

## From Deposit to Concentrate: The Basics of Tungsten Mining Part 1: Project Generation and Project Development

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### INTRODUCTION

This article provides an overview of the many facets of tungsten mining, tracing the path from tungsten resources through exploration, development and mine operation to the production of tungsten concentrates that provide the feedstock for refineries and APT production. Some steps in the overall process are specific to tungsten, others are of a general technical nature.

Development and operation of tungsten mines are governed by a multitude of often interlacing factors, which can be grouped in a number of categories:

- Geological Factors: what is in the ground?
- Technical Factors: how can it be recovered?
- Social and Environmental Factors: cost and benefit for society and impact on the natural environment?
- Economic Factors: what does it cost?

Compared to other metals such as copper, lead or zinc, annual mine production of tungsten concentrates is modest. According to ITIA's 2011 Market Report, primary mine production of tungsten in 2010 totalled 97,000t WO<sub>3</sub>. Tonnage-wise, this is less than the production of a single porphyry copper mine like Highland Valley in Canada, which has also a feed grade similar (or even lower) than most tungsten mines. Or, if we look at value rather than tonnage, the metal value recovered annually in tungsten

mining, stemming from dozens of industrial mines and hundreds of semi-industrial and artisanal operations around the world amounts to just half of that of Freeport McMoRan's Grasberg copper-gold mine in Indonesia.

Despite its modest size, the tungsten mining industry is very diverse, exploiting deposits in different geological settings, and using a wide range of mining and beneficiation methods to produce saleable concentrates.

Currently, some 80% of primary mine production for tungsten stem from operations in China. However, significant tungsten deposits can be found on all continents.

This article covers the geological background, the stages of project development and mining and beneficiation techniques applied in the tungsten industry.

There are currently a number of Junior Resource companies promoting the possible development of tungsten deposits. To avoid inadvertently favouring the one or other of these opportunities, the current article draws examples mainly from active tungsten mines.

*Disclaimer: In order to improve clarity for the non-technical reader, usage of words like "ore" and "reserve" does not follow necessarily the conventions of International Reporting Standards for the Mineral Industry.*

**Figures 1-4** (top of page, left to right) **1.** Scheelite ore at Darwin, United States; **2.** Drilling campaign at the historic Yxsjöberg mine, Sweden; **3.** Ore haulage at Cantung mine, Canada; **4.** Flotation at Mittersill mine, Austria.

## GEOLOGICAL BACKGROUND

Average abundance of tungsten in the earth's crust is around 1.5ppm, and thus much less than, for example, most of the Rare Earth elements such as neodymium. Tungsten is a lithophile element, which means it is more abundant in granitic (around 2ppm) than basaltic (1ppm) and ultra-mafic rocks (0.5ppm).

### Mineralogy

There are numerous tungsten minerals, but only scheelite ( $\text{CaWO}_4$ ) and the wolframite ( $(\text{Fe,Mn})\text{WO}_4$ ) solid-solution series between the end members Ferberite and Hübnerite are of economic importance.

Weathering and other alteration processes lead to secondary tungsten minerals. Typical examples are hydrotungstite ( $\text{H}_2\text{WO}_4 \cdot \text{H}_2\text{O}$ ), anthoinite ( $\text{AlWO}_3(\text{OH})_3$ ) and cerotungstite ( $\text{CeW}_2\text{O}_6(\text{OH})_3$ ), which together often form whitish to yellowish earthy masses colloquially named as tungstic ochre. Presence of these minerals might lead to lower process recovery and/or lower concentrate grade and thus, could have an important negative economic impact.

For additional information about the mineralogy of tungsten, refer to the ITIA Newsletter 06/2006.

#### Scheelite – $\text{CaWO}_4$

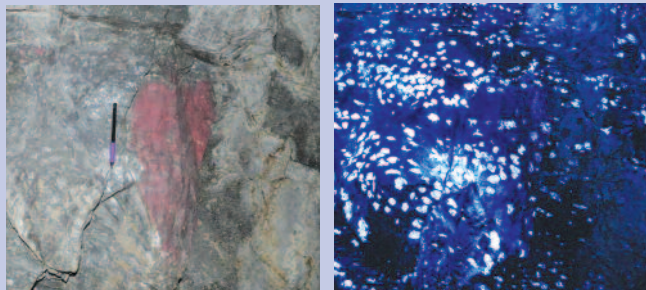
Specific gravity:	5.9 – 6.1	Hardness:	4.5 – 5
Tenacity:	brittle	Crystal system:	tetragonal
Colour:	colourless, whitish, ochre, yellow, grey		
Other properties:	strong fluorescence under short-wave UV light: whitish blue, turning into yellow with increasing molybdenum content.		

