: 7.3 (2020)</td>
</tr>
<tr>
<td><strong>Other minerals:</strong> Samarskite-(Y) (\text{(YFe}^{3+}\text{Fe}^{2+}\text{U, Th, Ca)}_2\text{(Nb, Ta)}_2\text{O}_8)</td>
<td><strong>RECYCLING RATIO:</strong> 1 %</td>
</tr>
<tr>
<td>Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia, ETSIME-UPM.</td>
<td><strong>SUBSTITUTION:</strong></td>
</tr>
<tr>
<td></td>
<td>- Magnets (NdFeB magnets, ferrite magnets, AlNiCo magnets).</td>
</tr>
<tr>
<td><strong>COUNTRY OF ORIGIN:</strong> China (86 %)</td>
<td><strong>USES:</strong></td>
</tr>
</tbody>
</table>

## 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).

Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia, ETSIME-UPM.
### Terbium ($^{65}\text{Tb}$)

#### MINERAL(S)

**By-product**

- Monazite \((\text{Ce,La,Nd,Th})\text{PO}_4\)
- Euxenite \((\text{Y,Ca,Ce,U,Th})(\text{Nb,Ta,Ti})_2\text{O}_6\)
- Xenotime \(\text{YPO}_4\)

#### PRODUCTION:

- 206 tonnes/year (2012-2016)

#### SUPPLY RISK (SR):

- Heavy REEs: 5.5 (2020)

#### ECONOMIC IMPORTANCE (EI):

- Heavy REEs: 4.1 (2020)

#### RECYCLING RATIO:

- 6%

#### SUBSTITUTION:

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

#### COUNTRY OF ORIGIN:

- China (86 %)

### PROPERTIES

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

### USES

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

![Image of Terbium](https://example.com/terbium_image)

**Xenotime**

*Source: Mindat.org*
## Yttrium (\text{^{39}Y})

### MINERAL(S)

<table>
<thead>
<tr>
<th>Bastnäsite-(Y)</th>
<th>((Y, Ce)CO_3F)</th>
</tr>
</thead>
</table>

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

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

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

### RECYCLING RATIO:
31%

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

### COUNTRY OF ORIGIN:
China (86%)

### PROPERTIES

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

---

**Source:** Mindat.org

---

**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 radioimmunootherapy (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** \(K(Mg,Fe)_3AlSi_3O_{10}(F,OH)_2\)

## PRODUCTION:

Refining: 15,2 tonnes \((\text{Sc}_2\text{O}_3)/\text{year}\) (2012-2016)

## SUPPLY RISK (SR):

3.1 (2020)

## ECONOMIC IMPORTANCE (EI):

4.4 (2020)

## RECYCLING RATIO:

0 %

## SUBSTITUTION:

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

## COUNTRY OF ORIGIN:

China (66 %), Russia (26 %), Ukraine (7 %)

## PROPERTIES

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

## USES

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

---

**Biotite**

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

**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.
**Silicon metal** ($^{14}$Si)

<table>
<thead>
<tr>
<th>MINERAL(S)</th>
<th>PRODUCTION: 2,541,000 tonnes/year (2012-2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz ($\text{SiO}_2$)</td>
<td>SUPPLY RISK (SR): 1.2 (2020)</td>
</tr>
<tr>
<td></td>
<td>ECONOMIC IMPORTANCE (EI): 4.2 (2020)</td>
</tr>
<tr>
<td></td>
<td>RECYCLING RATIO: 0 %</td>
</tr>
<tr>
<td></td>
<td>SUBSTITUTION:</td>
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<tr>
<td></td>
<td>- Metallurgical (serious loss of end performance or increase of cost).</td>
</tr>
<tr>
<td></td>
<td>- No substitutes of silicon in silicones and silanes.</td>
</tr>
<tr>
<td></td>
<td>- Si based technology for solar applications (CdTe, CIGS technology).</td>
</tr>
<tr>
<td></td>
<td>- Micro-electronics industry (GaAs).</td>
</tr>
<tr>
<td></td>
<td>COUNTRY OF ORIGIN: China (66 %), US (8%), Norway (6 %), France (4 %)</td>
</tr>
</tbody>
</table>

