

# TUNGSTEN

## SHORT DESCRIPTION

Tungsten (W) is a lustrous greyish-white metal, which is a solid at room temperature. It has the highest melting point and lowest vapor pressure of all metals, and at temperatures over 1650°C has the highest tensile strength. It has excellent corrosion resistance and is attacked only slightly by most mineral acids [11]. Tungsten has been listed as one of critical raw materials in Europe due to its high economic importance and the fact that its supply is at risk.



Fig. 1 Tungsten metal

## APPLICATIONS

### CURRENT APPLICATIONS

The main applications of Tungsten are in hard materials (Tungsten carbides) and in alloys and steels. Less than 10% is used in other chemical compounds [2].

- **Hard materials (60% of Tungsten consumption):** Tungsten carbide (WC) is one of the hardest carbides, with a melting point of 2770°C. WC is an electrical conductor, used to make wear-resistant abrasives, and cutting tools such as knives, drills, circular saws, milling and turning tools used in the metalworking, woodworking, mining, petroleum and construction industries. Cobalt is present in WC [1].
- **Alloys:** Tungsten is used in high speed steel, which can contain as much as 18% Tungsten [3]. Due to its properties, Tungsten is used in aerospace and automotive industries and radiation shielding [4].
- **Chemical applications:** Tungsten (IV) sulphide is a high temperature lubricant and is a component of catalysts for hydrodesulfurization [5]. Tungsten oxides are used in ceramic glazes and calcium/magnesium tungstates are used widely in fluorescent lighting. They are also used in selective catalytic reduction (SCR) catalysts found in coal-fired power plants. Crystal tungstates are used as scintillation detectors in nuclear physics and nuclear medicine. There are a number of Tungsten chemicals that have been used in the medical and dental fields for X-ray shielding and conversely, X-ray opacity. Other salts that contain tungsten are used in the chemical and tanning industries [6].
- **Electronics:** Elemental Tungsten is used in many high-temperature applications, such as light bulb, cathode-ray tube, and vacuum tube filaments, heating elements, and rocket engine nozzles. Thanks to its conductive properties it is also used in electrodes and in the emitter tips in electron-beam instruments that use field emission guns, such as electron microscopes [7][8].



Fig. 2 Some Tungsten applications

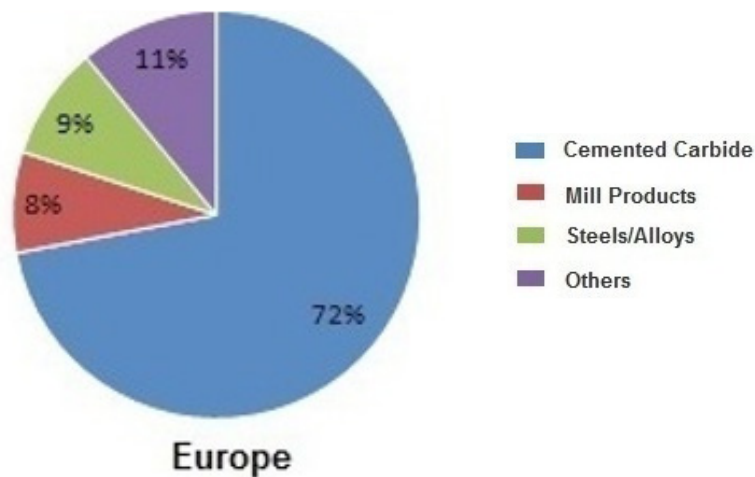


Fig. 3 Estimated global consumption of Tungsten in 2010 (ITIA-International Tungsten Industry Association)

**NEW TECHNOLOGIES**

Tungsten-based materials and components are expected to play a significant role in future energy sector developments. Current global issues such as global warming and greenhouse gases represent a great opportunity for Tungsten-containing products, as they are strategically important in the field of fossil energy production, renewable power generation and power transmission and distribution [10].

**EU SUPPLY AND DEMAND: CURRENT AND FUTURE**

Worldwide production of Tungsten concentrate in 2013 was distributed over quite a large number of countries, with China being the main producer, accounting for 83.58% of the production. Total global supply of Tungsten ranges between 100,000 and 120,000 tons, with the balance being provided from scrap recovery and reprocessing.