Scheelite is a calcium-tungstate with theoretical 80.5%  $\text{WO}_3$  content. The mineral forms a solid-solution series with powellite ( $\text{CaMoO}_4$ ), and naturally occurring scheelite contains often up to several % of Mo. This has an impact on usability as raw material.

Large crystals often show the typical bi-pyramidal (pseudo-octahedral) habit and are sought-after collector items.

Properties that influence use as ore material:

- high density: can be enriched with gravitational methods.
- brittle: not a good placer mineral; risk of overgrinding during comminution.
- Mo content: not suitable for certain downstream processes.
- fluorescence: easy to identify in exploration and mining.
- amenable to flotation.



**Figures 5 – 6:**

*Scheelite as the miner sees it: skarn ore at Bonfim mine, Brazil, under normal light (left) and UV light (right). Image width about 80cm.*

#### Wolframite – $(\text{Fe, Mn})\text{WO}_4$

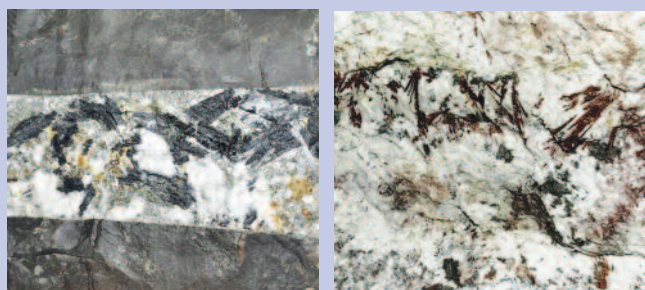
Solid-solution series between Ferberite ( $\text{FeWO}_4$ ) and Hübnerite ( $\text{MnWO}_4$ )

Specific gravity:	7.0 – 7.5	Hardness:	4 – 4.5
Tenacity:	brittle	Crystal system:	monoclinic
Colour:	greyish black (Ferberite), brownish to reddish black, dark red (Hübnerite)		

Wolframite is an iron/manganese-tungstate with theoretical 76.3 – 76.6%  $\text{WO}_3$  content. Crystals are usually tabular or prismatic. Pseudo-morphs of wolframite after scheelite are called reinite: the wolframite replaces earlier scheelite and retains thus the bi-pyramidal shape of scheelite.

Properties that influence use as raw material:

- high density: can be enriched with gravitational methods.
- brittle: not a good placer mineral; risk of overgrinding during comminution.
- not amenable to flotation.
- paramagnetic – can be upgraded by high-intensity magnetic separation.



**Figures 7 – 8:**

*Wolframite as the miner sees it: prismatic ferberite at Panasqueira, Portugal (left, image width 50cm) and hübnerite at Pasto Bueno, Peru (right, image width approximately 80cm)*

## Tungsten Deposits

Tungsten deposits occur world-wide. There are some noticeable clusters, where deposits of similar age and type are concentrated, such as the scheelite skarn deposits in NW Canada and the western USA, wolframite quartz vein deposits in Bolivia and Peru and the Hercynian skarn and vein deposits of the western Iberian Peninsula. The world's largest accumulation of tungsten deposits is found in Eastern Asia, extending from Korea, Japan and China into Vietnam and Thailand. This includes the countless, in part giant tungsten deposits of the Jiangxi and Hunan provinces in China.

Tungsten deposits are generally formed by magmatic-hydrothermal processes in relation to granitic intrusions. The deposits can be found either within the peripheral part of the intrusive itself (greisen, porphyry, stockwork and vein deposits), or in its vicinity (stockwork, vein and skarn deposits). Tungsten deposits are often associated with tin or molybdenum mineralisation.

There are some exotic deposit types such as breccia pipes or brine (salt lake) deposits, but these are of subordinate economic importance (refer to ITIA Newsletter 12/2006). One well-known deposit type was the group of "stratabound deposits relating to mafic volcanism" with the Mittersill deposit in Austria as type location. It appears, however, that the Mittersill deposit is better described as stockwork deposit relating probably to a granitic intrusive, and as this, it would be a classic tungsten deposit as described above.

In general, the exact mechanism for the formation of ore deposits is often controversially discussed.

