

Tungsten

January 2011

Definition, mineralogy and deposits

Definition and characteristics

Tungsten, also known as wolfram, is a very dense lustrous greyish-white to steel-grey metal with some unique properties which make it impossible to replace in certain specialised industrial applications. It has the highest melting point of all non-alloyed metals and is second only to carbon among all elements. Tungsten has the highest tensile strength¹ at temperatures above 1650°C and the lowest coefficient of expansion² of any pure metal. It is remarkable also for its very high density, similar to gold, which gave rise to its name (from the Nordic *tung sten* meaning 'heavy stone'). In its purest form tungsten is quite pliant and ductile but the inclusion of small amounts of carbon and oxygen give the metal considerable hardness and brittleness and it is difficult to work in its raw state. Tungsten has high thermal and electrical conductivity. Key physical properties and other features are summarised in Table 1.

The average abundance of tungsten in the Earth's crust is estimated to be 1.25–1.50 parts per million (ppm), about the same as tin and molybdenum, and half as plentiful as uranium. Its oceanic abundance is 0.1 micrograms per litre. The average concentration in workable ores is usually between 0.1 and 1.0 per cent tungsten trioxide³. Tungsten is the heaviest element known to be used by any living organism and is an essential nutrient for some bacteria. However, it has no essential role in the health of plants, humans, or animals. Although the metal's toxicity is low compared with other elements, such as lead or mercury, there is some evidence that, in certain forms, tungsten may be mobile in the environment and may inhibit particu-

¹ Tensile strength is the maximum load a material can withstand when being stretched.

² Coefficient of expansion is the degree of expansion of a substance as temperature increases; a low coefficient means that an element expands little as temperature rises.

³ Tungsten trioxide has a chemical formula of WO_3 , meaning it is a compound with one tungsten atom and three oxygen atoms.

Unless otherwise stated, copyright of materials contained in this report are vested in NERC. BGS © NERC 2011. All rights reserved.

Symbol	W (wolfram)	
Atomic number	74	
Atomic weight	183.84	
Density at 293 K	19300	kg/m ³
Melting point	3422	°C
Boiling point	5555	°C
Crystal structure	Body centred cubic	
Hardness	7.5	Moh
Specific heat capacity at 293 K	133.89	J/kg
Electrical conductivity at 293 K	18.2	10 ⁶ S/m ⁻¹

Table 1 Selected properties of tungsten.



Figure 1 Tungsten and tin-bearing vein from Hemerdon deposit, Devon, UK. The tungsten is present in wolframite, the dark mineral along the edge of the quartz vein in the centre of the photo. BGS©NERC.

Name	Formula	Tungsten content (WO ₃ %)	Specific gravity (g/cm ³)	Appearance (colour and lustre)	Crystal structure
Ferberite	FeWO ₄	76.3	7.5	Black, sub-metallic to metallic	Monoclinic
Wolframite	(Fe,Mn)WO ₄	76.5	7.1-7.5	Dark grey to black, sub-metallic to metallic	Monoclinic
Hübnerite	MnWO ₄	76.6	7.2-7.3	Red-brown to black, sub-metallic to adamantine	Monoclinic
Scheelite	CaWO ₄	80.6	5.4-6.1	Pale yellow to orange, green to dark brown, pinkish-tan, dark blue to black, white or colourless, vitreous or resinous	Tetragonal
Stolzite	PbWO ₄	50.9	8.28	Reddish-brown to yellow-green, sub-adamantine to resinous	Tetragonal

Table 2 Properties of the most common tungsten minerals.

lar functions in some plant or animal species. Considerable further research is required to determine the importance of such effects (Petkewich, 2009). Chronic inhalation or severe exposure to airborne tungsten dust particles and ingestion of large amounts of soluble tungsten compounds is known to be hazardous to human health.

Tungsten is a typical metal of transition element Group VIB of the periodic table, which also includes chromium and molybdenum. It exhibits oxidation states from +6 to -2 and, particularly in its oxides, forms many non-stoichiometric compounds⁴. Naturally occurring tungsten consists of five isotopes: 180 (0.12 per cent of total), 182 (26.3 per cent), 183 (14.28 per cent), 184 (30.7 per cent) and 186 (28.6 per cent). These have extremely long half-lives and can be considered stable.

Mineralogy

Tungsten does not occur naturally as a free metal. The most important tungsten minerals are the monotungstates, such as scheelite (calcium tungstate, CaWO₄), stolzite (lead tungstate, PbWO₄), and wolframite, which is a solid solution⁵ or a mixture, or both, of the isomorphous⁶ substances ferrous tungstate or ferberite (FeWO₄), and manganous tungstate or hübnerite (MnWO₄). In practice, the name wolframite is often used for the intermediate 20-80 per cent range between the ferberite and hübnerite end-member compositions. Some basic properties of the monotungstates are given in Table 2.

⁴ Non-stoichiometric compounds have an elemental composition that cannot be represented by a simple ratio of definite proportions and for which the chemical formula varies over a limited range.

⁵ Solid solution: a solid crystalline substance in which the composition varies in a continuum between two end members as a result of substitution or omission of atomic constituents.

⁶ Isomorphous: similarity of crystal structure between two or more distinct substances.

Scheelite is the most abundant tungsten mineral and is present in approximately two thirds of known tungsten deposits. An important property of scheelite is the bluish-white fluorescence under short-wavelength UV radiation which is especially valuable in exploration and mining. The colour of the fluorescence light is influenced by the molybdate content. With increasing molybdenum concentration in scheelite, its colour changes from blue to pale yellow and orange. Stolzite can occur as a result of hydrothermal alteration of scheelite.

Tungstenite (WS₂) is the most common example of the sulphide group of tungsten minerals. It has the same hexagonal layered structure as molybdenite (MoS₂); the chief difference being its higher specific gravity. Tungstenite is a dark lead-grey mineral that occurs in massive form and in scaly or feathery aggregates.

Deposits

All primary tungsten deposits are associated with granitic intrusions or with medium- to high-grade metamorphic rocks⁷. Most (i.e. more than 70 per cent) of intrusion-related tungsten deposits formed during the Mesozoic period (251-65 million years), although other ages are also known. Tungsten deposits are usually located within or near to orogenic⁸ belts resulting from subduction-related collisional plate tectonics.

Major tungsten deposits occur in the orogenic belts of the Far East (southern China, North and South Korea, Japan, Thailand and Burma), the Asiatic part of southern Siberia, Kazakhstan, Uzbekistan, Kyrgyzstan (Altay-Sayan fold belt) and Caucasus, the eastern coastal fold belt of Aus-

⁷ Metamorphic: rocks changed by temperature and pressure within the Earth's crust.

⁸ Orogenic: tectonic forces that leads to the creation of mountains.

Deposit type	Deposit size range (metric tonnes)	Typical grade (WO ₃ %)	Estimated tungsten metal content of known deposits (thousand tonnes)	% of total
Skarn	<10 ⁴ – 5x10 ⁷	0.3 -1.4	1764	41
Vein/breccia/stockwork	<10 ⁵ - 10 ⁸	Variable	1475	35
Porphyry	<10 ⁷ - 10 ⁸	0.1 – 0.4	679	16
Disseminated	<10 ⁷ - 10 ⁸	0.1 - 0.5	217	5
Stratabound	<10 ⁶ – 10 ⁷	0.2 -1.0	118	3
Total			4253	100

Table 3 Size and grade of major tungsten deposit types. Sourced from Schubert et al. (2006), ITIA (2010) and Werner et al. (1998). WO₃% = tungsten trioxide content.

tralia and the Alpine fold belt from France to Turkey. The Western Cordilleras of the Americas (Rockies and Andes), part of the Circum-Pacific belt, contain a number of major deposits in Canada, USA, Bolivia and Peru. In Western Europe the Variscan belt that arcs from Germany and the Czech Republic through France and south-west England and into Spain and Portugal also has some important tungsten deposits. In Brazil (Rio Grande do Norte, Rondônia and São Paulo states) and Africa (Rwanda, Uganda and the Democratic Republic of Congo) deposits of tungsten, either with or without tin, are associated with tectonic rift settings.

Five types of tungsten ore deposits are of major importance as indicated in Table 3.

Other deposit types include pegmatite, placer, brine/evaporite and hot spring deposits. Most current production of tungsten is from vein/stockwork, skarn, porphyry and stratabound deposits. Hydrothermal processes are important in many of these and may give rise to complex mineralisation styles and morphologies.

Tungsten deposits associated with granitoid⁹ rocks may be conveniently grouped into two broad categories:

- i. deposits associated with I-type granite¹⁰ series that typify continental volcanic arcs above subduction zones¹¹.
- ii. deposits associated with alumina-rich S-type granites¹² that are emplaced during the late stages of continental plate collision and alkali-rich or A-type granites derived

⁹ Granitoid: pertaining to the granite clan, a series of silica-rich medium to coarse-grained intrusive rocks with variable amounts of quartz, feldspars and dark minerals rich in iron, magnesium and/or calcium.

¹⁰ I-type granite: derived by the melting of mainly igneous rocks.

¹¹ Subduction zone: a belt of tectonic convergence where one crustal plate is forced below an adjacent plate.

¹² S-type granite: derived by the melting of mainly sedimentary (or metasedimentary) rocks.

from mantle depths and emplaced in zones of large-scale extension of the Earth's crust.

The key characteristics of the most important types of tungsten deposit are set out below, and summarised in Table 4.

Major deposit classes

Skarns

Skarns are calc-silicate rocks composed of an assembly of calcium-iron-magnesium-aluminium silicate minerals which develop by metasomatic processes¹³ during metamorphism of carbonate-bearing rocks (such as limestone) at or near contacts with granitic intrusions. They are commonly associated with hornfels (a fine-grained non-foliated metamorphic rock produced by contact metamorphism), marble and broader zones of calc-silicate rocks within the thermal aureoles. Uncommon types of skarns are formed in contact with sulphidic or carbonaceous rocks such as black shales, graphite shales and banded iron formations.

Calcic skarns, which are characterised by calcium- and iron-rich silicates (e.g. andradite, hedenbergite, etc), are the most common host for tungsten mineralisation (Ray, 1995). Scheelite is the principal tungsten mineral which occurs both as disseminated grains and fracture infillings. Other metals that may accompany tungsten include copper, molybdenum, tin, zinc and bismuth.

Tungsten skarns are separable into two types: reduced skarns (e.g. Cantung, North West Territories, Canada), formed in carbonaceous rocks and/or at greater depths; and oxidised skarns (e.g. King Island, Tasmania, Australia), formed in non-carbonaceous rocks, and/or at shallower depths.

¹³ Metasomatic process or metasomatism is the process of chemical alteration of a rock by interaction with hydrothermal or other fluids and replacement of one mineral by another without melting.



Figure 2 Wolframite from Portugal (specimen is approximately 5 cm long).¹⁴

Vein/stockwork deposits

Vein-style deposits consist of simple to complex fissure fillings or replacement quartz veins up to several metres in width, that occur in or near granitic intrusions. They are genetically related to fracture development coeval with granite emplacement and crystallisation. The vein mineralogy varies from simple, consisting almost entirely of quartz and wolframite, to complex as at Pasto Bueno in Peru and Panasqueira in Portugal where more than 50 vein-forming minerals have been identified. The wolframite series is commonly the principal tungsten mineral but some deposits contain scheelite. Economically important accompanying metals include tin, copper, molybdenum, bismuth and gold. Complex uranium, thorium, rare earth element oxide and phosphate minerals may also be present.

These deposits vary in complexity and may comprise:

- a. a series of discrete quartz veins (lode-type)
- b. sheeted vein systems comprising multiple narrow, closely-spaced parallel quartz veins (stringer-type)
- c. swarms of parallel to sub-parallel veins, commonly interconnected by veins and veinlets (stockwork-type).

Sheeted vein and stockwork deposits are generally low grade but can be exploited by bulk mining methods such that grades as low as 0.1 per cent tungsten trioxide are economic. Exogenous¹⁵ vein-type tungsten deposits have greater vertical and lateral extension and fewer constituent veins than endogenous (i.e. granite-hosted) veins.

¹⁴ Wolframite image taken by 'Alchemist-hp' June 2008. Permission to use is given by a creative commons licence (accessed December 2010 at http://en.wikipedia.org/wiki/file:wolframite_from_Portugal.jpg. Copyright remains with the author).

¹⁵ Exogenous: located or originating outside the intrusive body.

Vein-type tungsten deposits typically have multi-stage mineral parageneses¹⁶ which exhibit a silicate-tungstate, oxide-sulphide (and tungstate)-carbonate sequence. In general, tungsten minerals form earlier, at higher temperatures and deeper levels in the crust, and closer to the igneous source than sulphide or carbonate minerals. Scheelite preferentially forms in veins emplaced in rocks rich in calcium such as limestone, mafic¹⁷ and intermediate¹⁸ igneous rocks and their metamorphic equivalents, and commonly in lower-temperature environments (Guilbert and Park, 1986).

Hydrothermal lode deposits are commonly characterised by a spatial zonation of mineralisation associated with the uppermost parts of granitic intrusions as typified by the Cornubian orefield in south-west England (see section on Britain). Tin, copper, lead-zinc, and iron zones are distributed sequentially around individual intrusive (or emanative) centres and arranged according to distance from the granite intrusion. Tungsten, together with arsenic, overlaps the tin and copper zones (Hosking, 1964; Scrivener and Shepherd, 1998).

Scheelite-wolframite-quartz vein deposits related to I-type granitoid intrusions are smaller in size. In these deposits scheelite is more abundant than wolframite. Lower temperature scheelite-bearing quartz veins commonly carry minor amounts of gold and sulphides. Tungsten may be recovered as a co-product of gold mining. The mineralisation occurs in greenstone belts in the deposits of Archaean age¹⁹ e.g. Hollinger (Ontario) and in Phanerozoic²⁰ meta-greywacke-slate belts e.g. Glenorchy (New Zealand).

Breccia deposits

Breccia zones consisting of rock fragments of various shapes and sizes commonly form integral parts of vein / stockwork and porphyry deposits. However, some tungsten-bearing breccia bodies, mainly pipes or chimneys, appear to have formed independently of other deposit types. Pipe deposits are near-vertical bodies that range from almost perfectly cylindrical to flared or bulbous forms and ovoid masses. They are formed either by magmatic-hydrothermal hydraulic fracturing and fluidisation or by phreatomagmatic²¹ explosions. They may be located within, above or marginal to the apex of an intrusion and are commonly localised at the intersections of fracture sys-

¹⁶ Parageneses: plural of paragenesis—the chronological order of formation of an assemblage of minerals.

¹⁷ Mafic: dark coloured rocks containing iron and magnesium-bearing minerals.

¹⁸ Intermediate igneous rocks: those which are part way between mafic and felsic igneous rocks.

¹⁹ Archaean: rocks that formed approximately 3.8 to 2.5 billion years ago.

²⁰ Phanerozoic: less than 542 million years.

²¹ Phreatomagmatic: resulting from interaction between water and magma.

tems. Mineralised breccias seldom propagate to surface but remain blind. The fragments are cemented by minerals deposited from the ore-forming fluids by open-space infilling, matrix replacement and intergrowth. The ore minerals are commonly erratically distributed in high grade shoots or pockets. The most common tungsten mineral present is wolframite or ferberite, locally accompanied by scheelite and minerals of molybdenum, tin, bismuth, copper, arsenic, zinc, lead and antimony.

Breccia deposits are small and, although historically important, particularly in Australia, there is little production from them at present. They are mostly found in association with I- and A-type granitic intrusions and are characterised by distinctive patterns of hydrothermal alteration.

Porphyry deposits

Porphyry deposits consist of large equidimensional to irregular stockwork zones of tungsten-bearing veins, veinlets and fractures that occur in or near high-level granitic intrusions. Mineralised breccia zones may be present, while disseminations with pervasive greisenisation²² are also common. However, the mineralisation is fundamentally structurally-controlled which distinguishes porphyries from disseminated/greisen deposits. Tungsten occurs either as wolframite or scheelite and in some deposits both minerals may be present together with subordinate amounts of molybdenum, bismuth and tin minerals.

Porphyry tungsten deposits appear to be part of a spectrum of deposits that include Climax-type porphyry molybdenum deposits²³ (Ludington and Plumlee, 2009) as one end-member and porphyry tin deposits as the other (Sinclair, 1995). Tungsten-bearing porphyry systems typically comprise multiple felsic intrusions in extensional zones within post-collisional tectonically thickened crust. The stockwork zones surround, or are superimposed on, small stocks²⁴ and sheeted dyke systems. They exhibit multiple stages of brecciation and mineralisation related to explosive fluid pressure release from the upper parts of small intrusions.

The hydrothermal alteration at the deposit-scale is concentrically zoned. It is commonly characterised by a pervasive greisenisation associated with relatively high-grade tungsten zones that pass outward into fracture-controlled alteration with a lower tenor of tungsten mineralisation. Potassic alteration, dominated by potassium-feldspar, occurs locally within the central zone of pervasive greisen

²² Greisenisation: the formation of greisen, highly altered granitic rock or pegmatite.

²³ Climax-type porphyry deposits are a particular type identified at the Climax Mine in Colorado, USA.

²⁴ Stock: an intrusive mass of igneous rock smaller in size than a batholith.

alteration. Propylitic alteration²⁵, mainly chlorite and sericite, may form an outer halo beyond the mineralised zones (Sinclair, 1995).

Porphyries are typically large deposits, hundreds of metres across and tens to hundreds of metres thick, containing tens to hundreds of millions of tonnes of mineralisation, but are of low grade which are seldom economic.

Disseminated or greisen deposits

In greisen deposits the tungsten minerals are disseminated in highly altered granite or granitic pegmatite. Greisen essentially comprises an aggregate of quartz and mica formed by post-magmatic metasomatic alteration of granitic rocks. Disseminated deposits are distinguished from the greisen-bordered veins and stockworks by the pervasive nature of the alteration and the general absence of structurally-controlled fluid pathways. In reality these deposit styles commonly coexist and are often inseparable.