The EU also produces Tungsten, although in lower quantities, accounting for 2.52% of total production. The main Tungsten-producing countries in Europe are: Austria (850 tons of  $WO_3$  /year), Portugal (850-950 tons of  $WO_3$  /year), Spain (650-750 tons of  $WO_3$  /year) and the UK (1100-1200 tons of  $WO_3$  /year) [18]. Wolf Minerals opened its Hemerdon Tungsten mine in Devon in the fall of 2015. Total mine production of Tungsten in Europe in 2014 and 2015 was 2341 and 2830 tonnes, respectively. However, this production still does not meet the demand of European industries.

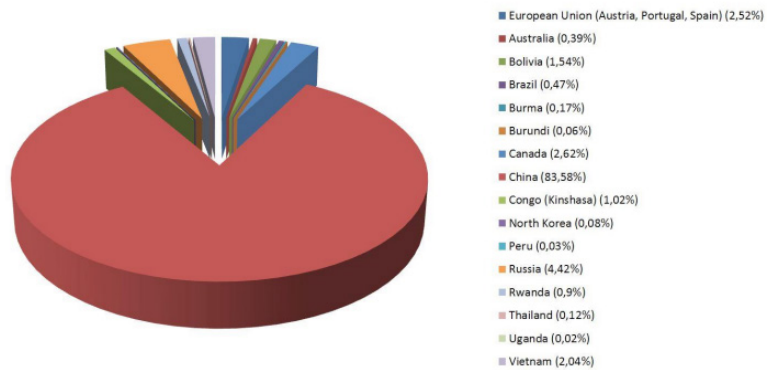


Fig. 4 W worldwide production

Tungsten consumption in Europe has been decreasing at an average annual rate of about 5% since 2013 to 2020. Demand for Tungsten in Europe has been rising steadily since 2013 and, according to a report published by H.C.Starck [19], the trend is expected to continue for the next several years.

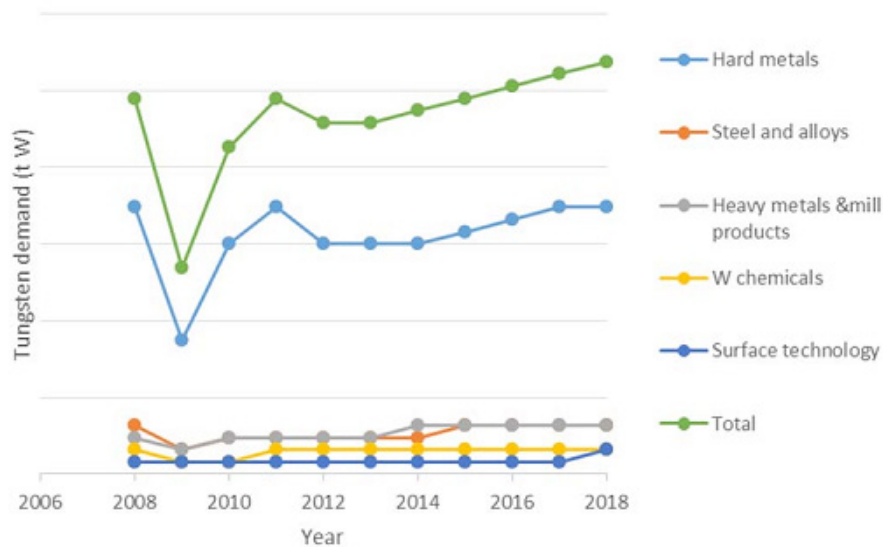
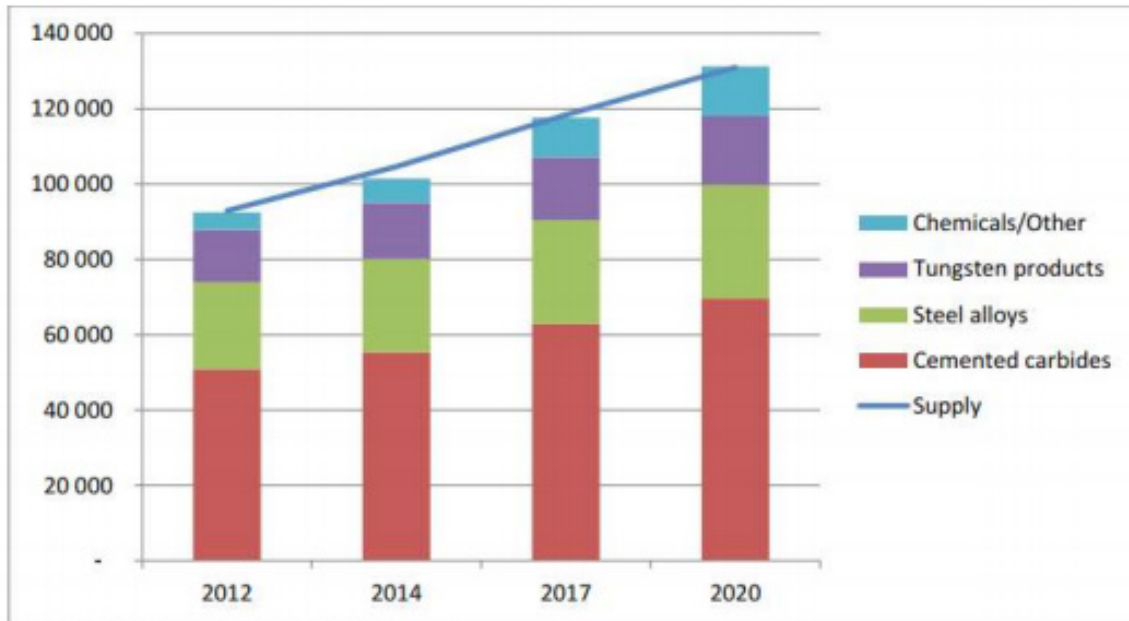