Scheelite and wolframite are rather stable with respect to chemical weathering, and thus might be enriched in laterites and eluvial placers (immediately above or close to the origin of the original mineralisation). However, due to their friable character, both minerals disintegrate swiftly during transport in water, and alluvial placers (similar to typical gold placers) are rare.

The classification of greisen, porphyry and stockwork deposits is often ambiguous, and it might just be a question of scale or scope whether an occurrence is described as (multiple-) vein or stockwork deposit.

While simplification does not allow encompassing all deposits, it appears practical to distinguish three main groups of deposits, which have a distinct relation between deposit type and technical challenges for their exploitation.

In order of increasing tonnage (and generally decreasing grade):

### Classical vein deposits

- More or less continuous veins of decimetres to metres in thickness, mainly comprising quartz. In granite itself or in surrounding host rock. Connection to granite not always clear. Most deposits have ferberite or hübnerite mineralisation, but scheelite vein deposits do also occur.
- Typical tonnages: few 10s to few 100,000s of tonnes of ore.
- Typical grades: 0.5 – 5%  $\text{WO}_3$
- Typical by-product: Sn
- Object of mining is the individual quartz vein with its content of tungsten mineralisation.
- Examples of active mines: Panasqueira, Portugal; San Fex, Spain; Pasta Bueno, Peru; Chollja, Bolivia.

### Skarn deposits

- Replacement of carbonate rock (e.g. limestone) by calc-silicate minerals (garnet, epidote, amphiboles and others) near to the contact of a granitic / felsic intrusion.
- Mineralisation might be mono-metallic tungsten (almost exclusively as scheelite) or polymetallic (often with Mo or base metals: Pb, Zn, Cu), also together with gold, fluorite or magnetite. In some cases, tungsten is only by-product.
- Typical tonnages: few million tonnes, but much larger deposits are known.
- Typical grades: 0.3 – 1%  $\text{WO}_3$
- Examples of active mines: Cantung, Canada; Shizhuyuan, China; Vostok-2, Russia; Los Santos, Spain; Bonfim and Brejui, Brazil.

### Bulk mineable deposits: greisen, porphyry, stockwork

- "Bulk mineable" is a mining term: it means that large volumes of low-grade material can be mined instead of following complex contacts of individual mineralised structures. Greisen and porphyry deposits are generally located in the apical parts of felsic intrusions, while stockwork vein deposits can be found either in the intrusions itself or in the surrounding country rock. Technically, some skarn deposits are also bulk mineable.



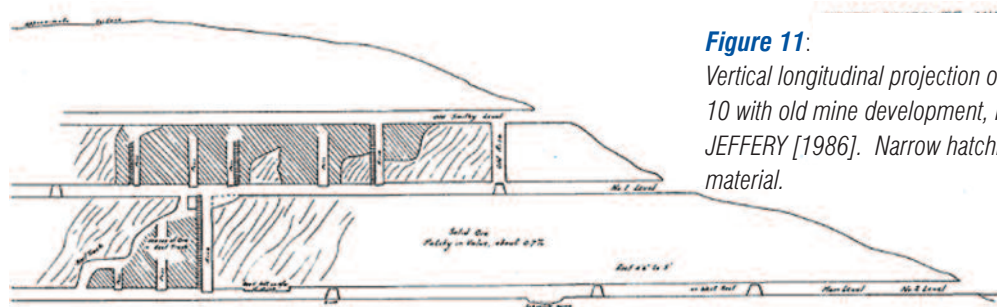


**Figure 9:** Location and type of major tungsten deposits and districts, redrawn and updated after BRITISH GEOLOGICAL SERVICE [2011].

- More often than not, these deposits are either W-Sn or W-Mo deposits. Both, scheelite and wolframite occur in bulk mineable deposits, and some deposits contain both minerals together, which leads to problems with beneficiation as mixed concentrates are more difficult to market.
- Typical tonnages: dozens or hundreds of million tonnes.
- Typical grades: 0.1 – 0.3% WO<sub>3</sub>
- Object of mining is not the individual mineralised vein but the entire rock mass including the quartz or greisen veins.
- Examples: active mines: Lianhuashan, China; Mittersill, Austria.