**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).
# Tantalum (\^{73}\text{Ta})

## MINERAL(S)

| Tantalite-columbite (Coltan) \((\text{Fe, Mn})(\text{Ta},\text{Nb})_2\text{O}_6\) | Production: 1,191 tonnes of Ta₂O₅/year (2012-2016) |
| Microlite \((\text{Na, Ca})_2\text{Ta}_2\text{O}_6(\text{O, OH, F})\) | Supply Risk (SR): 1.4 (2020) |
| Wodginite \(\text{Mn}^{2+}(\text{Sn, Ta})\text{Ta}_2\text{O}_8\) | Economic Importance (EI): 4.0 (2020) |
| Struverite \((\text{Ti, Ta, Fe}^{3+})\text{O}_2\) | Recycling Ratio: <1% |

## PROPERTIES

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

## USES

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

## COUNTRY OF ORIGIN

- Dem. Rep. of Congo (33%), Rwanda (28%), Brazil (9%)

---

**Cell phones (tantalum capacitors)**

**Jet engines**

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

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*Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.*
# Titanium (\(^{22}\text{Ti}\))

## MINERAL(S)

| Rutile \((\text{TiO}_2)\) and Ilmenite \((\text{Fe}^2+\text{Ti}^4+\text{O}_3)\) |

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

## SUPPLY RISK (SR)
1.3 (2020)

## ECONOMIC IMPORTANCE (EI)
4.7 (2020)

## RECYCLING RATIO
19 %

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

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

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

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

---

**Rutile**

*Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.*
# Tungsten (Wolfram) (74W)

## MINERAL(S)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wolframite (Fe,Mn)WO₄</td>
<td>Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.</td>
</tr>
<tr>
<td>Scheelite CaWO₄</td>
<td></td>
</tr>
</tbody>
</table>

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

## SUPPLY RISK (SR)
1.6 (2020)

## ECONOMIC IMPORTANCE (EI)
8.1 (2020)

## RECYCLING RATIO
42%

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

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

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

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

## SOURCES
- Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.
**Vanadium (\(23\text{V}\))**

<table>
<thead>
<tr>
<th>MINERAL(S)</th>
<th>PRODUCTION: 61,371 tonnes/year (2012-2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patronite (\text{VS}_4)</td>
<td>SUPPLY RISK (SR): 1.7 (2020)</td>
</tr>
<tr>
<td>Vanadinite (\text{Pb}_5(\text{VO}_4)_3\text{Cl})</td>
<td>ECONOMIC IMPORTANCE (EI): 4.4 (2020)</td>
</tr>
<tr>
<td>Carnotite (\text{K}_2(\text{UO}_2)_2(\text{VO}_4)_2\cdot3\text{H}_2\text{O})</td>
<td>RECYCLING RATIO: 3%</td>
</tr>
</tbody>
</table>

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 (55%), South Africa (22%), Russia (19%).

**PROPERTIES**
- Considerable increase of strength with small amounts of vanadium.
- Low-neutron-adsorption abilities and it does not deform in creeping under high T.
- \(\text{V}_2\text{O}_5\) 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.
GAME
INSTRUCTIONS
CRMs Memory Card Game Instructions

The aim of the game is to match the cards with the properties of the elements (blue cards) with their corresponding application (orange cards).

MATERIAL

The following material is needed for the game:

- The three sets of cards from Appendix 4, printed on a sheet of paper or cardboard on one side and having cut them out individually. Do not mix the cards of one group with those of another (as the properties and applications between elements are intended to be different from each other to avoid confusion). Each set is played individually.
- A dice (there are websites to roll a virtual dice).

The teacher can print out a copy of the cards for himself/herself and not cut them out, as the document has the elements matched with their applications. In this way, the teacher will have the solutions in case of doubt.

BEFORE STARTING

Divide up the class in 3 groups, preferably of 3-4 teams with 2-3 students per team, and distribute each group around a different table in the classroom. Each group will be given a different set of cards.

GAME PLAY

The cards should be placed face down on the table. On one side of the table all the blue cards are randomly distributed and on the other all the orange cards are randomly distributed as well. The game is played as follows:

- Each team turns over 2 cards (one from the blue pile and one from the orange pile) in his turn and show them to the other players. If the two cards match, they keep them, but if they don’t, they have to put them back face down in the same position.
- The next team clockwise takes its turn.
- The game continues until there are no more cards on the table. The winning team will be the one with the most pairs.
- There are 8 special cards that do not correspond to elements applications or uses (which are distinguished by the black colour) and their function is to make the game more dynamic. These cards must be placed face down on the table and shuffled like the rest of the cards. They can be distributed between the blue and
orange groups indistinctly, as long as 4 of them are placed in each group, so that there are the same number of cards in both groups. Each time a team turns over one of these cards, they must proceed as indicated on the card and then remove it from the game board so that it cannot be turned over again by another team. These cards do not count in the final score.