Fig. 5 Increase of Tungsten consumption in the EU between 2013 and 2018

Tungsten demand will continue to rise until 2020. The Tungsten produced in Europe can meet 80% of the demand. To address the problem of the remaining 20%, there are few feasible solutions: 1) increasing mine production; 2) increasing production from secondary resources (mining tailings, metallurgical wastes) and end-of-products recycling; and 3) increasing Tungsten substitution rates.



Source: Roskill Information Services for 2013 CRM study

Fig. 6 Total worldwide supply of Tungsten and end-use forecast to 2020

According to Investing News [20], increasing mine production to partially satisfy the demand is a possibility. Future estimates of mine production of Tungsten concentrate in the UK are estimated to be 5,000 tonnes per year. In Spain, the company W Resources completed a mine development study at La Parrilla mine and expects a 150 % increase in production there. Future Tungsten demand in Europe is forecasted to be about 10,000 tonnes over the next 10 years, and total Tungsten production, including mine production and production from recycled end-of-life scraps, could reach some 8,000 tonnes, which means that Europe could meet 80% of its own demand.

## MAIN PRIMARY AND SECONDARY RESOURCES

### PRIMARY RESOURCES

There are three types of Tungsten deposits:

- Classical vein deposits:** these are more or less continuous veins of varying thickness, ranging from several decimetres to several metres, mainly comprised of quartz contained in the granite itself or in the surrounding host rock. Most deposits exhibit ferberite or hübnerite mineralisation characteristics, but scheelite vein deposits occur as well. Typical grades of Tungsten are of 0.5-5%  $WO_3$ . Sn typically occurs as a by-product. In the EU, there are two active mines where Tungsten is extracted: the Panasqueira Mine in Portugal and the San Fix Mine in Spain.
- Skarn deposits:** formed by replacement of carbonate rock with calc-silicate minerals in close contact with a granitic/felsic intrusion. Mineralisation characteristics can be mono-metallic Tungsten or polymetallic (often with Mo or Pb,Zn,Cu), as well as gold, fluorite or magnetite. Typical grades are 0.3-1%  $WO_3$ . As for the the EU, one active mine of this type is found in the Los Santos mine in Spain.



- **Bulk mineable deposits (greisen, porphyry, stockwork):** are either W-Sn, or W-Mo deposits. Both scheelite and wolframite occur in bulk mineable deposits, and some deposits contain both mineral together, which leads to problems with beneficiation as mixed concentrates are more difficult to market. Typical grades are 0.1-0.3% WO<sub>3</sub>. In EU there is a mine of this type in Austria, Mittersill.

Only scheelite (CaWO<sub>4</sub>) and wolframite ((Fe,Mn)WO<sub>4</sub>) are mined commercially.

## SECONDARY RESOURCES

For the moment, secondary production is only being done in Germany (by H.C. Starck, Buss & Buss Spezialmetalle) using existing Tungsten products, but it is difficult to establish the exact amount being produced [18]. According to 2013 data from the International Tungsten Industry Association (ITIA), the recycling rate (RR) was 50% in Europe and the United States, compared to only 30% in Japan.