Greisenised granitic rocks are typically composed mainly of quartz, topaz and white mica, accompanied by tourmaline, fluorite and locally metallic oxides and sulphides and accessory phases. Tungsten is usually present as wolframite, but some deposits contain scheelite. It is usually accompanied by other ore minerals of tin, molybdenum, bismuth and other base metals.

Greisen fluids comprise the last highly gas- and water-rich phases of complete crystallisation of granite melts. Fluorine plays an important role in the mobilisation, transport, and deposition of the metals. This fluid is forced into the interstitial spaces of the granite and accumulates at the upper margins, where boiling and alteration occur.

Greisen may form in any wallrock²⁶ environment but typical assemblages develop in aluminosilicates. Abundant veins of quartz-topaz are characteristic of intensely greisenised zones. Greisen granites are associated with S-type granite suites and some highly fractionated alkaline granites e.g. Rondônia Tin Province, Brazil. They do not occur in I-type diorite to granodiorite suites. Disseminated greisen deposits are restricted to the uppermost parts of intrusions that are emplaced at a depth between one half and five kilometres, where fluids boil and are prevented from escaping to the surface.

Disseminated tungsten deposits may contain tens to hundreds of millions of tonnes of material in large lensoid or inverted cup-shaped ore bodies but are of low grade

²⁵ Propylitic alteration: caused by iron- and sulphur-bearing hydrothermal fluids.

²⁶ Wallrock: the rock that forms the walls of the vein or lode.

(typically 0.1-0.5 per cent tungsten trioxide). The tungsten minerals are usually accompanied by cassiterite²⁷ and tungsten is usually a co-product or by-product of the exploitation of tin. Greisen deposits are the dominant world source of lode tin but account for less than five per cent of tungsten production (Elliot et al., 1986).

The supergiant Shizhuyuan polymetallic deposit in south-east China (see Table 5) is one of the largest non-ferrous metal deposits in the world. It is genetically related to the Qianlishan granite with strong skarn and greisen alteration being responsible for the mineralisation (Mao et al., 1998; Li et al., 2004).

Stratabound deposits

The term 'stratabound' refers to deposits in which the tungsten mineralisation is confined to a single stratigraphic unit. However, they may not be strictly conformable to the bedding, i.e. mineralisation may cross bedding planes between layers. Because the stratigraphic control is critical, a syngenetic²⁸ origin is often assumed. This type of deposit does not include skarn deposits which are largely controlled by the composition of the host-rock lithology and are essentially epigenetic²⁹. Stratabound tungsten deposits occur in volcano-sedimentary sequences and are thought to be original tungsten-rich chemical sediments associated with submarine volcanic activity. Many of them appear to have been affected by later mobilisation and re-concentration.

The Mittersill–Felbertal scheelite deposit in the Salzburg province of Austria is the best known example of stratabound tungsten mineralisation. Tungsten occurs within the entire metavolcanic³⁰ sequence but is not currently economic. Mineable concentrations, which average 0.5 per cent tungsten trioxide, occur within quartzitic lenses and metamorphic vein-rich horizons within hornblendites³¹. One orebody consists of an eruption breccia which has been likened to siliceous sinters in recent explosion craters (e.g. Waiotapu, New Zealand). The tungsten mineralisation is accompanied by base metal sulphide and sulphosalt³² minerals. Similar deposits are known in China (Damingshan), Western Australia (Mount Mulgine), the Bindal area of Norway and the Hindu Kush of Northern Pakistan.

²⁷ Cassiterite: tin oxide ore mineral, SnO₂.

²⁸ Syngenetic: formed contemporaneously with the sediment deposition.

²⁹ Epigenetic: deposition or alteration by external agents after the rocks had formed.

³⁰ Metavolcanic: formed from volcanic rocks that have been altered by metamorphism.

³¹ Hornblendite: an igneous rock comprising more than 90 per cent hornblende, which is a rock-forming mineral predominantly composed of iron and magnesium.

³² Sulphosalt: complex sulphide minerals that include semi-metals such as arsenic and antimony.

Modern analogues of stratabound tungsten deposits exist in the form of continental evaporite sequences that drain highland areas with bedrock tungsten deposits and receive waters from thermal springs enriched in tungsten (see section on hot spring deposits).

There are stratabound tungsten-manganese oxide-quartzite deposits in which tungsten is contained in manganese, and less commonly in iron minerals that occur within sequences of carbonate, siliceous and volcanogenic sediments. These deposits are believed to have been formed by underwater, epithermal³³ hot springs.

Pegmatite deposits

Pegmatites are very coarse-grained igneous rocks (crystal size greater than 2.5cm) comprising segregations of specific minerals that commonly form metre- to kilometre-scale dyke-like masses concentrated around granitic bodies. They may occur singly, in swarms forming pegmatite fields or in linear pegmatite belts. Pegmatites are divided into simple unzoned to complex strongly zoned types with a more varied mineralogy. Tungsten-bearing pegmatites are essentially of granitic composition and include enrichments of other elements such as lithium, beryllium, niobium, tantalum, tin and uranium. They may be transitional with some greisens and be hosted by some mineralised skarns. Tungsten, however, is not a common constituent of pegmatites, and pegmatite deposits of tungsten are rare and small. The Okbang scheelite deposit in South Korea is the only example of a deposit of this type of any current economic significance. Wolframite is also produced as a co- or by-product from pegmatites along with columbite-tantalite³⁴, cassiterite, beryl and spodumene³⁵. Examples include the Wodgina mine in Western Australia, and Kular and Priskatel in the CIS³⁶. Most tungsten-bearing pegmatites are Precambrian in age³⁷. Although tungsten production from this type of deposit is relatively minor, some of them are an important source for placer deposits.

Hot spring deposits

Tungsten occurs in hot spring deposits such as Golconda in Nevada, United States and Uncia in Oruro Province, Bolivia. They are commonly associated with bedrock tungsten deposits from which they were probably derived by circulating hot ground water. The deposits are small and although there has been minor production from them in

³³ Epithermal: formed by warm waters at shallow depths.

³⁴ Columbite-tantalite: ore mineral containing niobium and tantalum.

³⁵ Spodumene: ore mineral containing lithium.

³⁶ CIS: Commonwealth of Independent States — a loose collection of sovereign states that includes most, but not all, of the countries that comprised the former Soviet Union.

³⁷ Precambrian: older than 542 million years.

Deposit type	Brief Description	Features	Examples
Skarn	Tabular or lenticular scheelite-dominated orebodies in calc-silicate rocks formed by replacement of carbonate rocks and more rarely carbonaceous rocks at contacts with S- and I-type granitoid intrusions	Commonly within extensive thermal aureoles; local greisens. May be associated with porphyry W±Mo and stockwork Sn deposits	Vostok-2 (E. Siberia), Uludag (Turkey), Mactung and Cantung (Canada), Sang Dong (S. Korea), King Island (Tasmania, Australia)
Vein	Single and multiple systems of simple or complex fissure filling and replacement veins of quartz + wolframite at margins of felsic plutonic rocks in clastic (meta-) sedimentary country rocks	Greisen-bordered veins that locally pass into stockworks, minor breccia zones. Multiple stages of veining ± ore zoning with Sn, Cu, etc	Panasqueira (Portugal), Xihuashan (China), Bolsa Negra (Bolivia), Erzgebirge (Czech Rep.), Hemerdon (south-west England)
Breccia	Near-vertical bodies of fragmented rock formed either by hydraulic fracturing or steam-dominated volcanic explosions marginal to I- or A-type granitic intrusions	Associated with vein / stockwork & porphyry deposits. Commonly zoned. Co- or by-product with Cu, Mo, Ag, Sb, Sn	Wolfram camp (Queensland, Australia), Doi Ngom & Khao Soon (Thailand), Washington (Mexico)
Porphyry	Medium to large, low-grade stockwork of quartz veinlets and disseminations in subvolcanic felsic intrusive rocks ± country rocks	Concentrically zoned metals and alteration; characterised by pervasive greisenisation. Co-product with Mo, Sn, Ag	Xingluokeng, Fujian and Yangchulin, Jiangxi, (China), Northern Dancer (Canada), Climax (USA)
Disseminated	Low-grade greisen deposits formed by pervasive metasomatic (endoskarn) alteration in the cupolas of granitic stocks	Locally merge with tungsten-bearing greisen-bordered veins and stockworks. Co- or by-product of Sn or Mo	Shizhuyuan, Xihuashan, & Dangping (China), Akchatau, Kara-Oba & Lultin (CIS)
Stratabound	Concordant lenses of stratiform scheelite in submarine volcanosedimentary sequences. Volcanogenic exhalative origin	May include eruption breccias. Metamorphic remobilisation into shears and veins	Mittersill (Austria), Damingshan, Guangxi Zhuang (China)
Pegmatite	Dyke-like masses around granitic bodies. Simple unzoned to complex strongly zoned types with more varied mineralogy	May be transitional with greisens and be hosted by skarns. Co- or by-product with Li, Be, Nb, Ta, REE and Sn	Okbang (S. Korea), Kular & Priskatel (CIS), Wodgina (W. Australia)
Hot spring	Siliceous or ferro-manganiferous precipitates deposited by hot groundwater and hot springs. Associated with bedrock tungsten deposits	Relatively high grade but small tonnage. May be associated with Au-Ag	Golconda (Nevada, USA), Uncia (Bolivia), Rotorua-Taupo area (New Zealand)
Placer	Heavy mineral concentrations in alluvial, eluvial or marine sediments derived from proximal bedrock sources of tungsten	Co- or by-product of Sn. Mostly small and only amenable to artisanal exploitation.	Heinze Basin (Burma), Dzhida district (E. Siberia), Bodmin Moor (south-west England)
Brine	Tungsten-bearing brines in recent lakes and / or the saline deposits of palaeolakes in arid continental regions	Also tungsten-rich bottom muds of brine-charged lakes & sabkha / playa basins.	Searles Lake (California, USA), other examples in the CIS and western USA

Table 4 Key features and examples of tungsten deposit classes (darker shade indicate bedrock deposits; paler shade are superficial deposits). Information partly sourced from descriptive models compiled by the US Geological Survey (Cox and Singer, 1986) and the Geological Survey Branch of the British Columbia Ministry of Energy, Mines and Mineral Resources (Lefebure and Ray, 1995). Ag = silver, Au = gold, Be = beryllium, Cu = copper, Li = lithium, Mo = molybdenum, Nb = niobium, REE = rare earth elements, Sb = antimony, Sn = tin, Ta = tantalum, W = tungsten.

the past, current output is insignificant. At Golconda mine tungsten-bearing ferruginous³⁸ and locally manganiferous³⁹ clayey gravels were worked. At Uncia, manganese oxides deposited by hot spring activity contained 2.19 per cent tungsten. Other examples occur at Talamantes, Mexico and Romanéche, France.

Recent and ongoing formation of scheelite-bearing orange precipitates can be seen at the Champagne Pool of the Waiotapu, New Zealand. Within the same geothermal field laminae with up to four per cent tungsten occur in microstromatolites (microbial mats) at Inferno Crater and water discharging from Frying Pan Lake, Waimangu is presently depositing siliceous sinter containing 4.1 per cent tungsten.

Placer deposits

Placer deposits consist of sedimentary concentrations of scheelite and wolframite in alluvial⁴⁰, eluvial⁴¹ or marine sediments and are typically located near the bedrock tungsten-bearing deposits from which they were derived. Scheelite and even wolframite eventually decompose upon weathering and hence, unlike the tin mineral, cassiterite, tend not to be preserved long enough to form widespread sedimentary deposits. Production of tungsten from placer deposits has been important historically e.g. Bodmin Moor, south-west England and Atolia, California.

Some tungsten placer deposits have been worked on an industrial scale e.g. Heinze Basin, Burma (Myanmar) and Dzhida district in East Siberia. Sherlovogorsk in the Dzhida district is one of Russia's largest tungsten/tin placer deposits. However, most tungsten placers are small and only amenable to small-scale artisanal exploitation.

Brine and evaporite deposits

Tungsten-bearing brines and evaporites occur in recent lakes and/or palaeolake⁴² deposits in arid regions of the CIS and western USA. Searles Lake in California, which covers an area of 90 km², contains about 70 parts per million (ppm) of tungsten trioxide in brines and 118 ppm in muds, equivalent to a total of 61 000 tonnes in the highly concentrated brines and a total reserve of 170 000 tonnes including the evaporites to a depth of 50 metres. The tungsten originated from the leaching of tungsten deposits in the upper drainage basin. This exceeds the total amount of tungsten in all other known deposits in the United States. Searles Lake and other

continental sabkha playa basins⁴³ in the Mojave Desert represent an important source of supply for the future.

Extraction methods and processing

Extraction

Tungsten mining techniques are similar to many other metals of similar occurrence. The mining method used depends on the physical and chemical properties of the mineral, tonnage and grade, the physical form in which it occurs, the geometry and the depth of the orebody. The common excavation types are surface (or open pit) mining and sub-surface (or underground) mining, or a combination of both.

Surface mining

Open-pit mining is used if the near-surface ore body is massive and/or when it occurs in steeply-dipping lode(s), sheeted vein systems, pipes, or makes up the bulk of the country rock as in disseminated or porphyry-style deposits. The whole ore body is mined with no overburden being put back into the void during the extractive operation. Open pit mining can reach depths of several hundred metres but rarely exceeds 100 metres in tungsten mine operations before going underground.

Some placer deposits are amenable to strip mining or dredging operations. In strip mining the overburden is removed and deposited in the hole left from the excavation of the previous strip or panel and the ore can be simply dug out.

Hydraulic mining is commonly used in reclamation of old mine tailings that still contain payable values of tungsten. This utilises one or more 'monitors' which deliver a very high-pressure jet of water that erodes the material which gravitates into a sluice where it is collected and pumped, via a pipeline, to the treatment plant.

Underground mining

Underground mining is preferred when surface mining is, or becomes, prohibitively expensive, for example if the deposit is too deep or if its form is such that underground mining is more efficient. A major factor in the decision to mine underground is the ratio of waste to ore (strip ratio). Once this ratio becomes large, surface mining is no longer economic. Underground access is through an adit⁴⁴, a shaft or a decline⁴⁵. Ore is mined in stopes⁴⁶ on a number of roughly

³⁸ Ferruginous: rich in iron.

³⁹ Manganiferous: rich in manganese.

⁴⁰ Alluvial: deposited by rivers or streams.

⁴¹ Eluvial: deposits formed by in-situ weathering of rocks and enriched by the removal of lower density materials.

⁴² Palaeolake: historical lake deposits.

⁴³ Sabkha playa basins: desert basins with no outlets that periodically fill with water to form temporary lakes.

⁴⁴ Adit: an entrance to a mine which is horizontal, or nearly horizontal.

⁴⁵ Decline: a mine entrance which is neither horizontal nor vertical; often it takes the form of a spiral ramp.

⁴⁶ Stope: the void created by extracting the ore.

horizontal levels at various depths below the surface. A modern underground mine is a highly mechanised operation with much emphasis on mine safety and environmental protection.

The Mittersill-Felbertal mine in Austria is situated in a protected landscape. Therefore, the whole mining operation including all the workshops and warehouses are installed underground. The waste-rock, which is mined during the development of the orebody, is deposited into open stopes underground in order to avoid waste-rock dumps on the surface. The fine waste from ore processing (tailings) is used for backfilling of the open stopes.

The gently dipping to nearly horizontal ore zone at the Panasqueira tungsten mine in Portugal requires more roof support and so employs 'room and pillar stoping'. About 85 per cent of the available ore can be mined in this way; the other 15 per cent has to remain underground as pillars to prevent the mine roof from collapsing.

Block caving is an underground mass mining method that is appropriate for bulk mining of large relatively low-grade orebodies. This method can be used on any tungsten-bearing orebody that is sufficiently massive and fractured such as porphyry/stockwork deposits. Many large open-pit mines have extended, or are planning to extend, their operations underground by block caving. Examples of block caving operations include Henderson Mine (Colorado) and Questa Mine (New Mexico). Both mines exploit Climax-type molybdenum porphyry deposits and produce tungsten as a by-product.

Processing

The first phase of processing the ore is beneficiation⁴⁷ at the mine site to increase the tungsten content. The resulting concentrate containing more than 65 per cent tungsten trioxide can then either be used directly for production of ferrotungsten and steel manufacture, converted to a number of intermediate tungsten compounds by hydrometallurgical⁴⁸ processes or further refined to pure tungsten using additional pyrometallurgical⁴⁹ techniques (Figure 3).

⁴⁷ Beneficiation: the separation of ore from gangue (or waste rock) and thereby increasing the metal content.

⁴⁸ Hydrometallurgical: processes that use aqueous chemistry to recover metals from the ore.

⁴⁹ Pyrometallurgical: processes that use heat to bring about physical or chemical transformations that enable the recovery of metals.