**SPECIAL CARDS**

Functions of the special cards:

- **Lose your turn**: The team who flips over this card must pass the turn without being able to keep any cards, even if they have discovered a match pair during this turn, putting the cards back face down in the same position.

- **1 extra turn**: The team raise another card of the same group and at the end of their turn have a new chance.

- **Steal a pair of cards**: The team who flips this card may steal a pair from any other team (if any team had already achieved a match pair).

- **Extra cards**: The team who flips this card must roll a dice and depending on the number obtained they have to:
  - # 1: Turn over 1 extra card from the group of their choice.
  - # 2: Turn over 2 extra cards, 1 from the blue group and 1 from the orange.
  - # 3: Turn over 3 extra cards, 2 from the blue group and 1 from the orange.
  - # 4: Turn over 1 extra card from the group of their choice.
  - # 5: Turn over 2 extra cards, 1 from the blue group and 1 from the orange.
  - # 6: Turn over 3 extra cards, 1 from the blue group and 2 from the orange.

  All the pairs that are found with the extra cards can be kept by the team who has discovered them.

- **Extra secret card**: The team turn over an extra card but must not show them to the other players. If that card matches the other one, they can keep it, if not they put it back face down on the table without the other players seeing it.
STUDENTS
PLAY CARDS
CARD SET 1
<table>
<thead>
<tr>
<th></th>
<th><strong>BARIAUM (\text{Ba})</strong></th>
<th><strong>BISMUTH (\text{Bi})</strong></th>
<th><strong>ANTIMONY (\text{Sb})</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baryte ((\text{BaSO}_4))</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Bismuthinite ((\text{Bi}_2\text{S}_3))</strong> [By-product of Pb and W extraction]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Antimonite ((\text{NaSb(OH)}_4))</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Property:</strong></td>
<td>High specific gravity</td>
<td>Sn-Bi Low melting point</td>
<td>Slow development of ignition</td>
</tr>
<tr>
<td><strong>Property:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Source:</strong></td>
<td>Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.</td>
<td>Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.</td>
<td>Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.</td>
</tr>
</tbody>
</table>

- **Weighting agent in drilling fluids (Oil production)**
- **Fusible alloys in solders (replacement of harmful metals, such as lead)**
- **Flame-retardant plastics**
<table>
<thead>
<tr>
<th><strong>BORON (borates) (5B)</strong></th>
<th><strong>PLATINUM (78Pt)</strong></th>
<th><strong>WHITE PHOSPHORUS (15P)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Boracite (Mg$_3$B$<em>7$O$</em>{13}$Cl)</td>
<td>Ores of nickel and cooper</td>
<td>White phosphorus powder (P$_4$)</td>
</tr>
<tr>
<td><strong>Property:</strong></td>
<td><strong>Property:</strong></td>
<td><strong>Property:</strong></td>
</tr>
<tr>
<td>Enhance stain removal and bleaching</td>
<td>Platinum black - Catalyst</td>
<td>Systemic toxicity</td>
</tr>
</tbody>
</table>

<p>| <strong>Laundry detergents and industrial cleaning products</strong> | <strong>Automobile emissions control system</strong> | <strong>Rodenticide</strong> |</p>
<table>
<thead>
<tr>
<th>THULIUM ($^{69}$Tm)</th>
<th>LANTHANUM ($^{57}$La)</th>
<th>SAMARiUM ($^{26}$Sm)</th>
</tr>
</thead>
</table>
| Monazite (Ce,La,Nd,Th)PO$_4$  
*Source: Mindat.org* | Bastnäsite-(La) ((La,Ce)CO$_3$F)  
*Source: Mindat.org.* | Smarskite-(Y) ((YFe$^{3+}$Fe$^{2+}$U,Th,Ca)$_2$(Nb,Ta)$_2$O$_8$)  
*Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.* |
| **Property:** Fluorescence (blue color exposed to ultraviolet light) | **Property:** La$_2$O$_3$ improves alkali resistance of glass, high refraction index and low dispersion | **Property:** Radioactive Sm-153 is β-emitter with half-life of 46.3 hours (injected intravenously) |
| Anti-counterfeiting phosphors in a 50€ banknote | Telescope lenses | Used in treatment of cancer (lung cancer, prostate cancer, breast cancer) |
**SILICON METAL \((^{14}\text{Si})\)**

Quartz (SiO\(_2\))