### *Waste rock and mill tailings*

Mineral processing wastes are generated during the extraction and beneficiation of ores and minerals. Tungsten can be recovered from waste rock and mill tailings contained in these wastes. In the EU, waste-rock and tailings are found at the Panasqueira mine, which produces 100 t/d and several million tons of these materials, respectively. At the Barruecopardo mine in Spain, Tungsten-containing dumps and tailings are found. Coarse tailings and slimes can also be found at La Parilla mine in Spain, with a grade of 0.28% of WO<sub>3</sub>. At Los Santos mine in Spain, tailings of coarse (643 kt, 0.14% WO<sub>3</sub>, 2013-2015) and fine (76 kt, 0.14% WO<sub>3</sub>, 2013-2015) rejects are also produced.

### *W-Containing grinding sludge/swarf*

The fine metal cuttings that result from grinding processes of high speed steel or cemented Tungsten carbide are collected and referred to as "swarf", which contains considerable amounts of Tungsten which can be recycled.

### *Mill scale*

Mill scale is generated during continuous casting and rolling mill processes, where steel is subjected to hot working in an oxidant atmosphere. It represents 2% of all steel produced. To give an example, there was the case of a mini-mill plant in Brazil where mill scale was reported to contain 0.83% Tungsten.

### *Other residues*

Steelmaking dust, grinding dust, floor sweeps, etc.

## PROCESSING AND EXTRACTING TECHNIQUES

### PRIMARY RESOURCES

#### *Mining*

Selection of a suitable mining method, for example, the choice between open pit or underground mining, depends on the physical and chemical properties of the mineral, tonnage extracted and grade, the physical form in which it occurs and the geometry and the depth of the orebody. Because there are many different types of deposits, both open pit and underground mining methods are used in tungsten mining operations.

Open pitting is used, for example, at Los Santos mine (skarn) in Spain, at Kara mine (skarn, containing tungsten as a by-product) in Australia, for part of the production at Cantung mine (skarn) in Canada and in various Chinese operations as well. Most of the tungsten mining projects that are currently being promoted would also employ open-pitting techniques. Tungsten open-pit mining rarely exceeds a depth of 100 meters.



Underground mining techniques are used at Panasqueira mine in Portugal, Chollja mine in Bolivia, Mittersill mine in Austria, Cantung mine in Canada, and Pasta Bueno mine in Peru, among others.

### Mineral processing

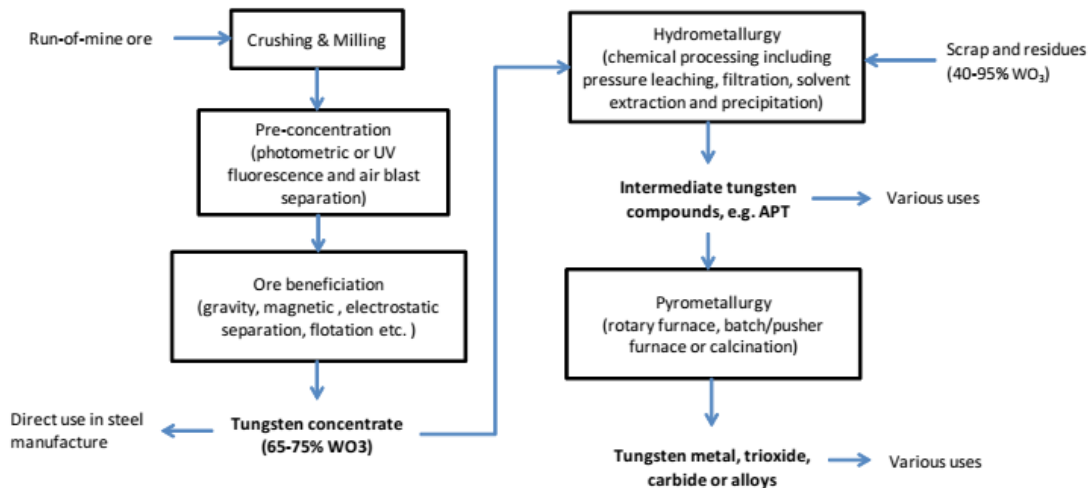


Fig. 7 General flowsheet for Tungsten production

Beneficiation processes normally involve a pre-concentration step after crushing and grinding the run-of-mine ore, which is followed by processing the pre-concentrate, cleaning the concentrate or subjecting it to an up-gradation process, and lastly, a final purification stage to meet market specifications. Only scheelite is readily amenable to flotation. Wolframite is paramagnetic. Thus, the beneficiation techniques of gravity concentration and flotation are applied for scheelite ore, and gravity and/or magnetic separation for wolframite. Moreover, pre-concentration methods are usually used to discard a portion of the run-of-mine ore and increase the head grade prior to traditional beneficiation stages. The beneficiation flow-sheet depends on the nature of the mineralization in the ore body and on the liberation size of the Tungsten minerals.