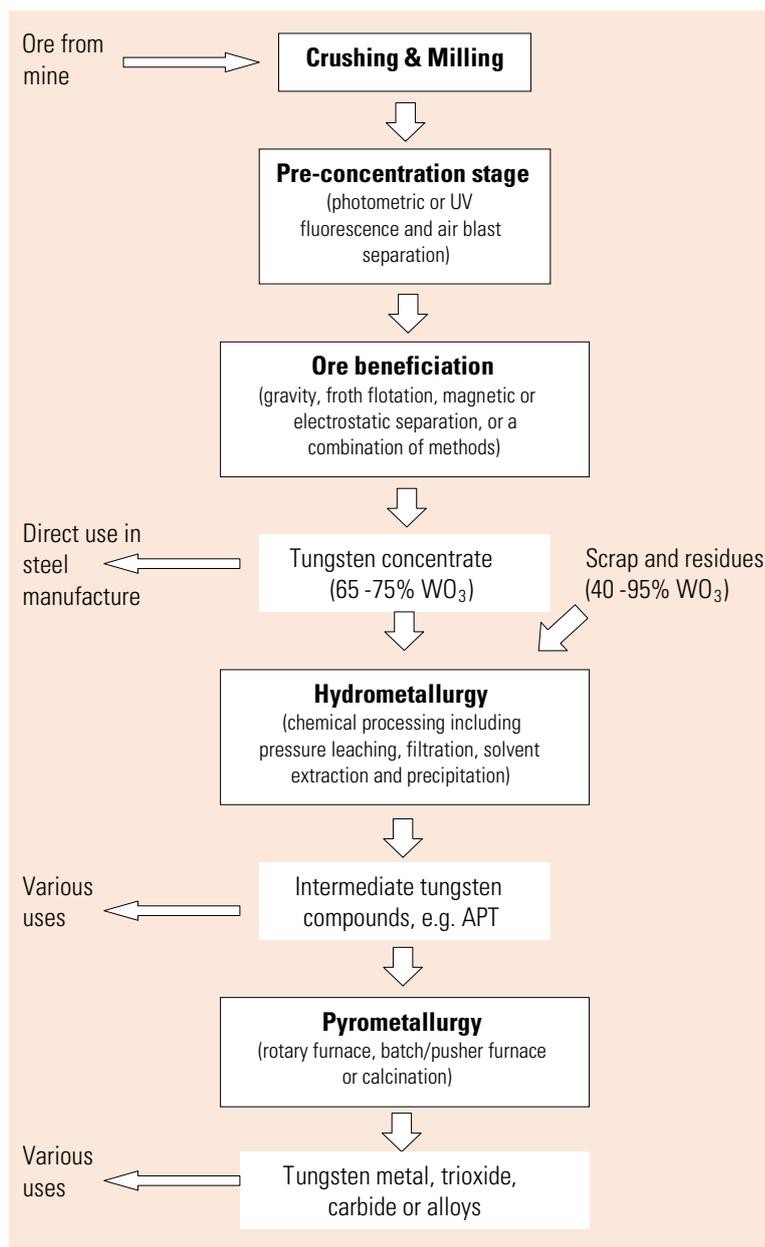


Figure 3 Simplified flow diagram illustrating the generic steps in processing tungsten.

Ore beneficiation

The tungsten ore is first crushed in jaw, cone or impact crushers and milled in rod or ball mills working in closed circuits with vibratory screens and classifiers to liberate the tungsten mineral grains. The slurry containing tungsten minerals and waste rock is then concentrated to 65 per cent or more of tungsten trioxide using several methods (e.g. gravity, froth flotation, magnetic and electrostatic separation) depending upon the characteristics and composition of the ore. Some plants incorporate a pre-concentration stage before other conventional processing methods. This usually involves an ore sorting process whereby a continuous stream of rock particles is subjected to a 'sensing' stage and are subsequently separated using

an air blast. The sensing stage can consist of a photometric method if the dark tungsten ore minerals are contained within white quartz or a UV fluorescence process if the ore is scheelite (Lassner & Schubert, 1999).

After that, scheelite ore can be concentrated by gravity methods, often combined with froth flotation⁵⁰, whilst wolframite ore can be concentrated by gravity, sometimes in combination with magnetic separation⁵¹. Gravity methods usually involve the use of spirals, cones and/or vibrating tables⁵². Magnetic separation is sometimes also used to clean scheelite (i.e. to remove magnetic gangue minerals from the ore). Electrodynamic or electrostatic separators⁵³ are used only for scheelite-cassiterite mixtures.

Direct use in steel manufacture

Wolframite concentrates can be smelted directly with charcoal or coke in an electric arc furnace to produce ferro-tungsten (FeW) which is used as alloying material in steel production. Pure scheelite concentrate may also be added directly to molten steel. Recycling of tungsten is important in high speed steel production with a typical melt containing 60 to 70 per cent scrap.

Hydrometallurgy

The raw materials currently processed by hydrometallurgical methods are concentrates of scheelite and wolframite containing 65–75 per cent tungsten trioxide. Secondary raw materials such as recycled (oxidised) scrap and residues that contain 40–95 per cent tungsten are also an important feed for chemical tungsten processing.

The production of tungsten metal from the concentrates and scrap consists of conversion of tungsten minerals to an intermediate compound that can be readily purified and then reduced. In modern plants most tungsten concentrates are processed chemically to an ammonium paratungstate (APT) intermediate.

In this process, scheelite is first digested by sodium carbonate pressure leaching and wolframite by sodium hydroxide. The scheelite requires simultaneous mechanical

activation e.g. use of a ball mill autoclave, to overcome the formation of insoluble scale on the crystals that would otherwise slow down the dissolution. Wolframite-scheelite mixtures can be successfully digested by a pressure leach with sodium hydroxide under simultaneous mechanical activation.

Tungsten scrap with only a few exceptions is easier to convert to APT than ore concentrates because it does not contain detrimental elements like phosphorus, arsenic and silicon. The tungsten scrap is first oxidised by heating in air, or oxygen-enriched air, in a rotary or multihearth furnace to facilitate dissolution in the alkaline leach process. Dissolution is achieved either by sodium hydroxide pressure digestion or an oxidising alkaline melt (sodium carbonate with additions of sodium nitrate and sodium nitrite), or by electrolysis.

Following the dissolution process the undissolved digestion residues are removed by filtration. The sodium tungstate solution after filtration, however, may still contain contaminants such as molybdenum. These can be removed by precipitation under carefully controlled conditions.

The sodium tungstate solution is converted into ammonium isopolytungstate by either solvent extraction (liquid ion exchange using an organic phase) or ion exchange by resins. The resultant ammonium isopolytungstate solution from either of these processes is evaporated whereby ammonia and water are volatilised. The ammonia concentration decreases relative to tungsten trioxide and paratungstate, whose ammonium salt has a low solubility, crystallises out. The degree of evaporation depends upon the purity of the feed solution and the required purity of the APT which may range from 90 to 99 per cent. The crystal slurry is filtered from the mother liquor, washed with deionised water and dried (Lassner & Schubert, 1999).

Pyrometallurgy

The calcination⁵⁴ of APT under oxidising conditions converts it to tungsten trioxide. However under slightly reducing conditions calcination results in tungsten blue oxide (see next section for more details of each tungsten form). Further treatment in a furnace is required to convert either oxide into tungsten metal powder, and to use this powder in the production of tungsten carbide or the various tungsten alloys.

⁵⁰ Froth flotation: a separation process that relies on difference in surface 'wettability' of different minerals. Particles which are wettable by water are termed hydrophilic and will fall to the bottom of the cell. Particles which are non-wettable, termed hydrophobic, will be carried on froth bubbles to the surface of the cell.

⁵¹ Magnetic separation: wolframite is weakly magnetic and therefore will be attracted to a strong electromagnet, whereas gangue minerals that are not would be left behind.

⁵² All these devices exploit the differences in specific gravity (or weight) between the metal and gangue minerals.

⁵³ Electrostatic separators: a process that uses an electrical charge to divert different minerals into separate collectors.

⁵⁴ Calcination: a thermal treatment process used to bring about the decomposition of a material, or the removal of a volatile phase.

Specification and uses

Specification

Tungsten is used and traded in a variety of forms, the most important of which are:

Ammonium paratungstate (APT) is a white free-flowing crystalline salt with the chemical formula $(\text{NH}_4)_{10}(\text{W}_{12}\text{O}_{41})\cdot 5\text{H}_2\text{O}$. It is the main intermediate and also the main tungsten raw material traded in the market. APT is usually calcined to yellow trioxide (WO_3) or blue oxide ($\text{W}_{20}\text{O}_{58}$).

Ammonium metatungstate (AMT), which corresponds to the formula $(\text{NH}_4)_6\text{H}_2\text{W}_{12}\text{O}_{40}\cdot x\text{H}_2\text{O}$, is a highly soluble white crystalline powder and a source of high-purity, water-soluble tungsten, which is essentially free of alkali and other metallic impurities. It is produced from APT in an electrolytic cell.

Tungsten trioxide (WO_3), or tungstic oxide, is light yellow powder synthesised by oxidative calcination of ammonium paratungstate in a rotary furnace operating at 500–750°C. It can also be produced by calcination of tungstic acid. It is stable in the air at normal temperatures but becomes orange on heating. WO_3 has now been largely replaced by blue tungsten oxide (TBO) as a precursor for tungsten metal and tungsten carbide production.

Tungsten blue oxide (TBO) is a dark blue or black powder with a nominal chemical formula of $\text{WO}_{2.97}$. It is not a well defined chemical compound but a mixture of constituents; the varying chemical and physical properties being dependent on production conditions and the equipment used. TBO is formed by calcination of APT under slightly reducing conditions.

Tungsten metal powder (W) is produced from yellow or blue tungsten oxide in hydrogen reduction furnaces. This is carried out in pusher furnaces, in which the powder passes through the furnace in boats, or in a rotary furnace, at 700–1000°C. Tungsten is sometimes used in powder form but commonly must be consolidated into solid form. The metal powder is not smelted directly because tungsten has the highest melting point of any metal. The pure tungsten powder is reheated in molds in an atmosphere of hydrogen and pressed into bars, which are hammered and rolled at high temperature to compact them and make them ductile. Consolidation is also achieved by blending the tungsten powder with a binder and very small amounts of other materials that will impart desired properties to the finished product.

Tungsten heavy-metal alloys (WHAs) are a category of tungsten alloy that typically contain 90 to 98 per cent by weight of tungsten in combination with some mix of nickel, iron, copper, and/or cobalt. These metals serve as a binder to hold the tungsten particles in place after sintering⁵⁵. There are four classes of high-density tungsten-base metal alloys produced by consolidating metal powder mixtures. These heavy metal alloys do not require millwork to enhance their properties and are machined much more easily than pure tungsten.

Tungsten carbide (WC) and semicarbide (W_2C) are produced by the reaction of tungsten metal powder with pure carbon powder at 900–2200°C in pusher or batch furnaces, a process called carburisation. Other methods include a fluid bed process that react either tungsten metal or TBO with a carbon monoxide/dioxide mixture and hydrogen at 900–1200 °C. By melting tungsten metal and WC together, a eutectic composition of WC and W_2C is formed. This melt is cast and rapidly quenched to form extremely hard solid particles having a fine feather-like crystal structure. The solids are crushed and classified to various mesh sizes.

Tungsten carbide is, quantitatively, the most important tungsten compound. In its most basic form, it is a fine grey powder, but it can be pressed and formed into shapes for a multitude of uses. Tungsten carbide is approximately three times stiffer than steel and is much denser than steel or titanium. It has a high melting point (2870°C), is extremely hard (8.5–9.0 on Mohs scale, comparable with corundum or sapphire) and can only be polished and finished with abrasives of superior hardness such as silicon carbide, cubic boron nitride and diamond. It also has a low electrical resistivity, comparable with some metals (e.g. vanadium). Tungsten carbide starts to oxidise at 500–600°C.

Ferro tungsten (FeW and Fe_2W) is an alloy with a steel-grey appearance formed by combining iron and tungsten. There are two grades with tungsten contents in the range 75–82 per cent and 70–75 per cent. Ferro tungsten is a remarkably robust alloy because of its high melting point. By combining iron with tungsten, the brittleness of metallic tungsten is much reduced.

Non-ferrous tungsten alloys in current use include composites with copper, silver, nickel and rare metals. Combination of tungsten (or tungsten carbide) with these metals produces relatively hard, heat resistant materials

⁵⁵ Sintering: a method of consolidating a powder into a solid by heating the material to a temperature that is less than its melting point but hot enough for particles to adhere to each other.

with superior wear resistance, robust physical properties at elevated temperatures, and good electrical and thermal conductivity. The tungsten component imparts a high density, high vibration and damping capacity, excellent radiation shielding, higher temperature strength and thermal shock resistance and improved corrosion resistance.

Superalloys are high-performance alloys that exhibit excellent mechanical strength and creep resistance at high temperatures, good surface stability, and corrosion and oxidation resistance. A superalloy's base alloying element is usually nickel, cobalt, or nickel-iron. Tungsten is a minor component of a number of nickel-based (Hastelloy®) and cobalt-based (Stellite®) superalloys.

Hastelloy® superalloys have an excellent combination of corrosion resistance, fabricability and high temperature strength. Stellite® superalloys are completely non-magnetic and corrosion resistant. They are extremely hard and tough and are most suited for cutting tools. They are resistant to wear and galling⁵⁶ and retain their physical and chemical properties at high temperatures.

Uses

The unique range of properties of tungsten make it an essential component in a wide range of products for many applications. These properties include:

- very high melting point
- very high density
- extreme strength
- high wear resistance
- high tensile strength
- low coefficient of expansion
- high thermal and electrical conductivity

The most important uses are shown in Figure 4.

Hard metals

Hard metals consist of tungsten carbide and cemented carbides, which are formed from tungsten carbides and cobalt, or occasionally other metals such as titanium, tantalum and niobium. They are very hard materials that are used for cutting, drilling and wear-resistant parts or coatings.

Tungsten carbide (WC) is important in the metal-working (40 per cent of its total), mining (30 per cent), and petroleum (20 per cent) industries. Its main applications are in machine tools especially where they need to withstand

⁵⁶ Galling: adhesive wear caused by friction that results in the transfer of material between metallic surfaces.

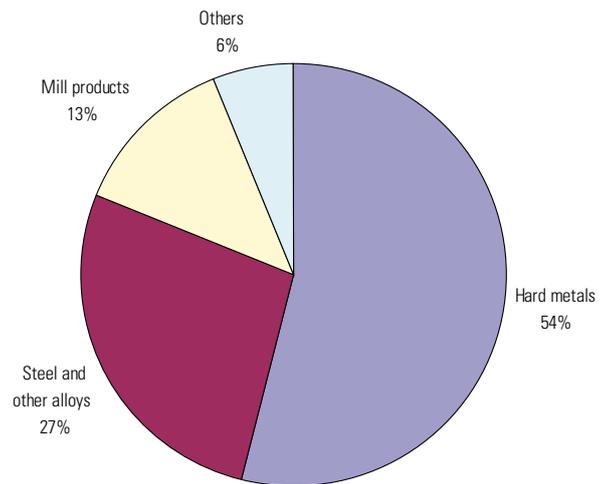


Figure 4 The main global uses of tungsten
Source: Roskill, 2010.

higher temperatures, e.g. punches, stamping dies, bushes, rollers, drill tips, milling inserts, tile and glass cutters, in armour piercing ammunition, sports equipment (for example the tips of trekking poles which impact hard surfaces) and domestic items such as scratch-resistant jewellery and as the rotating ball in the tips of ballpoint pens. Fine and ultrafine grained WC hard metals are becoming increasingly important because they last even longer than conventional WC and can be used for specialist applications where very fine tools are required, e.g. the drilling of holes in electronic circuit boards.

Cemented carbides are not only very hard and abrasion resistant, but also very tough. As a consequence they have widespread applications in high tech tools, wear parts and mining and stone-cutting tools, as well as for many sectors of the engineering industry. Most wear parts (e.g. punches, dies or hot rolls for steel rolling mills) and the mining tools are made from tungsten carbide-cobalt hard metals without any addition of other carbides.

The addition of titanium carbide and tantalum carbide to hard metals yields excellent cutting tools for the machining of steel. This superior performance has revolutionised productivity in many industries.

Steel and other alloys

Tungsten was one of the first elements to be systematically alloyed with steel to improve its properties. Specialist steel alloys, such as high speed steels, heat resistant steel and tool steels, are largely utilised in metal cutting and specialist engineering applications where hardness and strength are required, particularly over a wide temperature range.

High speed steel (HSS) is a variety of tool steel in which tungsten is a common heat-resisting alloying element. It is superior to the older high carbon steel in that it can withstand higher temperatures without losing its hardness. HSS will operate at temperatures up to 700°C whereas high carbon steel softens at around 220°C. This property allows HSS to cut faster than high carbon steel which gave rise to the name. There are many different types and designations of high speed steel, each with its own combination of added metals. These may be classified into two broad categories according to their chemical composition: T-type (tungsten-based) and M-type (molybdenum-based).



Figure 5 Tri-cone drill bits used in the mining industries often contain significant quantities of tungsten carbides⁵⁷.

The grade type T-1 with 18 per cent tungsten but no molybdenum, has not changed its composition since 1910 and was the main type used up to 1940, when substitution by molybdenum took place. Since tungsten is relatively expensive, manufacturers try to use more molybdenum and in recent times T-1 has accounted for only 5–10 per cent of the HSS used in Europe and only two per cent in the United States. M-2 is a HSS in the tungsten-molybdenum series containing six per cent tungsten and five per cent molybdenum. M-2 has high wear resistance. After heat treatment, its hardness is the same as T-1, but its bending strength, toughness and thermoplasticity are 50 per cent higher than T-1. M-type high speed steels in general are particularly useful in applications requiring shock resistance e.g. saw blades, punches and dies.

⁵⁷ Drill bits image taken by Phil Bentley. The author has granted anyone permission to use this work for any purpose (accessed December 2010 at http://en.wikipedia.org/wiki/file:Drill_bits-Italy.jpg).



Figure 6 One of the most common uses of tungsten is the filament in incandescent light bulbs⁵⁸.

Super high speed steels, such as M-48 have very high wear resistance, improved temperature resistance or both. These steels are used for high cutting speeds, dry or semi-dry cutting or simply to maximise tool life. Because of the high hardness and wear resistance some grades are considered to provide a bridge between HSS and hard metals (Tarney, 2004). Heat treatment (usually with a laser or electron beam), surface finish and coatings can provide significantly enhanced HSS tool performance.