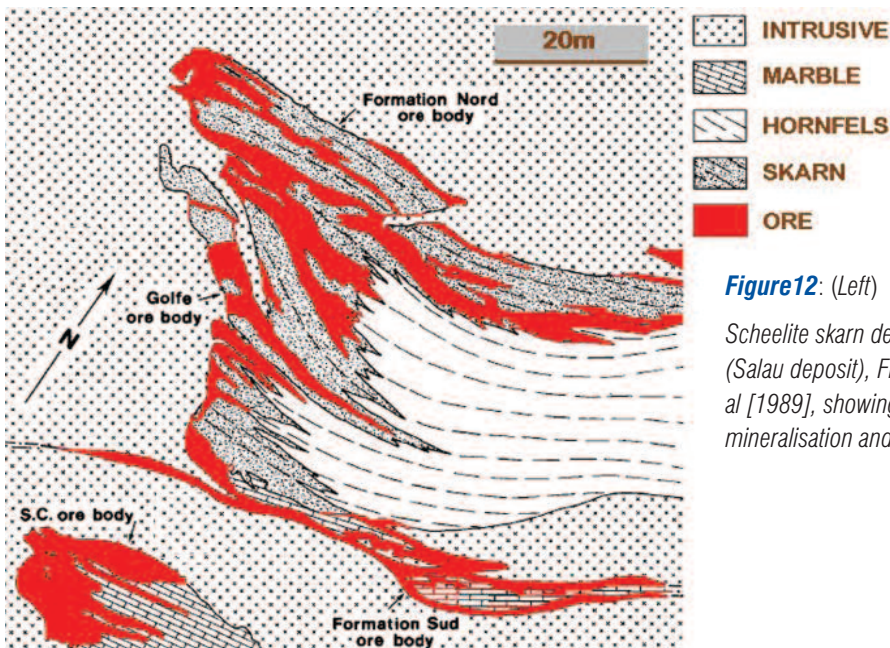


**Figure 10:**  
Quartz-scheelite vein deposit: Paradise Mine, New Zealand.



**Figure 11:**  
Vertical longitudinal projection of the quartz-scheelite vein from figure 10 with old mine development, Paradise mine, New Zealand, from JEFFERY [1986]. Narrow hatching indicates stoped (mined out) material.





**Figure12:** (Left)

Scheelite skarn deposit: Map of level 1452 of the Anglade mine (Salau deposit), French Pyrenees modified from FONTEILLES et al [1989], showing the lithological control of skarn and scheelite mineralisation and relation to the intrusive sequence.



**Figure13:** (Left)

Scheelite skarn deposit: Bonfim mine, Brazil. The about 1m thick skarn of orebody "A" shows strong lithological control, can be followed over hundreds of meters and comprises three layers: high grade Au-Bi-WO<sub>3</sub> mineralisation in the top; intermediate schist and lower-grade basal skarn.



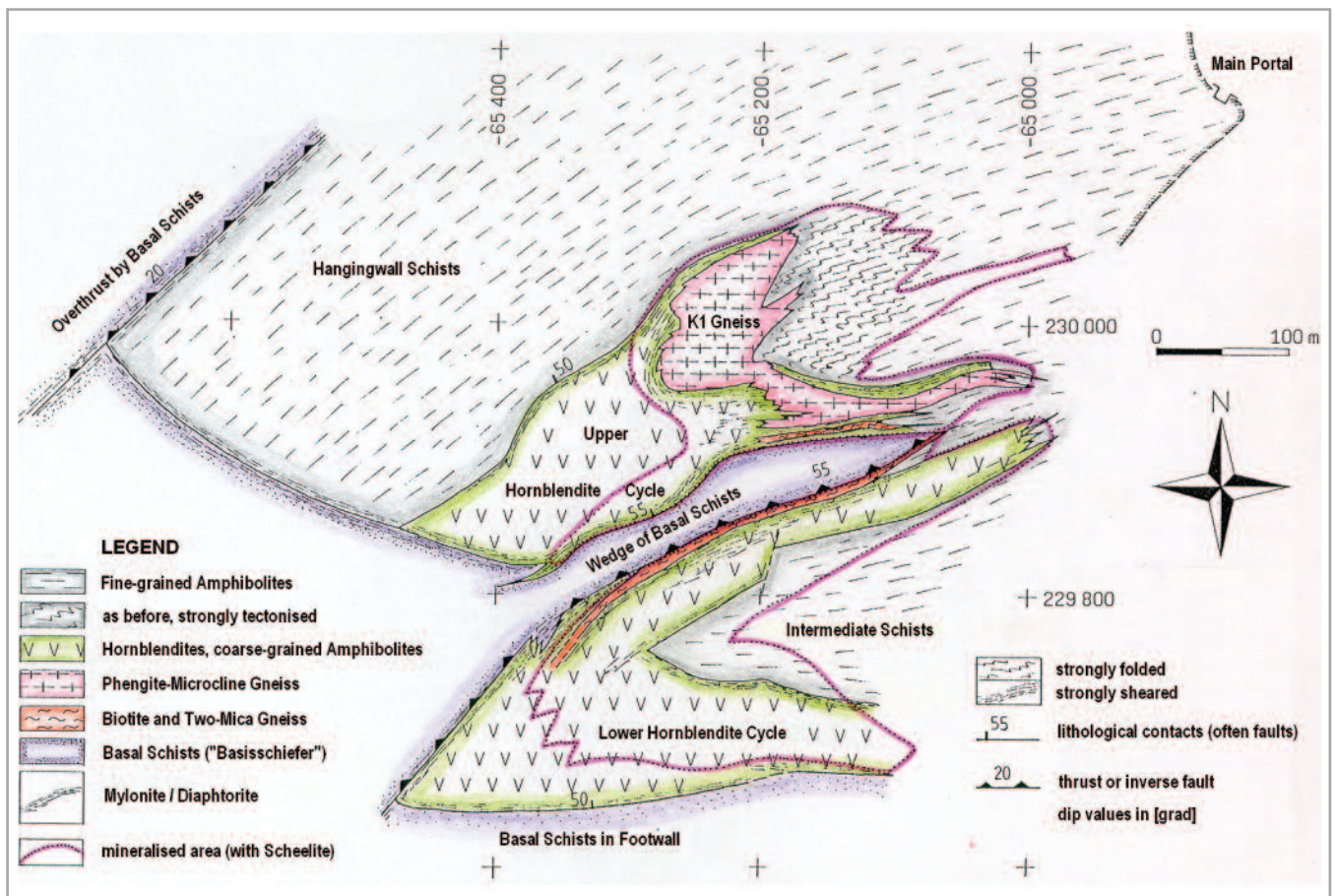
**Figures 14-15:** (Above)