### Extractive metallurgy

- **Hydro-metallurgy:** After digestion and purification of the raw material, the concentrated leachates enter the solvent extraction cycle. There are several processes to produce high-purity ammonium paratungstate (APT), the most important intermediate for pure Tungsten production:
  1. **Digestion:** alkali leaching, pressure leaching with soda and acid leaching.
  2. **Purification:** filtration and precipitation. Silicates are common impurities, which can be precipitated by aluminium sulphate or magnesium sulphate solution at pH 8-11. Phosphates and fluorides are co-precipitated. Molybdenum is precipitated with sodium sulphide in a neutral or slightly alkaline environment, forming triomolybdate, which is in turn precipitated into trisulfide, by adding sulphuric acid at pH 2.5-3. This is also selected for other sulphides: As, Sb, Bi, Pb and Co.
  3. **Solvent extraction:** tertiary or secondary aliphatic amines are the most important extractants. Extractants are dissolved in kerosene or other aliphatic solvents. Phase modifiers such as isodecanol can be added.
  4. **Ion exchange:** the sodium tungstate solution is contacted with a strongly alkaline ion exchange resin in the chloride form, where the tungstate is adsorbed. Desorption is carried out with an ammonium chloride solution.
  5. **Crystallization:** the isopolytungstate solution is evaporated and the water and ammonia are distilled, which are in turn recycled in the solvent extraction step. The solubility becomes lower and APT crystallizes in recirculating batch crystallizers, which is an additional purification step, in which soluble impurities remain in the mother liquid.

## Pyro-metallurgy

Tungsten concentrates that remain after processing the ore may be directly converted into Ferro-Tungsten (aluminothermic and carbothermic reduction process), steel (in an EAF) and Tungsten chemicals, or indirectly into metal powder (hydrogen reduction of tungsten oxide at 600-1000°C) and carbides (resulting in high purity Tungsten powder and Tungsten powder carbonization using high-purity carbon black, soot or graphite).

## SECONDARY RESOURCES

### Waste processing

- **From waste rock and tailings:** Waste rock generally consists of coarse, crushed, or blocky material covering a range of sizes, from very large boulders or blocks to fine sand-sized particles or dust. Mill tailings are the fine particles that remain after grinding, screening, or processing of raw materials. Typically, mill tailing particle size ranges from sand-sized to silt-clay-sized, depending on the degree of processing needed to recover the ore. At the Panasqueira Mine in Portugal, flotation, magnetic separation and gravity concentration testwork has been undertaken at both the laboratory and pilot scales. Current tailings were floated well using froth flotation. At La Parrila Mine in Spain in 1986, tailings were processed using cyclones, spirals, and shaking tables, resulting in a Tungsten recovery of 70%. Contaminated cemented carbide scrap, turnings, grindings and powder scrap are oxidized and chemically processed in a way similar to the ores.
- **Grinding sludge/swarf:** The main problem is the oil contained in the swarf. It must be removed using, for example, a high-pressure filter procedure. Moreover, the non-metallic and phosphorous contents of the sludge/swarf also needs to be reduced to no more than 5% and 0.03%, respectively, if the swarf is to be sent for smelting recycling. Phosphorous removal can be achieved through a combination of controlling oil contents and subjecting the sludge/swarf to to a water-washing process. The removal of non-metallic content is done using gravity concentration and magnetic separation procedures. The cleaned residues are then sent to smelting furnaces.
- **Mill scale:** It must first be crushed or ground into fine particles and formed into briquettes before being subjected to charging in the reduction reactor to extract Tungsten.

### Extractive metallurgy of waste rock and tailings

- **Hydrometallurgical**
  - **Digestion:** In concentrated NaOH (40-50%) at 100-150°C or by high-pressure digestion with dilute NaOH.
  - **Purification:** Sodium tungstate solutions are filtrated and precipitated to remove impurities. Sodium ion concentration must be reduced from 70 g/L to < 10 mg/L. After purification, it is subjected to a Tungsten concentration procedure.
  - **Solvent extraction:** The same procedure of that for primary resources.
  - **Ion exchange resin:** Sodium tungstate solution is contacted with a strongly alkaline ion exchange resin in the chloride form, causing the tungstate to be adsorbed. Desorption is carried out with ammonium chloride solution. Elements such as Si, P, As and Mo can also be removed.