Superalloys are high-performance alloys with particular applications in the aerospace, industrial gas turbine and marine turbine industries due to their very high corrosion and wear resistance in a variety of challenging environments. For example, Hastelloy[®] C-276 has applications in flue-gas desulphurisation systems, and in chemical processing components such as heat exchangers. Hastelloy[®] X is used in industrial furnaces and jet engine combustion chambers. Stellite[®] 6 superalloy is the most widely used of the cobalt-based alloys. Its exceptional wear resistance is due mainly to a hard carbide phase dispersed in the cobalt-chromium alloy matrix. It is used for valve seats and gates, pump shafts and bearings, and erosion shields.

Heavy-metal alloys (WHA) are mostly tungsten-nickel-iron alloys, although the addition of cobalt enhances both strength and ductility. For extremely demanding applications, superior mechanical properties are obtainable from

⁵⁸ Light bulb image taken by KMJ. Permission to use given by a creative commons licence (accessed December 2010 at http://en.wikipedia.org/wiki/file:Gluehlampe_01_KMJ.jpg).

the tungsten-nickel-cobalt alloys with nickel-to-cobalt ratios ranging from 2 to 9. The tungsten-molybdenum-nickel-iron alloy has greater strength but reduced ductility. Tungsten-nickel-copper alloys are occasionally used for applications in which ferromagnetic character and electrical properties must be minimised but they otherwise offer inferior corrosion resistance and lower mechanical properties than the present industry standard tungsten-nickel-iron alloys.

The unique properties of conventional WHAs — high density, high strength, high ductility, good corrosion resistance, high radiation adsorption capability, and reasonably high toughness — make them well suited for a variety of defence and civilian applications including X-ray and radiation shields, counter weights, kinetic energy penetrators, vibration dampening devices, medical devices for radioactive isotope containment, heavy-duty electrical contact materials and gyroscopes.

Tungsten-copper (WCu) alloys are dense, high performance, easily machinable materials with excellent thermal and electrical conductivity. WCu alloys are widely used in the electrical and aerospace industries in applications such as electrical contacts, high voltage switches, electrodes, circuit breakers, refractory parts, self-cooling heat sinks, etc. As electrodes they exhibit low wear and maintain high contour sharpness.

Nickel-tungsten (WNi) alloys remain stable indefinitely at room temperature and are highly resistant to decomposition when heated. WNi electroplating is harder and longer lasting than chrome. Furthermore, the electroplating process is more efficient than that for chrome, because multiple layers can be applied in one step, and it is potentially safer and less environmentally polluting to produce. This is a relatively new technology with potential applications in coating shock absorbers, print rolls and connectors for portable electronics (Nanomaterials, 2009).

Several other tungsten alloys exist including molybdenum-tungsten (MoW), tungsten-rhenium (WRe), tantalum-tungsten (TaW) and niobium-tungsten (NbW). These have superior properties in terms of strength, corrosion resistance, temperature stability, etc and are used for specialist applications in the glass, aerospace and electrical industries.

Mill products

The term 'mill products' is used in the industry to refer to tungsten wire, sheets or rods. The combination of extremely high melting point, conductivity and ductility

of pure metallic tungsten makes it ideal for electrical and electronic applications, most notably in incandescent light bulb filaments, vacuum tubes and heating elements. In medical X-ray tubes both the filament and target is usually tungsten or tungsten alloy. Unalloyed tungsten is also used in electronic circuit interconnects, filaments in vacuum-metallising furnaces, and for electrical contacts such as the distributor points in automotive ignition systems. Its high melting point is the basis for the use of tungsten in tungsten inert gas (TIG) welding. Water-cooled tungsten tips are used for non-consumable electrode vacuum-arc melting of alloys.

Chemicals and other specialist applications

Many of the intermediate tungsten products have uses in their own right. For example, ammonium paratungstate (APT) can be used as a colouring agent in the porcelain industry or in catalysts, phosphors and absorbent gels; ammonium metatungstate (AMT) is used as a reagent for chemical analysis during medical diagnosis or as a corrosion inhibitor; and tungsten trioxide (WO_3) can be used as a catalyst or as a pigment in ceramics and paints.

Other substances containing tungsten have a wide range of applications. For example, sodium tungstate is a widely used tungsten chemical with applications in the manufacture of organic dyes and pigments, catalysts, fireproofing of textiles and hard surfacing for graphite crucibles.

Tungsten hexafluoride (WF_6) gas is most commonly used in the production of semiconductor circuits and circuit boards through the process of chemical vapour deposition. The semiconductor industry consumes around 200 tonnes of WF_6 per year worldwide. It is also used to deposit films of tungsten on ceramics or metal products such as bearings.

World resources and reserves

World tungsten resources⁵⁹ have been estimated at seven million tonnes (contained tungsten metal) including deposits that have so far not been proven to be economically workable (Hinde, 2008). It is suggested that 30 per cent of the resources are wolframite (76.5 per cent tungsten trioxide) and 70 per cent are scheelite (80.5 per cent tungsten trioxide) ores. The largest known deposits of tungsten minerals occur in Kazakhstan, China, Canada, UK and Russia (Table 5). The locations of these and other known deposits are shown on Figure 7.

⁵⁹ A mineral resource is a concentration of minerals or a body of rock that is, or may become, of potential economic interest for the extraction of a mineral commodity.

Deposit name (province)	Country	Type of deposit	Estimated contained tungsten metal (thousand tonnes)
Verkhne-Kayraky (Dzhezkazgan Oblast)	Kazakhstan	Vein/stockwork	872
Mactung (Yukon & North West Territories)	Canada	Skarn	617
Shizhuyuan (Hunan)	China	Porphyry	502
Hemerdon (SW England)	UK	Vein/stockwork	309
Tyrnyauz (Kabardino-Balkaria)	Russia	Skarn	244
Northern Dancer (Yukon Territory)	Canada	Porphyry	168
Yangchuling (Jiangxi)	China	Porphyry	160
Xingluokeng/Xianglushan (Fujian)	China	Porphyry	144
O'Callaghan's (Western Australia)	Australia	Skarn	135
Damingshan (Guangxi)	China	Stratabound	116
Vostok-2 (Primorskye)	Russia	Skarn	102
Ta'ergou (Gansu)	China	Vein/stockwork	100
TOTAL			3 284

Table 5 World's largest tungsten deposits (partially adapted from Werner et al., 1998).

The USGS (Shedd, 2010) estimated in January 2010 that reserves⁶⁰ stood at 2.8 million tonnes (contained tungsten metal) with more than 60 per cent of these located in China (Figure 8).

China has an estimated 1.8 million tonnes of proven tungsten reserves. China's wolframite reserves are being rapidly depleted with an estimated 12 years of reserves or 600 000 tonnes remaining. China does, however, have substantial scheelite resources but they are of a much lower grade and quality. The richest and largest deposits occur in the Cathaysia Block of the Huanan plate, situated in the provinces of Fujian, Jiangxi, Guangxi and Guangdong (Pitfield et al., 2010). Many new deposits also have been found in Gansu, Xinjiang and Jilin. The provinces of Jiangxi, Guangdong and Hunan currently account for 61.4 per cent of the country's known tungsten reserves. All the main types of tungsten deposits can be found in this region including the largest scheelite mine in the world, Shizhuyuan (Hunan Province).

World production

In 2009, total world production was just over 62 000 tonnes of tungsten (metal content of concentrates). This was an eight per cent increase compared to 2008 but a seven per cent decrease compared to a peak output achieved in 2004 (Figure 9).

Tungsten is currently produced in 20 countries. China has been the world's leading tungsten producer for many

years. In 1989 it accounted for 58 per cent of the world total but this rose to reach a high of 89 per cent in 2004. In recent years this proportion has fallen slightly but it remained at 80 per cent in 2009 (Figures 9 and 10).

The principal producing countries in 2009 are shown in Figure 10. Lesser amounts are also produced in Brazil, North Korea, Uzbekistan, Spain, Burma (Myanmar), Kyrgyzstan, Burundi, Uganda, Mongolia and Australia. In recent decades the Czech Republic, France, Japan, Mexico, South Korea, Sweden, Turkey and United Kingdom have ceased to be tungsten producers.

In recent years there has been a revival in the development of new mines and the reopening of inactive mines in Asia, Australia, Europe and North America with new production of tungsten concentrates recorded in Peru and Spain. Central Europe (Poland, Slovakia), New Zealand, South Korea, Vietnam and the UK all have deposits with identified reserves that may be exploited in the near future. However, the onset of the global financial crisis in late 2008 affected the start-up of some projects and additional proposed production.

Newcrest's O'Callaghan's polymetallic skarn deposit near the Telfer gold mine in the Pilbara region of Western Australia, which was discovered in mid 2008, could become the world's largest tungsten mine by 2013 accounting for seven per cent of global output. Newcrest expects to produce 4800 tonnes of tungsten concentrate per year for at least eight years (Newcrest, 2009). This is twice the size of China Minmetals-controlled Xianglushan mine in Jiangxi Province which is currently the largest operating tungsten mine producing about 2650 tonnes per year of tungsten

⁶⁰ A mineral reserve is the part of the resource which has been fully geologically evaluated and is commercially and legally mineable with current technology.

Tungsten

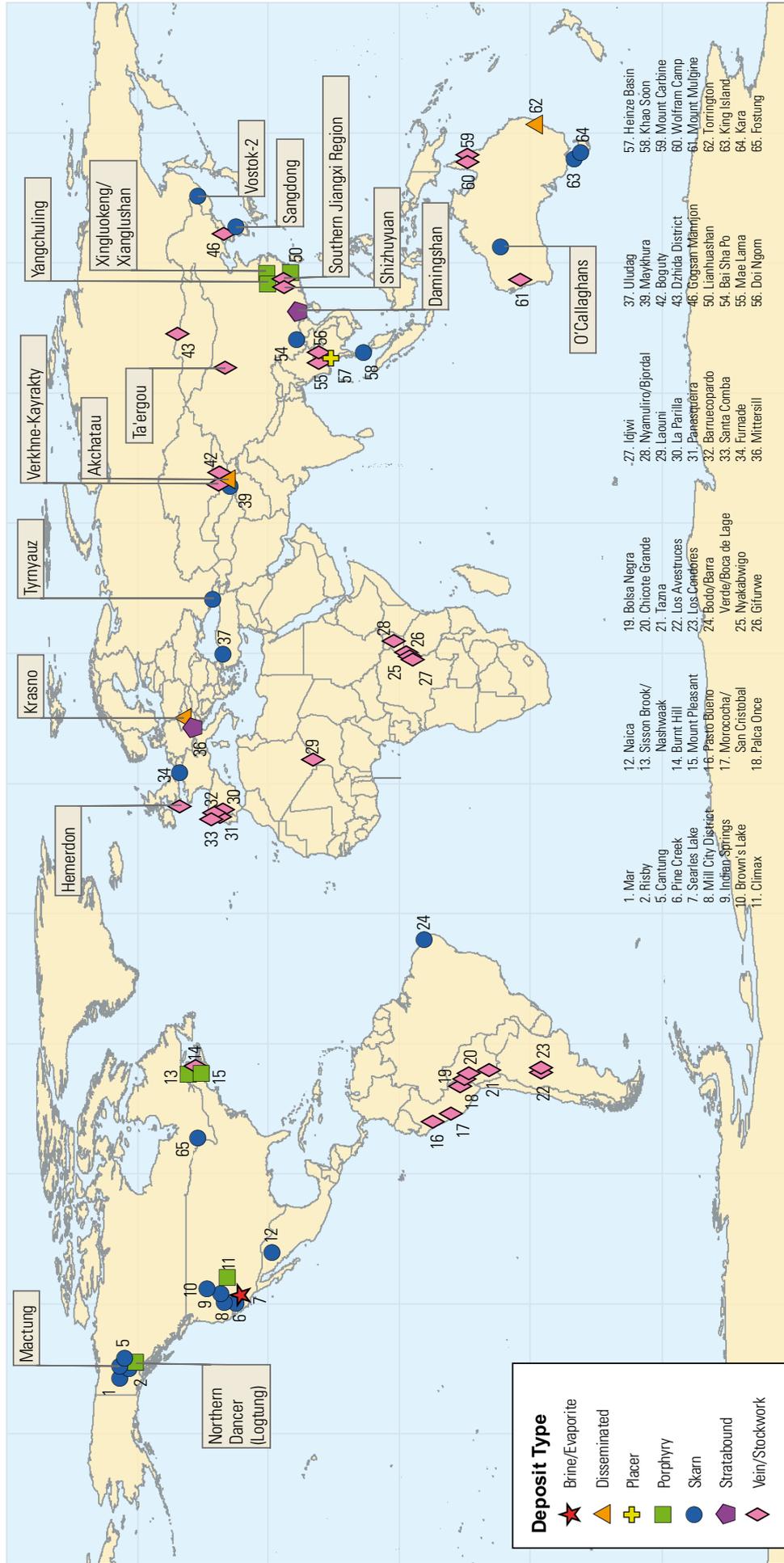


Figure 7 Location and type of major tungsten deposits and districts in the world (modified after Werner, et al, 1998). The largest deposits are named; the smaller ones are numbered according to the key at bottom right.

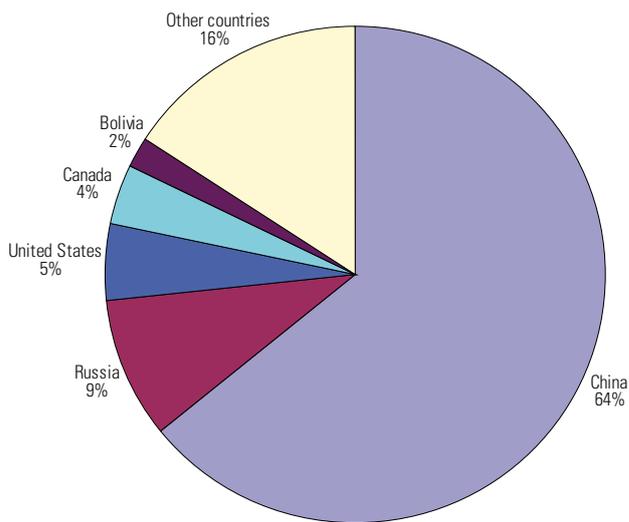


Figure 8 Global distribution of tungsten reserves, January 2010. Source: Shedd (USGS), 2010.

concentrate. The O’Callaghan’s deposit, with a resource of 59 million tonnes at a grade of 0.29 per cent tungsten trioxide, also contains zinc, copper and lead.

In addition to being the world’s largest producer, in recent years China has become the world’s largest tungsten consumer, accounting for an expected 37 per cent of the world’s total consumption in 2010 (CTIA, 2010a). To

conserve its resources the Chinese Government has introduced controls on tungsten production and, in particular, on exports of tungsten concentrates and APT. Rapid development of the automotive, machinery manufacturing, construction metals and communications industries has increased China’s domestic demand and the production limits have risen accordingly while export quotas have fallen. The extraction of tungsten ore in 2010 was officially limited to 66 480 tonnes, an increase of nearly ten per cent on the limit for 2009 (CTIA, 2010b). The province of Jiangxi was allocated the largest share of this extraction quota (44 per cent) with Hunan province the next largest (at 24.75 per cent). There are also severe restrictions on new licence applications for exploration and mining of tungsten at least until 30 June 2011. The hard alloy sector (e.g. tungsten carbide) accounts for 58 per cent of China’s tungsten consumption, with speciality steel alloys consuming an additional 22 per cent (CTIA, 2010a).

Tungsten industry

The structure of the tungsten industry comprises three principal sectors:

- **Primary tungsten producers** – the mines which extract the ore and perform primary mineral processing to produce tungsten mineral concentrates
- **Secondary tungsten processors** – the processing

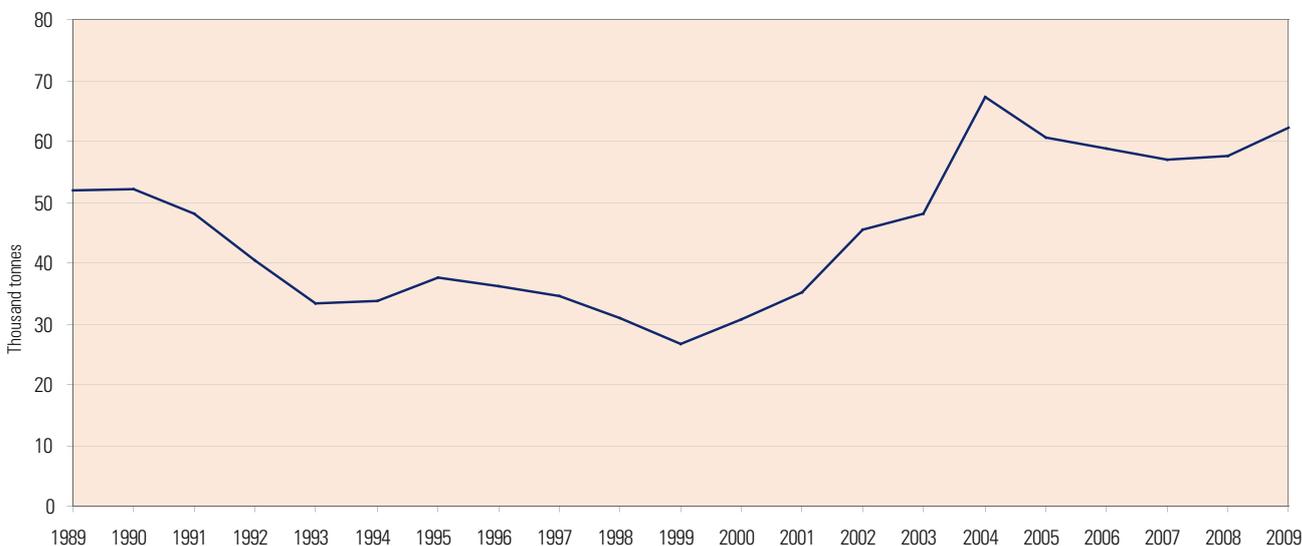
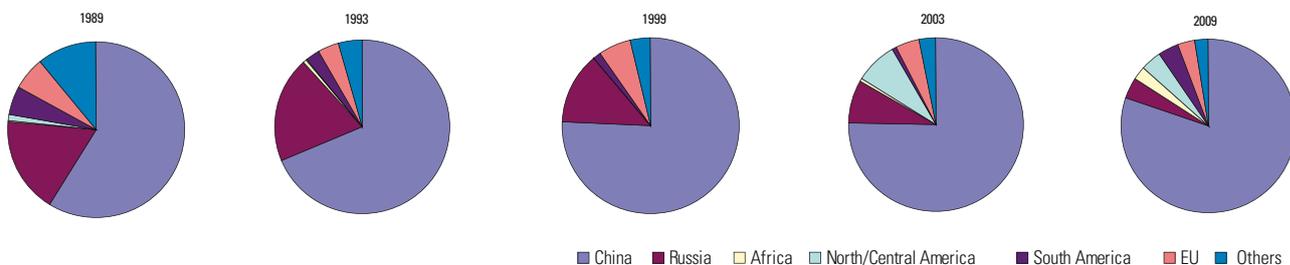


Figure 9 World production of tungsten between 1989 and 2009. Pie charts show the percentage extracted in selected countries and regions at five year intervals. Source: World Mineral Statistics database, British Geological Survey.