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

**Property:**
Crystalline silicon is a semiconductor material, which converts light into electricity.

---

**ALUMINIUM \((^{13}\text{Al})\)**

Bauxite (AlO\(_x\)(OH)\(_{3-2x}\)) \(\times\) \(\epsilon\) [0,1]

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

**Property:**
Calcined alumina is a very hard material.

---

**UPS! You lose your turn.**
If you have found two matching cards in this turn you cannot keep them,
**Sorry...**

---

**Solar panels**

---

**Abrasives**

---

**UPS! You lose your turn.**
If you have found two matching cards in this turn you cannot keep them,
**Sorry...**
Roll the dice to see how many **extra cards** you can turn over:

*nº 1:* 1 card from the group of your choice.

*nº 2:* 2 cards, 1 from the blue group and 1 from the orange.

*nº 3:* 3 cards, 2 from the blue group and 1 from the orange.

*nº 4:* 1 card from the group of your choice.

*nº 5:* 2 cards, 1 from the blue group and 1 from the orange.

*nº 6:* 3 cards, 1 from the blue group and 2 from the orange.

You have **1 extra turn.**
Raise one more card from the same group this turn.
Then you have a new chance.

Turn over 1 **secret extra card** but do not show it to the rest of the players. If that card matches the other one, you can keep it, if not put it back face down again, not letting anyone knowing which card it is.

Roll the dice to see how many **extra cards** you can turn over:

*nº 1:* 1 card from the group of your choice.

*nº 2:* 2 cards, 1 from the blue group and 1 from the orange.

*nº 3:* 3 cards, 2 from the blue group and 1 from the orange.

*nº 4:* 1 card from the group of your choice.

*nº 5:* 2 cards, 1 from the blue group and 1 from the orange.

*nº 6:* 3 cards, 1 from the blue group and 2 from the orange.

You have **1 extra turn.**
Raise one more card from the same group this turn.
Then you have a new chance.

**Steal a pair of cards** from the team of your choice.
CARD SET 2
<table>
<thead>
<tr>
<th><strong>COBALT</strong> (<em>^{27}\text{Co}</em>)</th>
<th><strong>INDIUM</strong> (<em>^{49}\text{In}</em>)</th>
<th><strong>CARBON</strong> (Graphite) (<em>^{6}\text{C}</em> )</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Skutterudite</em> (<em>\text{CoAs}_3</em>)&lt;br&gt;Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.</td>
<td><em>Sphalerite</em> (<em>(\text{Zn}, \text{Fe})\text{S})</em>&lt;br&gt;[Trace element in sphalerite (20-200 ppm of In)]&lt;br&gt;Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.</td>
<td><em>Natural Graphite</em> (<em>\text{C}</em>)&lt;br&gt;Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.</td>
</tr>
<tr>
<td><strong>Property:</strong>&lt;br&gt;LiCoO$_2$ cathodes.</td>
<td><strong>Property:</strong>&lt;br&gt;Light absorber material and maximizes light transmission.</td>
<td><strong>Property:</strong>&lt;br&gt;High temperature stability and chemical inertness</td>
</tr>
<tr>
<td>Stable capacity batteries</td>
<td>Film solar cells (CIGS, ITO)</td>
<td>Foundry refractory materials (steel making and hot metal-forming)</td>
</tr>
<tr>
<td><strong>ERBIUM ((\text{Er}^{68}))</strong></td>
<td><strong>EUROPIUM ((\text{BiEu}^{63}))</strong></td>
<td><strong>YTTERBIUM ((\text{Yb}^{70}))</strong></td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-----------------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td><strong>Xenotime ((\text{YPO}_4))</strong>&lt;br&gt;[By-product]&lt;br&gt;(Source: Mindat.org)</td>
<td><strong>Loparite-(Ce) ((\text{Ce,Na,Ca})(\text{Ti,Nb})\text{O}_3))</strong>&lt;br&gt;[By-product]&lt;br&gt;(Source: Mindat.org)</td>
<td><strong>Gadolinite ((\text{Ce,La,Nd,Y})_2\text{FeBe}_2\text{Si}<em>2\text{O}</em>{10})</strong>&lt;br&gt;(Source: Mindat.org.)</td>
</tr>
<tr>
<td><strong>Property:</strong>&lt;br&gt;(\text{Er}^{3+}) ions have pink colour</td>
<td><strong>Property:</strong>&lt;br&gt;(\text{Eu}_2\text{O}_3) phosphorescence</td>
<td><strong>Property:</strong>&lt;br&gt;Yb-169 emits gamma rays</td>
</tr>
<tr>
<td>Pigment in glass</td>
<td>Helical fluorescent light bulbs</td>
<td>Radiography of small objects</td>
</tr>
<tr>
<td>NEODYMIUM (\textsubscript{60}Nd)</td>
<td>YTTRIUM (\textsubscript{39}Y)</td>
<td>TUNGSTEN (Wolfram) (\textsubscript{74}W)</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>---------------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>Monazite-(Nd) (Nd,La,Ce,)PO\textsubscript{4} [By-product of Bastnäsite]</td>
<td>Bastnäsite-(Y) ((Y,Ce)CO\textsubscript{3}F) [By-product]</td>
<td>Wolframite ((Fe,Mn)WO\textsubscript{4}) [Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.]</td>
</tr>
<tr>
<td><strong>Property:</strong> Nd-doped crystals (Nd:YVO\textsubscript{4}) serve as a gain media for infrared wavelengths</td>
<td><strong>Property:</strong> Yttria (Y\textsubscript{2}O\textsubscript{3}) stabilized-zirconia (YSZ) hard ceramic used as a strong base material</td>
<td><strong>Property:</strong> Hardness and strength combined with toughness and plasticity</td>
</tr>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>Lasers</td>
<td>Base material in full dental ceramic restorations</td>
<td>Button bits (mining and tunneling cutting tools)</td>
</tr>
<tr>
<td></td>
<td><strong>VANADIUM</strong> ($^{23}$V)</td>
<td><strong>TITANIUM</strong> ($^{22}$Ti)</td>
</tr>
<tr>
<td>----------</td>
<td>--------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td><strong>Properties</strong></td>
<td>Low-neutron-adsorption abilities without deforming under high temperatures</td>
<td>Nontoxic and biologically compatible</td>
</tr>
<tr>
<td><strong>Source</strong></td>
<td>Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.</td>
<td>Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.</td>
</tr>
<tr>
<td><strong>Examples</strong></td>
<td>Vanadinite ($\text{Pb}_5(\text{VO}_4)_3\text{Cl}$)</td>
<td>Rutile ($\text{TiO}_2$) and Ilmenite ($\text{Fe}^{2+}\text{Ti}^{4+}\text{O}_3$)</td>
</tr>
<tr>
<td></td>
<td>Titanium knee and hip replacement implant</td>
<td></td>
</tr>
</tbody>
</table>