### Extraction from grinding sludge/swarf

After proper processing, grinding sludge/swarf briquettes can be charged into the smelting furnace to produce Ferro-Tungsten or Tungsten alloy. In this way, the Tungsten in the scrap is recovered from the steel in the end. Alternatively, it is also possible to use a NaOH pressure-leaching procedure to extract Tungsten, which is recovered as ammonium paratungstate (APT), an important intermediate product in Tungsten metal powder and carbide production.

### *Extraction from mill scale*

Reduction can be applied and Tungsten be used in steel, by charging the mill scale in the EAF. The same leaching technique as that used for swarf can be applied.

### *Recycling of Tungsten carbides*

The most common method involves the separation of the carbides from the binder phase or oxidation followed by alkali leaching. However, coarse powders are formed, the cost is high and large amounts of chemicals are required.

## ENVIRONMENTAL AND SOCIAL IMPACTS FROM ITS EXPLOITATION

As with any mining operation, Tungsten mining is likely to have a significant environmental footprint, and environmental management plans must be devised and implemented to minimise the impact. Closure plans and environmental bonds are typically required from the onset of mining to ensure that the mine site is adequately cleaned and rehabilitated once the ore deposit is exhausted.

Apart from the mining operation itself (the impact on nearby buildings and, in the case of open pitting, the “hole in the ground” it creates), the most significant impacts are those stemming from waste rock dumping and disposal of tailings (mill rejects). Tungsten deposits typically have grades of less than 1%  $WO_3$  and, together with the swell factor (blasted rock takes up a far larger volume than in-situ material), Tungsten mines produce, volume-wise, more waste than the volume of the material actually mined, in addition to the waste rock that has to be removed to access the Tungsten ore.

Landscaping of waste piles is a common approach, and there have been examples in which the original landscape has been enriched by the legacy of mining activity. However, in many cases, at least part of the waste material needs to be backfilled into the void created by mining. In underground mining operations, backfilling can be done concurrently with the mining operation itself, whereas in the case of open-pit mining, adequate funding must be set aside to cover the backfilling operation after mining has been completed.

Tailings of many Tungsten projects are benign as they do not contain any chemical reagents (except for perhaps only minor quantities of fatty acids) and contain only small quantities of heavy metals. Projects meeting these criteria are classified as non-Class A facilities as defined in the EU Mining Waste Directive. Nonetheless, these tailings facilities are large engineered structures often containing millions of tonnes of fine-grained material and require adequate supervision and long-term stability planning. Many underground mining methods allow or require backfilling of voids, and depending on grain size distribution and other physical properties, tailings may constitute a significant portion of the backfill material. However, large amounts of slime contained in tailings must be removed if backfill stability is a concern, especially if consolidated backfill is generated by mixing the tailings with a binder such as cement and /or fly-ash.

In the same way that mining operations can have an impact on their local environments, the natural local environment, in turn, can also pose extraordinary challenges for the mine. In remote areas, infrastructure might be totally absent and the mine operator might find it challenging (or very costly) to attract qualified personnel, whereas in densely populated areas there may virtually be no place to locate the mine, or it would need to be completely concealed to be accepted. Tungsten mining and beneficiation processes often account for high losses (10 – 40 %) and high amounts of waste rock and landfill. In light of the fact that demand is growing year by year [29], it is impractical to think that primary production could be entirely replaced by recycling. However recycling methods do indeed require lower processing energies, and hence, produce lower carbon emissions and do not create the waste rock, waste water and leachates that result from mining operations [30].

Tungsten is not as toxic as other metals, such as lead or mercury, for which it is sometimes used as a substitute. However, it should no longer be considered to be absolutely non-toxic [35].





A recent study by Clauson and Korte found that particles of Tungsten metal could oxidise in the air and then dissolve into the soil as a result of natural rainfall. The Tungsten, in this more soluble form, became mobile in the soil and elevated levels were detected in local groundwater. Elevated levels of Tungsten have been found in soils, trees and plant tissue, aquatic systems, the atmosphere, animals and human beings in various locations. Often these appear to be associated with natural Tungsten deposits but also occur in the vicinity of anthropogenic activities such as the processing of Tungsten ore or metal, military firing ranges, the use of agrichemicals and the disposal of waste in various forms [35].