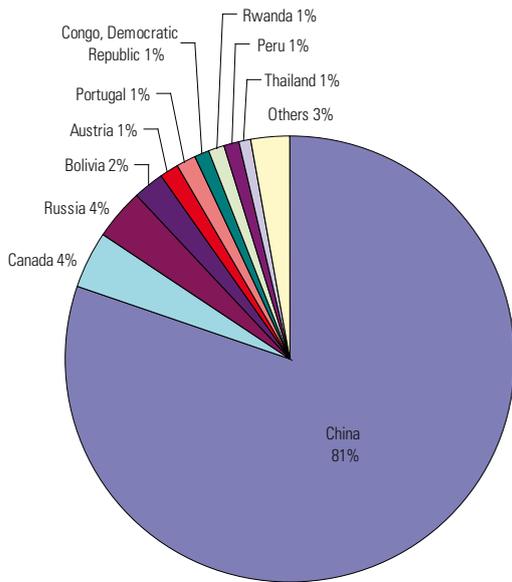


Figure 10 World production of tungsten in 2009. Source: World Mineral Statistics database, British Geological Survey

plants which use the mineral concentrates to produce a number of intermediate products, e.g. tungsten powders or ammonium paratungstate (APT), suitable for use in downstream metal and alloy manufacturing.

- **Tertiary tungsten product manufacturers** – the plants that use the intermediate products to produce finished tungsten metal and alloys or the tungsten end products such as machine tools or wear resistant components.

Whilst in the past there has been some vertical integration within the industry between secondary processing and tertiary manufacturing facilities, this rarely extended upstream to the primary producers. However, the expansion of demand for tungsten, particularly in China, has resulted in considerable vertical integration, either through common ownership or contractual arrangements, with a move away from exports of concentrates into downstream processing and manufacturing. This apparent desire to secure long term concentrate supply within China has resulted in various large Chinese companies investing in Western tungsten projects. This activity has also had a wider affect in the industry outside China, with a number of strategic mergers, acquisitions and investments within the Western tungsten industry in recent years.

World trade

Tungsten is traded in a variety of forms, chiefly as ores and concentrates, as intermediate products such as APT, and as tungsten oxide (or trioxide). Although China is by far the largest producer of tungsten ores and concentrates, it does not export much material in these forms, preferring to process the raw material into either APT or other products. The main exporting countries in 2008 are shown in Figure 11. China is, however, the largest importer of tungsten ores and concentrates, followed by the USA and Austria (Figure 12).

According to the China Tungsten Industry Association, China now accounts for about one third of the world's total

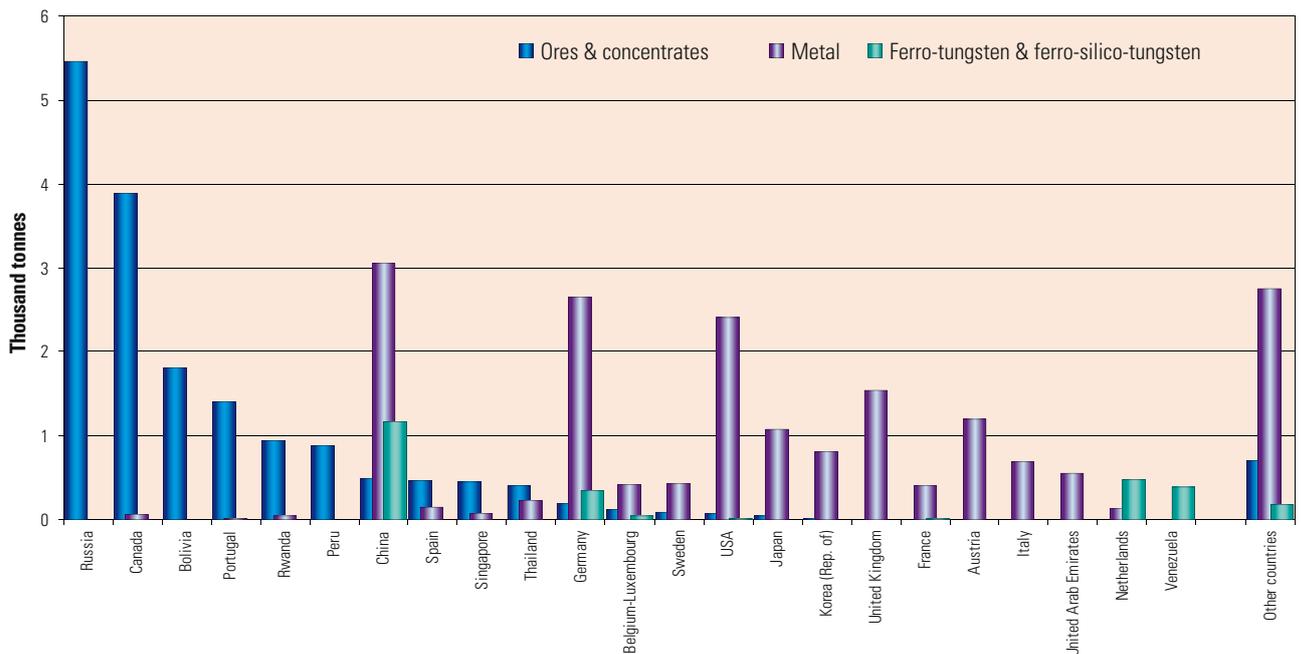


Figure 11 Top exporting countries of tungsten ores and concentrates, tungsten metal and ferro-tungsten in 2009. Countries exporting less than 300 tonnes are included in 'other countries'. Source: World Mineral Statistics database and UN comtrade database.

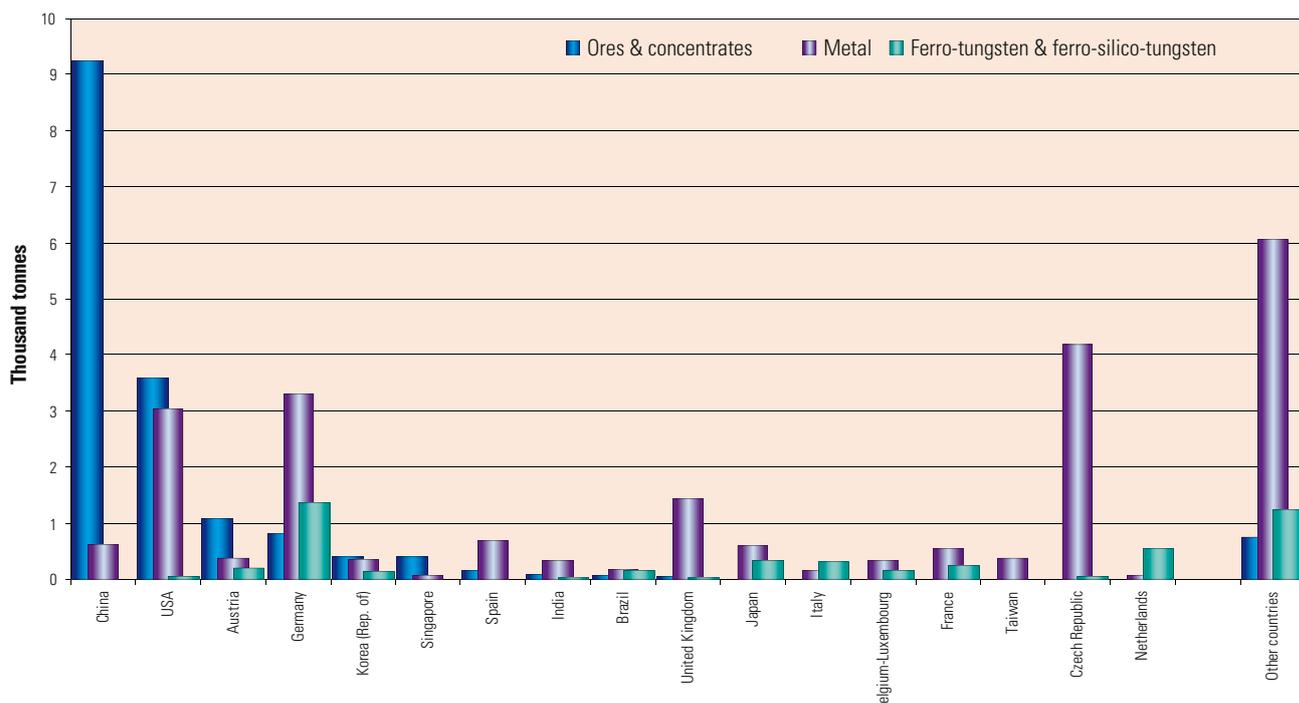


Figure 12 Top importing countries of tungsten ores and concentrates, tungsten metal and ferro-tungsten in 2009. Countries importing less than 300 tonnes are included in 'other countries'. Source: World Mineral Statistics database and UN comtrade database.

tungsten consumption and this is expected to increase further as their economy continues to develop. This increase in Chinese demand, combined with increased controls by the Chinese Government on their tungsten exports, has contributed to:

- i. an increase in the tungsten price of more than 300 per cent since 2004 (Figures 13, 14 and 15).
- ii. concerns over security of supply of tungsten concentrates to western processors and industry end users.

Due to its high economic importance, together with concerns over access to raw tungsten materials and uncertainty over the ability of Western producers to compete with China in the sale of tungsten products, the European Commission (EC) has identified tungsten as one of its 14 'critical' raw materials (EC, 2010). This means that they consider there to be a risk of supply shortage with an associated potential impact on the European Union economy. Strategies to reduce this risk are being considered. These include stockpiling of critical raw materials. Various countries, including China, USA, Japan and Russia, already have stockpiles of tungsten.

Prices

Prices for tungsten concentrates produced by mines, and the intermediate tungsten powders produced by the secondary processors, are quoted in terms of metric

tonne units (mtu). A metric tonne unit is the equivalent of 10 kilograms of contained tungsten trioxide. Ten kilograms of tungsten trioxide contains 7.93 kilograms of tungsten metal.

Tungsten is traded either on undisclosed supply contracts between the primary producers, secondary processors and tertiary manufacturers, or via traders, working both as agents and as principals. The Chinese price for APT is the benchmark in the tungsten market. This price, and those in Europe and the USA, is reported in trade publications such as Metal Bulletin (www.metalbulletin.com), Platts Metals Week (www.platts.com) and Fast Markets Ltd. (www.minormetals.com).

Tungsten prices for the main traded forms all show a similar trend with a very sharp increase during the latter part of 2004 through to the early part of 2006 (Figures 13, 14 and 15). Since then prices for ores and concentrates have generally stabilised, despite a drop at the end of 2008. Prices for APT and ferro-tungsten have been more volatile, with a notable decrease towards the end of 2008, in common with many other metal prices, caused by the global recession, followed by increases in the second half of 2009 and in 2010.

Overall prices for tungsten ore, APT and ferrotungsten more than doubled between 2004 and late 2010.

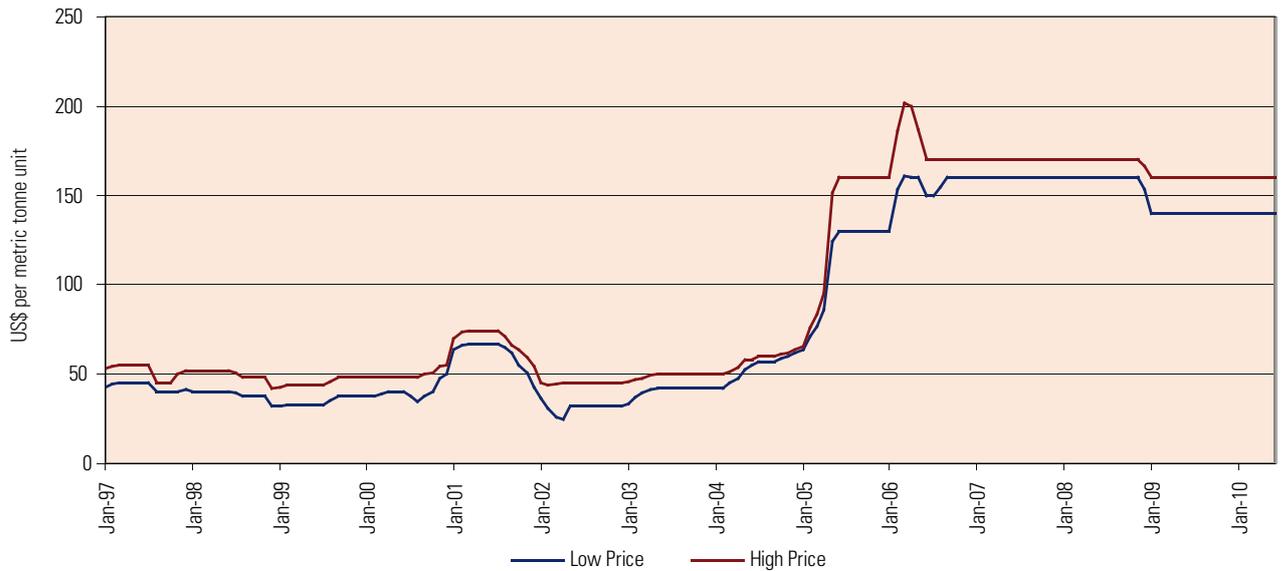


Figure 13 Tungsten ore prices: European minimum content WO_3 65% Cif Monthly average. (Source: Metal Bulletin)



Figure 14 Tungsten APT prices: Chinese (f.o.b. main Chinese ports). (Source: Metal Bulletin).



Figure 15 Ferro-tungsten prices: min. 75% W (f.o.b. main Chinese ports). (Source: Metal Bulletin)

Recycling and substitution

Tungsten and its alloys have a diverse range of commercial, industrial and military uses from electric lamp filaments and electrical contact points to high tech components of nuclear fusion reactors (e.g. plasma facing material) and ion drive motors in space probes. As the price has increased substantially in the last decade there are economic and environmental imperatives to use tungsten more efficiently, to seek substitutes for less demanding applications and to recycle it more effectively.

Recycling

Recycling is an important element of the world's tungsten supply and it is estimated that 35–40 per cent is recycled (EC, 2010). The tungsten processing industry is able to treat almost every kind of tungsten-containing scrap and waste to recover tungsten and, if present, other valuable constituents. In fact, recovery and reclamation rates during manufacturing operations are frequently in excess of 98 per cent.

Tungsten is among the most highly recycled commodity metals, eclipsing most major industrial metals such as iron, aluminium and tin, as well as more specialised metals such as tantalum, niobium, molybdenum and cobalt.

Old scrap

Old scrap, also referred to as end-of-life scrap, consists of tungsten-bearing products that are no longer being used. These include:

- cemented carbide parts
- tungsten metal and tungsten alloy parts
- old superalloy scrap
- tungsten-bearing catalysts

New scrap

This is generated during the processing of tungsten concentrates, scrap, and chemicals to make metal powder, carbide powder, or chemicals, and during the fabrication of tungsten products from these materials. In tungsten processing, recovery rates are high, and metal losses are kept to a minimum by internal recycling of the scrap generated. Losses from production have been estimated to be in the range of 2–6 per cent of the tungsten in raw materials consumed.

Alloy industries that produce parts by cast or wrought processes typically generate large quantities of new scrap. During the casting of corrosion-resistant alloys 40 to 60 per cent of the melt becomes new scrap, which is either recycled in-house or sold to be recycled elsewhere.

Unrecovered scrap

In various applications scrap tungsten is not recovered, either due to the lack of an efficient collection system or because it is not economic to recycle owing to contamination. Most uses of tungsten in chemical applications, except for catalysts, are dissipative. Tungsten is also lost in use due to wear of cemented carbide parts and hard-faced products, arc erosion of electrical contacts and electrodes, and the oxidation of alloys under high-temperature conditions.

Recycling methods

The tungsten industry uses a variety of recycling methods to optimise recovery and reduce costs. Metallurgical and hydrometallurgical techniques have the ability to treat all scrap types and remove impurities.

Contaminated cement carbide scrap, turnings, grindings and powder scrap can be oxidised and chemically processed to APT in a similar way to that used for the processing of tungsten ores (see Figure 3). If present, cobalt, tantalum and niobium are also recovered separately. Other tungsten-containing scrap might require a modified process (EC, 2010; Roskill, 2010).

Clean cemented carbide inserts and compacts are converted to powder by the zinc process, i.e. molten zinc forms an alloy with the contained cobalt which disrupts the integrity of the cemented carbide. The zinc is then removed by distillation, leaving a spongy material which is easily crushed. This material is added to new, ready-to-press tungsten powder. This process not only allows tungsten carbide to be recycled but also carbides of cobalt, tantalum and other metals (EC, 2010; Roskill, 2010).