**Nuclear reactors**

**Titanium knee and hip replacement implant**
Roll the dice to see how many **extra cards** you can turn over:

| nº 1: | 1 card from the group of your choice. |
| nº 2: | 2 cards, 1 from the blue group and 1 from the orange. |
| nº 3: | 3 cards, 2 from the blue group and 1 from the orange. |
| nº 4: | 1 card from the group of your choice. |
| nº 5: | 2 cards, 1 from the blue group and 1 from the orange. |
| nº 6: | 3 cards, 1 from the blue group and 2 from the orange. |

You have **1 extra turn**. Raise one more card from the same group this turn. Then you have a new chance.

Turn over 1 **secret extra card** but do not show it to the rest of the players. If that card matches the other one, you can keep it, if not put it back face down again, not letting anyone knowing which card it is.

Roll the dice to see how many **extra cards** you can turn over:

| nº 1: | 1 card from the group of your choice. |
| nº 2: | 2 cards, 1 from the blue group and 1 from the orange. |
| nº 3: | 3 cards, 2 from the blue group and 1 from the orange. |
| nº 4: | 1 card from the group of your choice. |
| nº 5: | 2 cards, 1 from the blue group and 1 from the orange. |
| nº 6: | 3 cards, 1 from the blue group and 2 from the orange. |

You have **1 extra turn**. Raise one more card from the same group this turn. Then you have a new chance.