The dissolution of Tungsten powder appears to cause soil acidification with associated adverse consequences on micro-organisms, invertebrates and plant communities. However, the geochemistry of Tungsten is complicated and its mobility, bioavailability and toxicity in the environment depend on the exact form of the Tungsten compounds, the environmental conditions (e.g. composition of chemical substrates, pH, oxidation states) and the nature of the exposure pathway. Many studies have been conducted recently, but the environmental and health impacts of Tungsten are not yet fully understood [35].

Tungsten is included in the Best Available Techniques for Tailings Treatment and Waste Rock published by the European Commission, where the following data on current emissions and consumption levels have been included:

- No water is recycled from the tailings pond to the mineral processing plant
- The average emissions of dust particulates from the tailings pond area are around 50 mg/(m<sup>2</sup> 28 days)
- Emissions to water <0.1 mg/L

A study entitled “Life Cycle Assessment of Metals: A Scientific Synthesis” by Nuss and Eckelman (2014) concludes that Tungsten, compared to other refractory metals, presents a high cumulative energy demand (133 MJ eq/kg) but in the rest of impact categories (global warming, terrestrial acidification, freshwater eutrophication, and human toxicity) Tungsten presents low values.

## SUBSTITUTION POSSIBILITIES

Tungsten substitutes for most application results in a loss of performance or an increase in cost. In cemented carbides and other applications, W and its compounds can be replaced by Mo, Ti, ceramic-depleted uranium or hardened steel. For lightning equipment, Tungsten filaments can be substituted by carbon nanotube filaments, light-emitting diodes or other light sources [36]. Figure 8 represents the distribution of end-users and corresponding substitutability assessment for Tungsten [37], while Tungsten substitutability scoring, which is included in the report on critical raw materials for the EU, is presented in table 1.

Use	Substitutability score
Tungsten alloys	0,7
Superalloys	1
Fabricated products	1
Alloy steels (mainly tool steel, >80%)	0,7
Cemented carbides	0,7

Table 1 Substitutability of Tungsten score

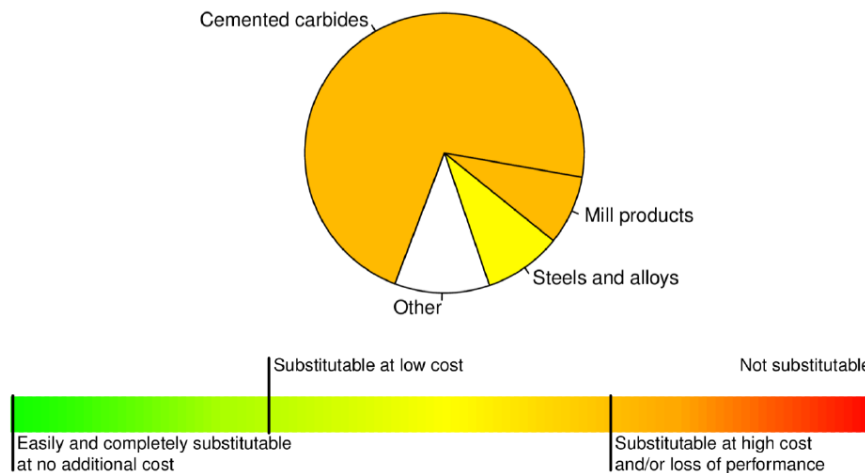


Fig. 8 Distribution of end-uses and corresponding substitutability assessment for Tungsten

Tungsten substitutes for most applications results in a loss of performance or an increase in cost:

- **Tungsten in cemented carbides (hard metal):** Tungsten and its compounds can be replaced by Molybdenum, Titanium, ceramic-depleted uranium or hardened steel, Niobium carbide [12-15].
- **For lighting equipment:** Tungsten filaments can be substituted by carbon nanotube filaments, light-emitting diodes or other light sources.
- **Tool/High Speed Steels:** Tungsten can be substituted with Molybdenum combined with alloying with chromium, and also with Vanadium and Nickel ASS (Alumina, silicon nitride, sialon). The addition of 5-10% Molybdenum increases hardness [12][16].
- **Super-alloys:** Molybdenum, Ceramic matrix composites made from a silicon carbide/nitride matrix toughened with a coating of silicon, and Rh fibres are potential substitutes of Tungsten [12] [17].
- **Mill products:** Carbon nanotube filaments, induction technology and light-emitting diodes [12].