Tungsten in high speed steel is frequently recycled, and a typical melt contains 60 to 70 per cent scrap, including internally generated scrap (EC, 2010; Roskill, 2010).

Substitutes

Because of the unique combination of properties of tungsten, there are limited options for substitution in many applications, especially where optimum performance is required at high temperatures. Unlike many other metals, there are no substitutes for tungsten that do not involve a considerable cost increase and compromise in product performance. In the aerospace and defence industries where product performance is paramount, substitution is generally avoided.

Potential substitutes for cemented tungsten carbides or hard metals include cemented carbides based on molybde-

num carbide and titanium carbide, ceramics, ceramic-metallic composites (cermets), diamond tools, and tool steels (EC, 2010). Potential substitutes for other applications are:

- molybdenum can replace tungsten in certain mill products;
- molybdenum steels can substitute for tungsten steels for some applications;
- lighting based on compact fluorescent lamps, low energy halogen light bulbs and light-emitting diodes (LEDs) are gradually replacing the traditional use of tungsten in light bulb filaments as inefficient incandescent light bulbs are being phased out;
- depleted uranium can be used in weights and counterweights instead of tungsten alloys or unalloyed tungsten, but generally it has been tungsten that has substituted for depleted uranium for health and environmental reasons;
- depleted uranium alloys can also be used in armour-piercing projectiles instead of cemented tungsten carbides or tungsten alloys.

Because of its perceived benign impacts on human and environmental health, tungsten alloys have been the preferred substitute for lead-based munitions since the mid-1990s. However, although the metal's toxicity is low compared with lead, there is some evidence that in certain forms tungsten may inhibit particular functions in some plant or animal species. Further research is required to evaluate the significance of these effects (Petkewich, 2009).

In some applications, substitution commonly results in a trade-off against the performance characteristics. For instance silver/tungsten composites are widely used in protective switchgear but are plagued by the formation of a high resistivity surface layer caused by the propensity of tungsten to oxidise. Composites of silver with diborides⁶¹ of zirconium, hafnium and titanium are more oxidation-resistant than tungsten but have a higher erosion rate.

Focus on Britain

Historical perspective

Mineral deposits that have been mined for tungsten in Britain are restricted to a few localities in south-west England (Cornubian batholith⁶²) and Cumbria (Lake District batholith). There are many deposits in the Cornubian orefield where it has been extracted as a by-product of tin and copper mining.

⁶¹ Diborides: compounds containing two atoms of boron.

⁶² Batholith: a large emplacement of igneous intrusive rock that forms from magma deep in the Earth's crust.

Prior to the late 19th century there was little demand for tungsten with only small amounts being used in the ceramic and glass industries. Ores of metals such as tungsten and zinc were discarded as waste. They were also components of complex ores that did not appear in the production records even when they made up a significant proportion of the ore at the time of mining. Until the mid 19th century removing wolframite from cassiterite involved heating the tin concentrate with sodium hydroxide to convert the wolframite to soluble sodium tungstate (named the Oxland Process) and by the end of the 19th century newly introduced magnetic separators made separation much easier. The value of tungsten for hardening steel was not understood until the late 1800s. It was first used as an additive (6–8 per cent tungsten) to steel in Sheffield in 1857 for cutting tools of various kinds.

As tin mining went into decline in Britain there was increasing focus on tungsten although it was also subject to fluctuating world market prices. Between 1859 and 1913 over 20 Cornish mines recorded sales of tungsten concentrates, dominated by East Pool, South Crofty, Carn Brea and Tincroft and Clitters United. Production of this high value by-product played an important role in mine finances. In 1898 the value of tungsten produced at Carn Brea and Tincroft accounted for 28 per cent of the total receipts. Similarly at South Crofty in 1907 tungsten accounted for over 20 per cent of the receipts and, together with arsenic, provided almost 40 per cent of total income (Mining History Network, 1996).

The outbreak of the First World War led to a significant increase in demand for tungsten alloys for munitions manufacture. World production of tungsten concentrates in 1913 was 7 837 tonnes, which was more than adequate to meet demand at the time. By 1916, however, this had increased dramatically to 19 845 tonnes (BGS, 1921). In 1918 the UK was producing about 20 000 tonnes of high speed steel which required 3 000 tonnes of metallic tungsten or its equivalent in ferrotungsten.

The military requirements for tungsten became even greater during World War 2 with the introduction of a tungsten carbide armour-piercing shell and for use in armour plate. Altogether tungsten was used in 15 000 different applications in World War 2 (Andrews, 1955). The US military requirement of tungsten during peak munitions production for World War 2 was approximately 13 600 tonnes of tungsten metal, more than twice that of Britain.

Immediately after World War 2, however, production of tungsten in the UK dropped significantly and in recent years has ceased altogether (Figure 16).

UK tungsten resources and production

South-west England

The Cornubian orefield in south-west England is by far the most important area in the UK for tungsten (Figure 17). The estimated total production of tungsten (as tungsten trioxide) from south-west England is 5 600 tonnes (after Dines, 1956; Alderton, 1993; Le Boutillier, 2002).

Historically there were six principal ore districts associated with major S-type granite plutons and satellite intrusions. From west to east these are (Figure 17):

1. Camborne-Redruth-St Day district associated with the Carnmenellis pluton together with the Carn Marth and Carn Brea intrusions
2. St Agnes district associated with the granite cusps of St Agnes and Cligga Head

3. St Austell district associated with the St Austell pluton and the satellitic intrusions of Belowda Beacon and Castle-an-Dinas
4. Bodmin Moor district associated with the Bodmin Moor pluton
5. Callington-Gunnislake district associated with the Kit Hill and Hingston Down granite intrusions
6. Tavistock district associated with the Dartmoor pluton and Hemerdon Ball intrusion

Camborne-Redruth-St Day district

A large number of tin and copper mines in the Camborne-Redruth-St Day area (Dolcoath, Carn Brea, Tincroft, East Pool and Agar, South Crofty, Peavor, Killyfretch, Wheal Busy and Wheal Gorland) produced tungsten as well as small amounts of other metals (see Table 6). The Camborne-Redruth lodes strike north-north-east and the St Day lodes strike east-north-east. The richest deposits of tungsten

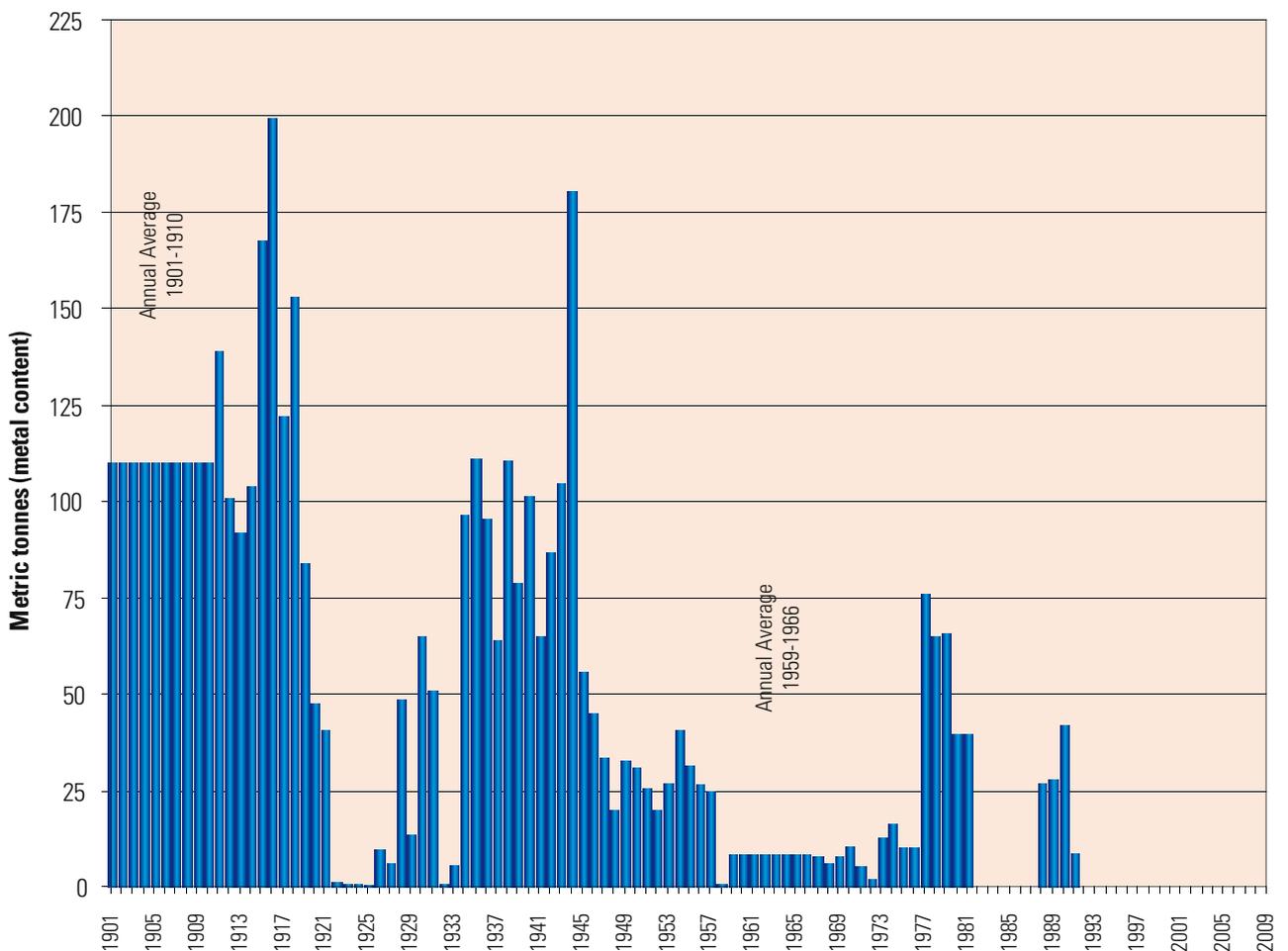


Figure 16 UK mine production of tungsten (metal content of concentrates), 1901–2009. Excludes production from tin streaming⁶³. All figures converted to metric tonnes. Annual average in the period 1901–1910 was 110 tonnes of contained tungsten. Total production in the period 1959–1966 was 68 tonnes of contained tungsten, which was all sold in 1966. Source: BGS, World Mineral Statistics dataset and Slater, 1973.

⁶³ Tin streaming: an early, small-scale method for recovering heavy minerals, including those containing tungsten, from alluvial deposits in stream beds by using the force of the flowing water to remove the lighter gangue material.

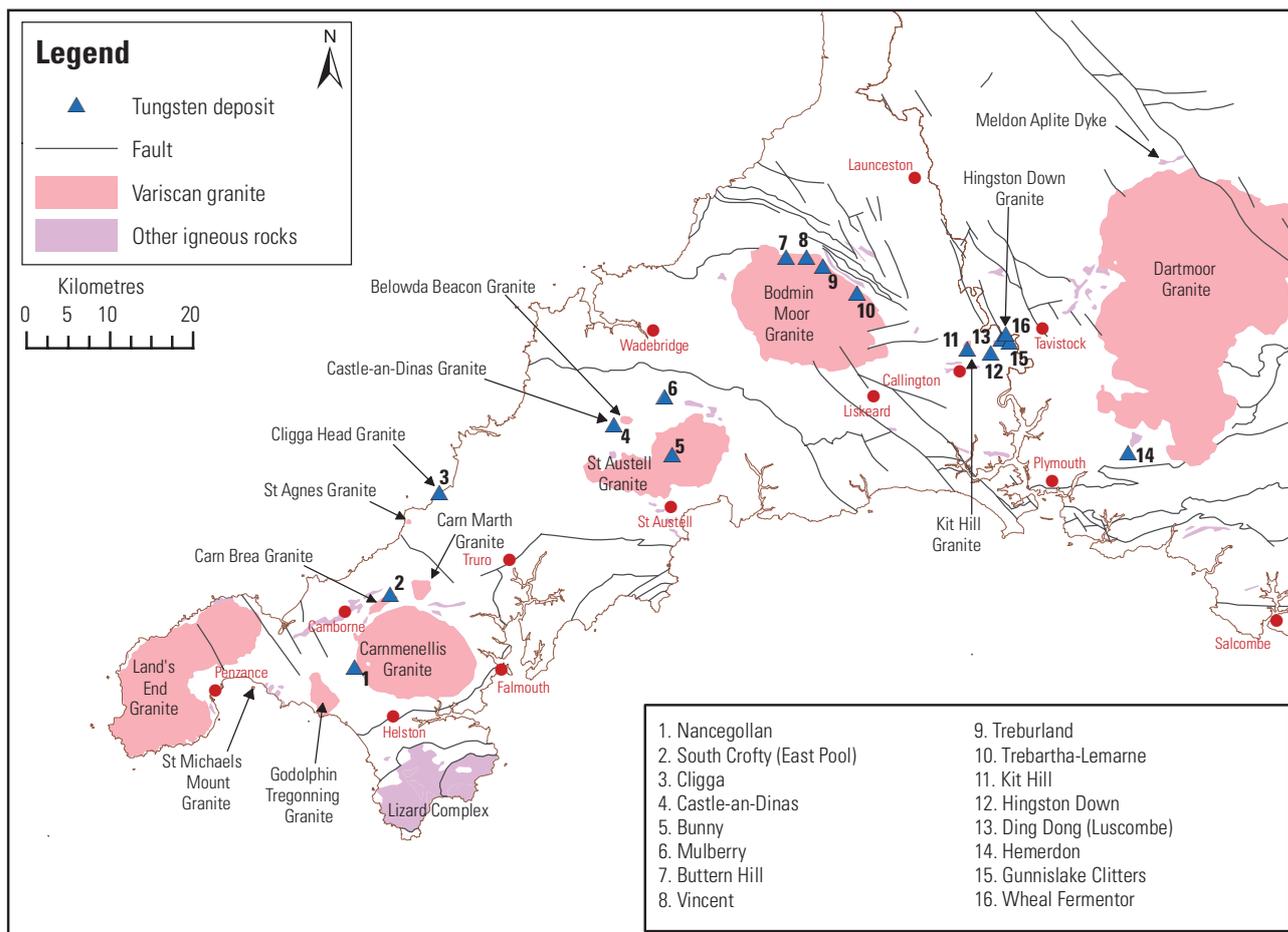


Figure 17 Location of deposits with recorded tungsten production in the Cornubian orefield of south-west England. BGS © NERC. OS topography © Crown Copyright. All rights reserved. BGS 100017897/2011.

were generally found within 15-20 metres of the granite contact and at depths of 275-365 metres below surface in lodes comprising stockworks of veinlets. These have yielded upwards of 135 kilograms of wolframite and cassiterite per tonne over stoping widths of as much as three metres. In the South Crofty Mine some wolframite was obtained from flat-lying pegmatitic lodes. In the East Pool section of the mine the north-dipping Roger's lode discovered in 1913 yielded values of 59 kilograms of mixed wolframite-cassiterite concentrate per tonne over a width of 1.2–1.8 metres. The tungsten zone near the top of the tin zone in the Great Lode in one place was reported to comprise massive wolframite 1.2 metres thick. At least six tin-tungsten lodes have been reported on the western side of the Carnmenellis granite in the old Nancegollan mine, which was abandoned in 1928.

St Agnes district

In the St Agnes district several attempts have been made to mine the tin-tungsten deposit at Cligga Head (see Table 6) where the partly kaolinised apex of a granite cusp is traversed by a swarm of narrow greisen-bordered

quartz veins grouped in three near vertical zones 6–12 metres wide averaging 5.5 kilograms per tonne of mixed wolframite-cassiterite. In 1941 the open-cast potential was evaluated but it was concluded that the grade was too low for economic extraction. Underground mining of the richer zones was carried out by Rhodesian Mines Trust Ltd between 1939 and 1945. Further investigations at the site were undertaken in the early 1960s by Geevor Mining Company and in the late 1970s by Wheal Concord Ltd. However both companies found mining to be uneconomic and no ore was extracted.

St Austell district

In the St Austell district tungsten occurs widely in lodes together with tin and other minerals. Mines with recorded outputs include Wheal Bunny (or Bunny), Great Beam (or Old Beam), Maudlin, Mulberry and Castle-an-Dinas. The Bunny Mine is reported to have produced nearly 100 tonnes of wolframite concentrate up to 1918. The Castle-an-Dinas deposit is the only lode in Cornwall to have been worked exclusively for tungsten and is described more on page 26.