**Steal a pair of cards** from the team of your choice.
CARD SET 3
<table>
<thead>
<tr>
<th><strong>COBALT ((^{27}\text{Co}))</strong></th>
<th><strong>GALLIUM ((^{31}\text{Ga}))</strong></th>
<th><strong>BORON (Borates) ((^{5}\text{B}))</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Skutterudite (CoAs(_3))" /> <strong>Property:</strong> (CoAl(_2)O(_4)) Coloured metal and chromatic stability</td>
<td><img src="image" alt="Gallite (CuGaS(_2))" /> <strong>Property:</strong> Improves magnetic properties and corrosion resistance</td>
<td><img src="image" alt="Boracite (Mg(_3)B(7)O({13})Cl)" /> <strong>Property:</strong> Material used to stop heat and sound from escaping or entering</td>
</tr>
<tr>
<td>Blue pigment for ceramics decoration</td>
<td>NdFeB magnets</td>
<td>Fiberglass and textile thermal and acoustic insulation</td>
</tr>
<tr>
<td>Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.</td>
<td>[By-product of Al extraction from Bauxite] Source: Mindat.org</td>
<td>Source: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.</td>
</tr>
<tr>
<td>FLUORINE (\text{_9F})</td>
<td>HAFNIUM (\text{_{72}Hf})</td>
<td>GERMANIUM (\text{_{32}Ge})</td>
</tr>
<tr>
<td>----------------------</td>
<td>-------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>Fluorspar (CaF$_2$)</td>
<td>Hafnon ((Hf,Zr)SiO$_4$)</td>
<td>Germanite (Cu$_{13}$Fe$_2$Ge$<em>2$S$</em>{16}$)</td>
</tr>
<tr>
<td><em>Source</em>: Colecciones del Museo Histórico Minero D. Felipe de Borbón y Grecia. ETSIME-UPM.</td>
<td><em>Source</em>: Mindat.org [By-product of Zr extraction from zircon and baddeleyite]</td>
<td><em>Source</em>: Mindat.org [By-product of Zn extraction from Zn ores and coal ashes]</td>
</tr>
<tr>
<td><strong>Property:</strong> Fluorochemicals-High heat of vaporization</td>
<td><strong>Property:</strong> High thermal neutron absorption cross section</td>
<td><strong>Property:</strong> GeO$_2$-increases reflective index preventing signal loss</td>
</tr>
<tr>
<td>HCFCs refrigeration</td>
<td>Nuclear control rods in nuclear reactors</td>
<td>Fibre optics</td>
</tr>
<tr>
<td>MAGNESIUM (\text{_{12}Mg})</td>
<td>NATURAL RUBBER</td>
<td>IRIDIUM (\text{_{77}Ir})</td>
</tr>
<tr>
<td>-------------------------</td>
<td>---------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>Dollomite (CaMg(CO_3)_2)</td>
<td>Rubber tree</td>
<td>Ores of nickel and cooper</td>
</tr>
<tr>
<td><strong>Property:</strong> Improves aluminium strength without removing its workability</td>
<td><strong>Property:</strong> Inertness, chemical attacks resistant, elasticity</td>
<td><strong>Property:</strong> Iridium-192 radioisotope</td>
</tr>
</tbody>
</table>

- Metal packaging
- Latex gloves
- Source of gamma radiation for the treatment of cancer (brachytherapy)
| PHOSPHATE ROCK (Phosphorus) \((^{15}P)\) | LITHIUM \((^3Li)\) | UPS! You **lose your turn**. If you have found two matching cards in this turn you cannot keep them, Sorry...

**Property:** Vital part of plant and animal nourishment

Apatite \((Ca_{5}(PO_4)_{3}(F,Cl,OH))\)

[More than 300 minerals]

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

**Property:** Lightest solid metal

Pegmatite

*Source: Mindat.org*

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Fertilizer

Automotive structure

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UPS! You **lose your turn**. If you have found two matching cards in this turn you cannot keep them, Sorry...
Roll the dice to see how many **extra cards** you can turn over:

<table>
<thead>
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<th>nº</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1 card from the group of your choice.</td>
</tr>
<tr>
<td>2</td>
<td>2 cards, 1 from the blue group and 1 from the orange.</td>
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<td>3</td>
<td>3 cards, 2 from the blue group and 1 from the orange.</td>
</tr>
<tr>
<td>4</td>
<td>1 card from the group of your choice.</td>
</tr>
<tr>
<td>5</td>
<td>2 cards, 1 from the blue group and 1 from the orange.</td>
</tr>
<tr>
<td>6</td>
<td>3 cards, 1 from the blue group and 2 from the orange.</td>
</tr>
</tbody>
</table>

You have **1 extra turn**. Raise one more card from the same group this turn. Then you have a new chance.

Turn over 1 **secret extra card** but do not show it to the rest of the players. If that card matches the other one, you can keep it, if not put it back face down again, not letting anyone knowing which card it is.

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Roll the dice to see how many **extra cards** you can turn over:

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You have **1 extra turn**. Raise one more card from the same group this turn. Then you have a new chance.

Steal a pair of cards from the team of your choice.