## HEADING TOWARDS THE FUTURE: RECENT RESEARCH ACTIVITIES

### PROCESSING OF TUNGSTEN ORES FROM PRIMARY RESOURCES

Innovative studies have been conducted on selective reagents and a combined gravity-magnetic-flotation process, resulting in an improvement on Petrov's process for scheelite concentration.

Intense magnetic separation followed by gravity separation with shaking tables, and in the case of wolframite concentrated from carbonate-type wolframite-scheelite ore, followed by heated flotation and acid leaching for scheelite concentration, has been applied, resulting in wolframite and scheelite concentrates of 33.6% and 66.6%  $WO_3$  grades, respectively, and a total recovery rate of 69.2% W [21].

Recovery of tungsten and tantalum from slimes was experimentally investigated through a process of centrifugal separation and sulphide flotation [31]. The material of slimes from a mine in China contained 0.041%  $WO_3$  and 0.011% of  $Ta_2O_5$ . The centrifugal separation process consisted of one roughing session and four cleaning sessions, whereas the sulphide flotation process involved one roughing session, followed by a scavenging session and a cleaning session. W-Ta bulk concentrate with 33.35%  $WO_3$  and 3.36% Ta was obtained, recovering 65.5% W and 24.3% Ta.

## HYDROMETALLURGY

Innovative studies have been conducted on acidic leaching with nitric and phosphoric acid [22], biosorption (applied to alloy scrap), direct solvent extraction from an alkaline medium and emulsion liquid membranes. A flowsheet, including the conditions used for and results of the study have been published [24].

- For Tungsten biosorption, E.Coli and beer yeast have high uptake capacities, comparable to those of an ion-exchange resin [23].
- The application of quaternary ammonium carbonate salts as extractants in direct solvent extraction from an alkaline medium was studied but the extraction results were not very good [25]. However, this process was optimized [26] using Trioctyl methyl ammonium chloride transformed into quaternary ammonium carbonate as an extractant. The extraction results were much better, achieving 98%  $WO_3$  and 89.49 Molybdenum concentrations.
- ELM was applied to recover Tungsten from a multi-component waste stream of printed circuit boards in a stirring tank, using Aliquat 336 in hexane for the organic phase and NaOH for the internal strip phase. Tungsten was selectively extracted, reaching 80% [22].

Future challenges lie in decreasing Tungsten losses in conventional precipitation and purification procedures, decreasing chemical consumption and improving the efficiency of conventional ion exchange and solvent extraction methods.

As for the recycling of cemented carbides, a new method was reported using molten salt solution to obtain an aqueous solution of  $Na_2WO_4$ , which is converted to  $(NH_4)WO_4$  through an ion exchange treatment [33].

## PYROMETALLURGY

The following innovative processes have been developed:

- Direct alloying of steel with Tungsten using Tungsten ore: Tungsten ore and carbonaceous material are charged into the melting furnace and the steel is directly alloyed with the Tungsten. This is a one-step process that is both economical and energy efficient and can result in a Tungsten recovery of over 95% [28].
- Tungsten carbide production using the one-step carbonization method: Tungsten oxide and carbon powder, mechanically processed in a mill, form Tungsten carbide with the help of generated energy [24].
- An electrolytic process for the preparation of Tungsten powder and Tungsten carbide: Metal oxide is formed into a cathode and soaked in molten salt. Under the driving force of the direct current, oxygen in the metal oxide is ionized and transported to the anode through the molten salt. This process is highly energy efficient [24].
- For recycling scrap Tungsten carbide roll collars, a new method was developed in which, after crushing the high-Tungsten content scrap in crystallites, the crystallites were melted with other Tungsten scrap and metal material to produce a mixture of a specific chemical composition, which was then re-melted and refined electrostatically, after which roll collar ingots were produced and heated. The final product was a Tungsten alloy roll collar containing 20% W [32].
- For recycling Tungsten carbide from hard material sludge, oxidation in air at 973 K in a muffle furnace followed by carbothermal reduction processes have been applied. Carbon powder was added to the oxide, milled and then reduced in an alumina crucible at 1073-1273 K, resulting in the formation of WC and CO metal [34].

## EUROPEAN RELATED PROJECTS

- **OPTIMORE:** Aimed at optimizing crushing, milling and ore separation processing technologies for Tungsten and Tantalum mineral processing by means of improved (faster and more flexible) fine-tuned production process control based on new software models, advanced sensing and a more thorough study of the overall physical process, which could increase yields by 7-12% and result in increased energy savings of 5%, compared to the best production processes currently in use.



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