Mine and mine district	Location (UK National Grid)	Main period of working	Production (tonnes)	Deposit style	Minerals	Other information
Carn Brea & Tincroft United Mine, Camborne-Redruth-St Day mining district	SW 670409	Worked for Cu from 1680s; changed to Sn in 1865; Closed in 1945	470000 t Cu & 53000 t Sn. 100.5 t W in the period 1914-16	ENE-striking lodes NW of Carn Brea stock. Includes Great Flat Lode (45° dip)	Wolframite-cassiterite-chalcocopyrite-bornite-quartz with arsenopyrite, tennantite, scorodite, fluorite, torbernite & 27 other minerals	Amalgamated in 1896 includes Tregajoran, Wheals Druid, Fanny & Barncoose mines; incorporated Cooks Kitchen mines in 1917. Sn and Cu to 200 metres depth
East Pool and Agar Mines, Camborne-Redruth-St Day mining district	SW 674415	Early 1700s to 1784 for Cu; 1834-1945 mainly Cu & Sn	92000 t Cu & 47000t Sn concentrates. W mined from 1860; 334t W in the period 1914-16	Nine ENE-striking lodes dipping N and S associated with the Carn Brea stock	Wolframite-cassiterite-chalcocopyrite-stannite with quartz, fluorite, tourmaline, arsenopyrite, loellingite, skutterudite, base metal sulphides & Cu secondaries	Amalgamated with Wheal Agar in 1897 to become EPAL and subsequently taken over by South Crofty. Now a World Heritage site.
South Crofty Mine, Camborne-Redruth-St Day mining district	SW 667413	1592-1873 mainly Cu; 1873-1998 mainly Sn (below 475 m)	37000 t Cu & 12000 t Sn to 1919; c.88000 t Sn 1919-1998. 306 t W in the period 1914-16; 50-150 t/y W from 1916 to 1956	32 x ENE-striking subvertical en echelon lodes / composite veins associated with Carn Brea stock	Wolframite-scheelite, quartz, tourmaline, cassiterite, bornite, chalcocopyrite, sphalerite, enargite, arsenopyrite, scorodite, gustavite, bismuthinite, native Bi, matildite, Cu/Bi and Pb, Bi, Ag sulphides, etc.	Amalgamation of 12 other mines incl. New Cook's Kitchen (1893), Dolcoath (1936), East Pool (1947). Mined over 40 lodes to a depth of 910 metres. Currently being re-evaluated by Western United Mines Ltd.
Wheal Gorland Mine, Camborne-Redruth-St Day mining district	SW 730427	1792-1864 and 1906-1911 Worked mainly for Cu with by-product Sn, W, As, F & some Au	40750 t Cu, 15 t Sn & 18 t As in the period 1815-1851; 164 t W & 18 t Sn for 1906-09; total 208 t @ 65% W to 1911	Seven ENE-striking lodes (dip N & S) on east side of Carn Marth granitic stock	Wolframite, cassiterite, quartz, arsenopyrite, cuprite, fluorite & 75 other minerals including Cu secondaries.	1852-1864 Part of the St Day United Group. It worked the same lode as Wheal Unity to the east.
Cligga Mine, St Agnes mining district	SW 738538	1938-1945	300 t W and 200 t Sn ore in the period 1940-44	Greisen-bordered ENE-striking sheeted vein and stockwork in Cligga Head granitic stock	Wolframite and cassiterite with quartz, arsenopyrite, scorodite, loellingite, a variety of Fe, Cu, Co, U, La-Ce arsenates, Cu-Sn sulphides & secondary Cu minerals	Workings reach a depth of 170 metres from surface. Operated by Rhodesian Mines Trust Limited 1939-45.
Gunnislake Clitters Mine, Callington mining district	SX 423723	1820-1919 Mainly Cu with Sn, As & W by-products	33310 t Cu & >510 t Sn. 564 t W in the period 1903-09	Six fissure veins / lodes associated with the Kit Hill stock	Wolframite-ferberite, various Cu minerals, bismuthinite, cassiterite, galena, pyrite, tetrahedrite, fluorite, quartz, metatorbernite, etc.	Intermittent working; main periods 1820-27, 1860-90, 1902-09, 1914-20. During WW1 it also processed W ore from East Kit Hill and Hingston Down. Uranium not worked.

Table 6 Details of the tin and/or copper mines in south-west England that have also recorded significant tungsten production. Abbreviations:

Cu=copper, Sn=tin, As=arsenic, W=tungsten, Bi=bismuth, Pb=lead, Ag=silver, Fe=iron, Co=cobalt, U=uranium, La=lanthanum, Ce=cerium, F=fluorine, Au=gold

WW1 = First World War, t/y = tonnes per year, ENE = east-north-east, N=north, NW = north-west

Adapted from: Slater (1973); Burt et al (1987); Rastall & Wilcockson (1920); Cornish Mining (2010)

Castle-an-Dinas wolfram mine

The Castle-an-Dinas mine (SW 946623), at St Columb Major, was Cornwall's premier tungsten producer and historically one of only two mines in Britain where tungsten was the sole product. The deposit was discovered in 1915 and mined from 1916 to 1958. Output fluctuated until 1934 and thereafter mine production steadied at 180 to 260 tonnes (average 200 tonnes) of concentrates per annum until its closure. Overall recovery was reported to have been about 75 per cent to produce 13.4 kilograms of wolframite concentrate (60 per cent tungsten trioxide) per tonne of ore. The grade of the ore was, therefore, about 1.1 per cent tungsten trioxide.

The tungsten-bearing lodes occur within the Castle-an-Dinas topaz-bearing granite stock to the north-west of the main St Austell granite (285 Ma). The present level of exposure is close to the original roof of the pluton. The country rocks comprise grey slates with interbedded calc-silicate rocks intruded by late rhyolitic dykes and hydrothermal tourmalinite breccias. The mineralisation comprises greisen-bordered vein swarms with variable amounts of tourmalinisation, phyllic and argillic alteration. The tin-tungsten lodes and sheeted vein systems in the North St Austell area have a predominant north-east strike. The Castle-an-Dinas wolfram lode, by contrast, strikes approximately north-south which is more typical of the trend of late-stage, low temperature lead, zinc, silver, nickel, cobalt, uranium, iron and manganese mineralised structures. The wolfram lode, which can be traced over a strike length of 2.8 kilometres, is near vertical and varies from 0.3 to 2.0 metres in width (average 0.9 metre) averaging 0.8 per cent tungsten trioxide. It has been worked over a length of 550 metres. The principal ore mineral is wolframite which occurs with quartz, cassiterite and small amounts of sulphides and arsenides. It is the type locality for russelite (Bi_2WO_6).

The mine was developed on eight levels to a depth of 160 metres below the hilltop and first encountered granite in the floor of the second level. Most economic ore was obtained within 200 metres of the granite contact. On this basis the ore potential south of the old workings was estimated at about 1100 tonnes of recoverable tungsten over a 250 metre-long block assuming an extraction width of 1.5 metres, an average grade of 0.7 per cent tungsten trioxide and a recovery of 75 per cent. To the north the strike length of possible mineralisation is less predictable but the granite contact is gently sloping and if economic mineralisation was to persist above this contact then the potential could be considerable i.e. c. 440 tonnes of tungsten per 100 metres of strike. This could extend for up

to 1100 metres from the northernmost workings to a calc-silicate belt (Beer et al., 1986; Brooks, 2001).

Bodmin Moor district

Bodmin Moor was renowned for its eluvial and alluvial placer deposits above the 230-metre contour. Alluvial deposits occurring in this area are reported to have been up to 4.5 metres thick and to contain 57 000 m³ grading between 1.2 and 3.0 kilograms per cubic metre of mixed cassiterite and wolframite.

Tungsten-bearing lodes were also worked at Treburland, Halvana, Gazeland and Wheal Vincent mines. At Wheal Vincent near Altarnun tungsten mineralisation also occurred in pegmatite. Five lodes were recorded: the principal one, the Horseburrow Lode, was 1.2 metres wide and rich in tungsten. Wolframite was regarded as a contaminant of the tin ore during operations in the period 1881–1892, but the mine reopened to work both tin and tungsten in 1912 and is reported to have produced about 75 tonnes of wolframite annually before closing in 1920. Another small producer was Hawk's Wood Mine, operated by the Pena Copper Co., which closed in 1958.

At Halvana, also near Altarnun, quartz stringers carrying sporadic tungsten values were worked to produce some 8.5 tonnes of wolframite between 1916 and 1917. At Treburland Mine, located to the south-south-east of Altarnun, two lodes carried wolframite (18.1 kilograms per tonne) associated with cassiterite and arsenopyrite and yielded a little wolframite as a by-product of tin during the two World Wars. Wolframite occurs on the spoil heaps at the Trebartha Lemarne Mine. At Buttern Hill on Bodmin Moor thin alluvial and eluvial deposits over a wide area are variously reported to have contained up to seven kilograms per cubic metre of cassiterite and wolframite. Several tin-tungsten lodes are also known to occur in this area but values appear highly variable.

Callington-Gunnislake district

In the Callington-Gunnislake district of the Tamar Valley tungsten-bearing ores have been mined near Kit Hill and Hingston Downs. Mines east of Callington, e.g. Kit Hill United, produced over 100 tonnes of wolframite at the beginning of the 20th century. In this area wolframite is widely distributed in tin lodes, veinlets and greisenised granite, but values are sporadic and nowhere are true stockworks known to be developed.

The lodes in the neighbouring Gunnislake area, notably Hingston Down, were first worked for copper but later

mined for tin and tungsten and produced about 600 tonnes of wolframite concentrates until working ceased in 1917. The most renowned was the Gunnislake Clitters Mines which produced appreciable amounts of tungsten (see Table 6). The lodes averaged 1–17 per cent of tin and tungsten minerals. At Frementor Mine a lode worked during the First World War is reported to have produced over 11 000 tonnes of ore grading 6.25 kilograms cassiterite and 1.8 kilograms wolframite per tonne but attempts to restart the mine between 1925 and 1929 were unsuccessful. The Ding Dong Mine, which was investigated by the Non-ferrous Minerals Development Ltd between 1942 and 1944, reported values of one per cent combined cassiterite and wolframite in the ratio 2:3.

Other mines in this district, including Hawkmoor, Bedford United and Drakewalls, were primarily tin and copper producers but sold some by-product wolframite.

Tavistock district

In the Tavistock district the greisenised tin-tungsten vein stockwork occurring within the granite boss at Hemerdon is the only significant wolframite prospect near the Dartmoor pluton. Hemerdon was worked briefly for tungsten during both the First and Second World Wars and still has substantial tin-tungsten reserves — see below.

Hemerdon (Hemerdon Ball or Hemerdon Bal) wolframite mine

Hemerdon is one of the largest tungsten and tin resources in the western world. It is located 11 kilometres north-east of Plymouth, near Plympton in Devon adjacent to the existing china clay operations of Sibelco and Imerys.

The tungsten-tin deposit is a stockwork and sheeted greisen vein system hosted in the Hemerdon Ball Granite, a satellite cupola intrusion of the Dartmoor granite pluton, forming a dyke-like granite body some 1200 metres long and dipping steeply eastwards surrounded by Devonian slates. The southern and western areas of the granitoid body are only slightly altered but the north-north-east part is highly kaolinised and greisenised. The mineralised area extends for some 600 x 400 metres within the granite although the greisenisation and sparse tungsten-tin veins extend into the metasedimentary rocks.

Two vein types occur with three different orientations: quartz and/or feldspar veins without greisen borders that form a stockwork with minor mineralisation; and tungsten-tin-arsenic-mineralised, greisen-bordered, sheeted veins in sub-parallel sets. The main mineralisation comprises wolframite(-ferberite) with arsenopyrite and minor cas-

siterite. The main gangue minerals are quartz and tourmaline. The mineralisation begins at surface and extends to depths of at least 400 metres.

Due to supergene weathering by meteoric waters the arsenopyrite has been oxidised and the iron and arsenic remobilised to form the secondary arsenate minerals, scorodite and pharmacosiderite, in the upper part of the resource. A variety of secondary copper and tungsten minerals is also present. The locality is renowned for its high quality scorodite specimens. Pharmacosiderite, cassiterite and wolframite of specimen quality have also been recovered from the mine. The argillic alteration (kaolinisation) extends to a depth of up to 50 metres in the granitic body.

Discovery and early mining history 1867-1959

The Hemerdon tungsten-tin deposit was discovered in 1867. In 1916, due to war-associated tungsten shortages, an exploration and development programme outlined a tin-tungsten stockwork suitable for opencast extraction. In 1917, Hemerdon Mines Ltd constructed a 140 000 tonne per year mill, and shortly afterwards opencast mining operations began. The mine operated in 1918–1919, during which time it processed 16 000 tonnes of ore. When the British government stopped accepting tungsten ores under the war pricing scheme the mine was forced to close. In 1934 increased tungsten prices led to renewed prospecting of the deposit by the British Mining Corporation, along with metallurgical testwork. The deposit was investigated by shafts and crosscuts to a depth of 18 metres.

Further shortages of tungsten at the outset of World War 2 led to Hemerdon Wolfram Ltd constructing a 90 000 tonne per year mill with 55 per cent tungsten recovery, which began operation in 1941. The government took over the mine in 1942. A resource of 2.5 million tonnes at 0.14 per cent tungsten trioxide in addition to tin was outlined, and a new plant was commissioned in October 1943 with an enlarged capacity. The larger mill, beset by problems arising from a hasty design and the use of unskilled labour, operated for only 71 per cent of available time at well below design capacity. Ore output from a mixture of underground and open pit mining was documented as over 205 000 tonnes, with a resulting 184 tonnes of tin and tungsten concentrate during the period of government operation. The average yield was about 0.59 kilograms of 65 per cent tungsten trioxide concentrates and 0.14 kilograms of 65 per cent tin concentrates per tonne. Operations ceased in June 1944 when access to overseas supplies was restored and the plant was sold off in 1959.



Figure 18 Part of the Hemerdon site, BGS©NERC.

Exploration and development 1960–2006

Work on the prospect recommenced in the mid 1960s. By the early 1970s British Tungsten Ltd had outlined a resource of 5.6 million tonnes of ore. In 1976, the lease was transferred to a new company—Hemerdon Mining and Smelting Ltd (HMSL). In the autumn of 1977, the major American mining company, AMAX and HMSL signed a joint venture agreement. An extensive exploration programme costing in excess of US\$10 million was completed between October 1977 and 1980. Over 14 000 metres of diamond drilling was carried out, outlining a resource of over 49.6 million tonnes at 0.17 per cent tungsten trioxide and 0.025 per cent tin to a depth of some 200 metres with mineralisation continuing down to approximately 400 metres.

AMAX developed a 260 metre decline through the ore body in 1980 to determine continuity of the deposit and to recover 6670 tonnes of bulk samples. These were processed in a pilot plant to determine metallurgical recoveries (about 65 per cent) and establish a preferred process route (Wolf, 2010). A comprehensive feasibility study was completed in 1981.

The final revision of the mining feasibility study in 1982 concluded that, within a global resource of 73 million

tonnes of ore, at grades of 0.143 per cent tungsten trioxide and 0.026 per cent tin, there was an in-pit reserve of 38 million tonnes, at grades of 0.183 per cent tungsten trioxide and 0.029 per cent tin. The overall pit dimensions planned by AMAX were 800 metres in length, 450 metres in width and 230 metres in depth.

The venture was joined by Billiton Minerals Ltd, providing further finance and expertise, and forming a consortium that planned to commence production in 1986. The initial planning application made in 1981 was refused in 1984 resulting in Billiton Minerals Ltd pulling out of the consortium. Hemerdon Mining and Smelting Ltd also sold their 50 per cent stake in the project to AMAX.

Planning permission for mining was obtained in June 1986 but by then a collapse in both tin and tungsten prices had damaged the economic feasibility of the mine. Its tungsten assets were passed to Canada Tungsten Ltd in 1986 and then purchased by North American Tungsten PLC in 1997. With the continuing depressed tungsten prices assets of the Hemerdon prospect were disposed of in 2003.

Recent developments and feasibility studies

A five-fold increase of the APT price has resulted in

increased tungsten mining exploration and development globally since 2005.

On 4th December 2007 Wolf Minerals (UK) Ltd - owned by Australian-based Wolf Minerals Limited acquired the rights to mine the deposit, and current plans are to open a surface mine for tungsten and tin, producing up to 3000 tonnes of tungsten metal per year over the next 15–19 years. As such it will be the only tungsten and tin mine in the country, and Wolf Minerals claims that it could meet the UK's entire needs for many years (Wolf, 2010).

A JORC-compliant inferred resource was prepared by SRK Consulting (Australasia) Pty Ltd in August 2007 by re-logging and re-sampling 20 per cent of the historical drilling core and comparing it to the original drilling data. This resulted in an inferred resource of 82 million tonnes at 0.22 per cent tungsten trioxide and 0.022 per cent tin. This resource was 'inferred' due to the historical nature of the original data.

A confirmatory drilling programme of six diamond drill holes was completed by Wolf in October 2008 with a total of 1064 metres drilled. Combined with the 303 drill holes totalling 21 846 metres of drilling conducted by AMAX this enabled an inferred and indicated JORC-compliant resource to be delineated amounting to 97.4 million tonnes at 0.22 per cent tungsten trioxide, with 0.022 per cent tin. This represents a total of 21.3 million mtus (metric tonne units) of tungsten trioxide.

This resource estimate was further updated by SRK Consulting in June 2010. Revised geological modelling gave a total resource of 318 800 tonnes of tungsten metal, an increase of 83 per cent compared with the November 2008 figure. The measured, indicated and inferred resources are given in Table 7 at a cut-off of 0.08 per cent tungsten for a total of 39 million mtus of tungsten trioxide and 44 000 tonnes of tin metal. This revision confirms the project's position as one of the largest tungsten deposits in the world.

The definitive feasibility study is expected to be completed in early 2011 and it is planned that mining operations could commence in 2013. Development of Hemerdon mine will result in the formation of an open pit about 850 metres long by 540 metres wide and 200 metres deep. The existing planning permission remains valid until 2021.

North-west England

Carrock wolfram mine, Lake District, Cumbria

Carrock Wolfram mine is the only site in the UK outside Devon and Cornwall where tungsten ores have been worked. Carrock Mine (NY327327) is situated in the valley of Grainsgill Beck, a tributary of the River Caldew at Carrock Fell on the north-eastern side of the Skiddaw massif in the northern Lake District. The main part of the mine lies beneath Carrock Fell.

The tungsten mineralisation is associated with the Grainsgill Granite cupola, the northernmost of three small exposures of the otherwise concealed Late Caledonian Skiddaw Granite. Three principal wolframite-scheelite-bearing quartz veins strike approximately north–south across the granite and surrounding hornfelsed metapelites of the Skiddaw Group and gabbros of the Carrock Fell Complex. The Skiddaw intrusion is an I-type granite which is extensively greisenised in the northern part of its outcrop. The intrusion is a steep-sided dome with its long axis approximately north–south. The greisen-bordered veins are typically up to 0.5 metre in thickness in the granite but in the gabbro, where most of the ore extraction has taken place, they are wider and enclose screens of wallrock or divide into sets of thinner veins.

The quartz veins contain local pockets of wolframite, scheelite, arsenopyrite, pyrite, pyrrhotite, sphalerite and ankerite along with accessory molybdenite, chalcocopyrite, bismuthinite, apatite, carbonates, fluorite, and musco-

Resource Category	Ore Tonnage (Mt)	Sn grade (%)	WO ₃ grade (%)	W grade (%)	Contained Sn (tonnes)	Contained W (tonnes)
Measured	48.53	0.024	0.19	0.15	9700	72800
Indicated	22.39	0.023	0.18	0.143	4500	40300
Inferred	147.61	0.02	0.18	0.143	29500	206700
TOTAL	218.53	0.02	0.18	0.143	43700	318800

Table 7 Hemerdon JORC revised global resource estimate completed by SRK Consulting in June 2010 (Wolf, 2010). Abbreviations: Sn=tin, WO₃=tungsten trioxide, W=tungsten.



Figure 19 Carrock Fell Mine—the Smith Vein shows sharp contacts against the gabbro country rock. It consists mainly of white quartz but pockets of brown scheelite occur near the footwall (left of picture) and in the centre of the vein (above person). Black blades and patches in the vein are wolframite and iron-rich sphalerite. BGS@NERC.

vite (Hitchen, 1934; Ewart, 1962; Shepherd et al., 1976; Young, 1987). Despite variable mineral proportions, all the veins have a similar paragenesis with a wolframite-scheelite-apatite assemblage that pre-dates scheelite-arsenopyrite-pyrite-base metal sulphide assemblages (Hitchen, 1934; Shepherd et al., 1976; Ball et al., 1985). Narrow east-west cross-course veins carrying quartz, ankerite, galena and sphalerite slightly displace the tungsten-bearing veins.

Mining on the site dates back to the 1854 when the lead ore, galena, was extracted. At that time the wolframite was dismissed as worthless but by the turn of the twentieth century wolfram mining was becoming a worthwhile venture. The deposit was worked sporadically by a series of adits driven north and south into the valley with the main haulage level at 340 metres elevation.

The first major period of activity followed the formation of the Carrock Mining Syndicate in 1913. The work was partly government financed and almost 14 000 tonnes of ore

were mined of which 10 116 tonnes were milled on site to produce almost 200 tonnes of tungsten concentrate for use in the armaments industry, at an average grade of 1.29 per cent tungsten trioxide. By late 1918 the underground workings were closed down.

Interest in the mine revived during both World War Two and the Korean War when supplies of tungsten were threatened, but despite exploratory work no ore was produced. In 1943 estimated reserves amounted to at least 50 000 tonnes at one per cent tungsten trioxide.

A UK subsidiary of World Wide Energy Co Ltd of Calgary carried out pre-production trials in 1972. The mine then remained idle until 1977 when soaring world tungsten prices led to its reopening as the Carrock Fell Tungsten Mine which was producing 16 000 tonnes of ore annually until the market collapsed once again in 1981 leading to its final closure. Although the Harding Vein, the most productive part of the mine, has been worked out significant reserves of tungsten ores are believed to remain.

Tungsten occurrences associated with other late Caledonian granites in the UK

In the Lake District occurrences of tungsten mineralisation have been recorded in the Shap granite (NY 558 084: Firman, 1978) and on the south-eastern margin of the Eskdale granite-granodiorite intrusion at Buckbarrow Beck on Corney Fell (SE 1366 9097: Young et al., 1986). The tungsten-bearing veins in the granodiorite at Buckbarrow Beck mainly comprise quartz-scheelite-chalcopyrite with minor ferberite and pyrite. Supergene minerals include russellite, cuprotungstite, bismutoferrite and copper secondaries. This tungsten mineralisation and the arsenic-molybdenum-bismuth-fluorine mineralisation at Water Crag are thought to be genetically related to the late stages of emplacement of the Eskdale Granite. Wolframite and scheelite have been found in panned concentrates from the southern Lake District though the source has not been defined (Cameron et al., 1993).

Scotland

Wolframite and scheelite occur in trace quantities associated with molybdenite mineralisation around a small granite near Inverurie in north-east Scotland (Colman et al., 1989) and in the Etive complex in western Scotland (Haslam and Cameron, 1985). Tin-tungsten bearing quartz-fluorite veins carrying cassiterite, huebnerite and some scheelite are reported from the Cairngorms. Zoned niobium- and tantalum-rich wolframite is also reported from a quartz-wolframite-(cassiterite) vein and wallrock in a zinnwaldite-bearing granite that forms part of the Glen Gairn complex in the eastern Highlands (Tindle and Webb, 1989).

References

- Alderton, D H M. 1993. Mineralisation associated with the Cornubian Granite Batholith. In: Patrick, R A D. & Polya, D A. (Eds.) *Mineralisation in the British Isles*. Chapman and Hall. London.
- Andrews, M G. 1955. *Tungsten—The story of an indispensable metal*. Published by the Tungsten Institute, Washington DC, USA. Available from Midwest Tungsten Service, properties page at: <http://www.tungsten.com/mtstung.html>
- Ball, T K, Fortey, N J and Shepherd, T J. 1985. Mineralisation at the Carrock Fell Tungsten Mine, N England: Paragenetic fluid inclusion and geochemical study. *Mineralium Deposita*, 20, 57–65. Available at: <http://www.springer-link.com/content/k810016v14883624/>
- Beer, K E, Ball, T K and Bennett, M J. 1986. Mineral investigations near Bodmin, Cornwall. Part 5 The Castle-an-Dinas wolfram lode. Mineral Reconnaissance Programme Report No. 83. British Geological Survey, Keyworth, Nottingham. Available from: <http://nora.nerc.ac.uk/view/division/bgs/1986.html>
- British Geological Survey (BGS). 1921. *The Mineral Industry of the British Empire and Foreign Countries. Statistical Summary 1913–1920*. Imperial Mineral Resources Bureau, London. Data now held in the archive of the British Geological Survey, Keyworth, Nottingham.
- British Geological Survey (BGS). 2010. World Mineral Statistics dataset. British Geological Survey, Keyworth, Nottingham. Information available from: <http://www.bgs.ac.uk/mineralsuk/statistics/home.html>
- Brooks, T. 2001. *Castle-an-Dinas 1916–1957: Cornwall's Premier Wolfram Mine with brief comparative histories of other wolfram mines in Cornwall and West Devon*. Cornish Hillside Publications, St Austell, Cornwall. Available at: <http://www.cornwall-calling.co.uk/mines/>
- Burt, R, Waite, P and Burnley R. 1987. *Cornish Mines: Metalliferous and Associated Minerals 1845–1913*. Mineral Statistics of the UK 1845-1913.
- Cameron, D G, Cooper, D C, Johnson, E W, Roberts, P D, Cornwell, J D, Bland, D J and Nancarrow, P H A. 1993. Mineralisation in the Lower Palaeozoic rocks of south-west Cumbria, Part 1: regional surveys. British Geological Survey Technical Report WF/93/4 (BGS Mineral Reconnaissance Programme Report 128). Available from: <http://www.bgs.ac.uk/mineralsuk/exploration/potential/mrp.html>
- China Tungsten Industry Association (CTIA). 2010a. *China's Tungsten Demand to Rise Eight Percent this Year*. Available online at: <http://www.ctia.com.cn/TungstenNews/2010/44321.html>
- China Tungsten Industry Association (CTIA). 2010b. *Output of Tungsten Ore Extraction in China, 2010*. Ministry of Land and Resources Issued the Output of Year 2010 Tungsten Ore Extraction Quantity Control. Available online at: <http://www.ctia.com.cn/TungstenNews/2010/32663.html>
- Colman, T B, Beer, K E, Cameron, D G and Kimbell, G S. 1989. Molybdenum mineralisation near Chapel of Garioch, Inverurie, Aberdeenshire. British Geological Survey Technical Report WF/89/3 (BGS Mineral Reconnaissance Programme Report 100). Available from: <http://www.bgs.ac.uk/mineralsuk/exploration/potential/mrp.html>

Cornish Mining World Heritage. 2010. The World Heritage Site Areas. Available at: <http://www.cornish-mining.org.uk/sites/sites.htm>

Cox, D P and Singer, D A. (eds.). 1986. Mineral deposit models: United States Geological Survey Bulletin 1693, 379p. Available from: <http://pubs.usgs.gov/bul/b1693/>

Dines, H G. 1956. The Metalliferous Mining Region of SW England, HMSO, 689p.

Elliot, J E, Kamilli, R J, Miller, W R and Livo, K E. 1986. Vein and Greisen Sn and W Deposits. (Models 15a-c: Cox and Bagby, 1986; Reed, 1986a, b). In: D P Cox and D A Singer (eds.) Mineral Deposits models: U.S. Geological Survey Bulletin 1693, p62–69. Available from: <http://pubs.usgs.gov/bul/b1693/>

European Commission (EC), 2010. Critical raw materials for the EU. Report of the Ad-hoc Working Group on defining critical raw materials. European Commission Enterprise and Industry. Available from: http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm

Ewart, A. 1962. Hydrothermal alteration in the Carrock Fell area, Cumberland, England. *Geol. Mag.*, 99, 1–8. Available from: <http://journals.cambridge.org/action/displayAbstract?fromPage=online&aid=4624932>

Firman, R J. 1978. Intrusions. In: F Moseley, (ed.) *The Geology of the Lake District*, p146–167. Yorkshire Geological Society, Leeds.

Guilbert J M and Park, C F Jr. 1986. *The Geology of Ore Deposits*. Waveland press Inc., 985p.

Haslam, H W and Cameron, D G. 1985. Disseminated molybdenum mineralisation in the Eive plutonic complex in the western Highlands of Scotland. BGS Mineral Reconnaissance Programme Report 76. 38p. Available from: <http://www.bgs.ac.uk/mineralsuk/exploration/potential/mrp.html>

Hinde, C. (ed.). 2008. Tungsten. *Mining Journal Special Publication* (June 2008). pp16. Available at: http://www.mining-journal.com/__data/assets/supplement_file_attachment/0014/123314/Tungsten-scr.pdf

Hitchen, C S. 1934. The Skiddaw Granite and its residual products. *Quarterly Journal of the Geological Society of London*, 90, 158–200.

Hosking, K F G. 1964. Permo-Carboniferous and later mineralisation of Cornwall and south-west Devon. In: K F G Hosking and G J Shrimpton (eds.) *Present views of some aspects of the geology of Cornwall and Devon*. p201–245.

International Tungsten Industry Association (ITIA). 2010. Web pages on 'About tungsten', 'Tungsten products' and 'Tungsten uses'. Available at: <http://www.itia.info/Default.asp>

Lassner, E and Schubert, W-D. 1999. Tungsten: properties, chemistry, technology of the element, alloys and chemical compounds. Kluwer Academic/Plenum Publ. New York, 422p

Le Boutillier, N. 2002. Mineralisation in Cornwall – The Cornubian orefield. PhD project, Camborne School of Mines, Cornwall, UK. Part of a combined universities in Cornwall (CUC) project: 'The Tectonics of Variscan Magmatism & Mineralisation in South West England', Cornubian Orefield — A Review (Part 1). Available at: <http://myweb.tiscali.co.uk/geologyofcornwall/research.htm>

Lefebure, D V and Ray, G E. (eds.). 1995. Selected British Columbia Mineral Deposit Profiles Volume 1 — Metallics and Coal (version 2). British Columbia Ministry of Energy, Mines and Petroleum Resources, Open File 1995–20, 135 p. Available from: <http://www.empr.gov.bc.ca/MINING/GEOSCIENCE/MINERALDEPOSITPROFILES/Pages/default.aspx>

Li, X H, Liu, D Y, Sun, M, Li, W X, Liang, X R and Liu, Y. 2004. Precise Sm–Nd and U–Pb isotopic dating of the supergiant Shizhuyuan polymetallic deposit and its host granite, SE China. *Geological Magazine* 141, 225–31.

Ludington, S and Plumlee, G S. 2009. Climax Type Porphyry Molybdenum Deposits. Open File Report 2009–1215, U.S. Geological Survey, pp16. Available at: <http://pubs.usgs.gov/of/2009/1215/pdf/OF09-1215.pdf>

Mao, J W, Li, H Y, Song, X X, Rui, B, Xu, Y, Wang, D H, Lan, X M and Zhang, K J. 1998. Geology and geochemistry of the Shizhuyuan W–Sn–Mo–Bi polymetallic deposit, Hunan, China. Beijing: Geological Publishing House, 215 pp.

Mining History Network. 1996. Mineral Statistics of the UK: Cornwall Mineral Production. Available at: <http://projects.exeter.ac.uk/mhn/MS/co-intro.html>

Nanomaterials, 2009. New Nickel-Tungsten alloy that is not only safer than chrome but also more durable. News article posted on the A–Z of Nanotechnology webpage. 19 May 2009. Available at: <http://www.azonano.com/news.asp?newsID=11591>

Newcrest Mining Ltd, 2009. O'Callaghans Project Western Australia. Presentation by Tao Li (Group Manager Geotechnical Engineering) to the International Tungsten Industry Association Annual Conference in Vancouver on 17 September 2009. Available online at: <http://www.newcrest.com.au/presentations.asp?year=2009>

Petkewich, Rachel A. 2009. Unease Over Tungsten. Science & Technology, 19 January 2009, Volume 87, Number 3, pp.63–65. Available online at: <http://pubs.acs.org/cen/science/87/8703sci2.html>

Pitfield, P E J, Brown, T J and Idoine, N E. 2010. Mineral Information and Statistics for the BRIC countries 1999–2008. British Geological Survey. <http://www.bgs.ac.uk/mineralsUK>

Rastall, R H and Wilcockson, WH. 1920. Tungsten Ores. Monograph on Mineral Resources with Special Reference to the British Empire. London, John Murray. Available from: http://openlibrary.org/books/OL7023297M/Tungsten_ores

Ray, G E, 1995. Tungsten Skarns. In Selected British Columbia Mineral Deposit Profiles Volume 1 — Metallics and Coal, Lefebure, D V and Ray, G E. (Eds). British Columbia Ministry of Energy, Mines and Petroleum Resources, Open File 1995–20, p72–73. <http://www.empr.gov.bc.ca/MINING/GEOSCIENCE/MINERALDEPOSITPROFILES/Pages/default.aspx>

Roskill Consulting Group. 2010. A custom study of the market for tungsten. Commissioned by Wolf Minerals Ltd. Roskill Consulting Group, London, UK

Schubert, W-D, Lassner, E and Walser, P. 2006. Geology of Tungsten. International Tungsten Industry Association (ITIA) Newsletter, pp12. Available at: http://www.itia.info/FileLib/Newsletter_2006_12.pdf

Scrivener, R C and Shepherd, T J. 1998. Mineralisation. In: E B Selwood, EM, Durrance and C M BRISTOW (eds.) The geology of Cornwall, University of Exeter Press, 120–135.

Shedd, K B, 2010. Tungsten. U.S. Geological Survey, Mineral Commodity Summaries. Available at: <http://minerals.usgs.gov/minerals/pubs/commodity/tungsten/>

Shepherd, T J, Beckinsale, R D, Rundle, C C and Durham, J. 1976. Genesis of Carrock Fell tungsten deposits, Cumbria: fluid inclusion and isotopic study. Transactions of the Institution of Mining and Metallurgy, 85, B63-73.

Sinclair, W D. 1995. Porphyry Tungsten. In Selected British Columbia Mineral Deposit Profiles Volume 1 — Metallics and Coal, Lefebure, D V and Ray, G E. (eds.) British Columbia Ministry of Energy, Mines and Petroleum Resources, Open File 1995–20, p 97–99 and p 101–104. Available from: <http://www.empr.gov.bc.ca/MINING/GEOSCIENCE/MINERALDEPOSITPROFILES/Pages/default.aspx>

Slater, D. 1973. Tungsten. Mineral Resources Consultative Committee Mineral Dossier No.5. pp43. London HMSO.

Tarney, E. 2004. High speed steel properties: different grades for different requirements. Article for Gear Technology Journal, Randall Publishing, Elk Grove Village, IL60009, USA. Available at: <http://www.geartechnology.com/pa/members/sepoct04/section9.pdf>

Tindle, A G and Webb, P. 1989. Niobian wolframite from Glen Gairn in the Eastern Highlands of Scotland: a microprobe investigation. Geochimica et Cosmochimica Acta, 53, 1921–1935.

Werner, A B T. Sinclair, W D and Amey, E B. 1998. International Strategic Mineral Issues Summary Report — Tungsten. U.S. Geological Survey Circular 930-O, pp71. Available at: <http://pubs.usgs.gov/pdf/circular/c930-o.html>

Wolf Minerals Ltd. 2010. Projects and Exploration: Hemerdon Mine and News Releases. Available at: <http://www.wolfminerals.com.au/>

Young, B, Fortey, N J and Nancarrow, P H A. 1986. An occurrence of tungsten mineralisation in the Eskdale intrusion, west Cumbria. Proceedings of the Yorkshire Geological Society, 46, pp15–21.

This commodity profile was produced by the
British Geological Survey (2011).

It was compiled by Peter Pitfield and Teresa Brown
with the assistance of Gus Gunn and Debbie Rayner.

This report is one of a series of Commodity Profiles
available to download free-of-charge from
www.MineralsUK.com.

For further information please contact:

British Geological Survey, Keyworth, Nottingham,
NG12 5GG, United Kingdom

Tel: +44 (0)115 936 3100

Fax: +44 (0)115 936 3446

E-mail: minerals@bgs.ac.uk

Website: www.MineralsUK.com

Unless otherwise stated, copyright of materials
contained in this report are vested in NERC.
BGS © NERC 2011. All rights reserved.