Low-profile room & pillar mining of the "A" orebody at the Bonfim mine, Brazil, showing strong scheelite mineralisation in a narrow band along the top of the skarn layer. Top with normal light, below with UV light.

**Figure16:** (Left)

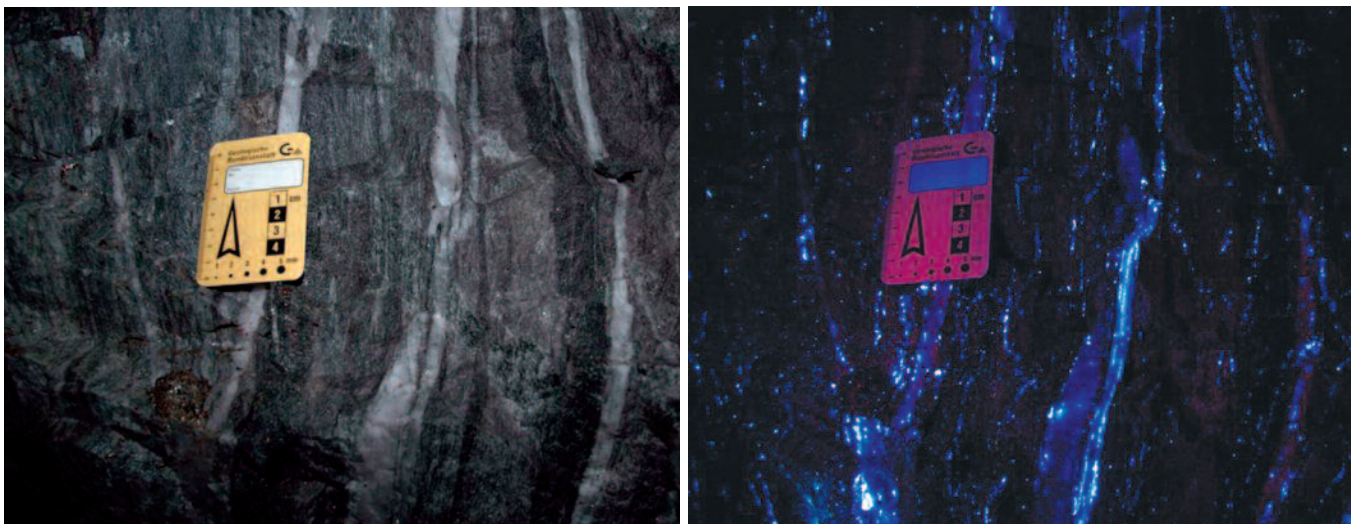
Stockwork deposit: Quartz-wolframite veins at Gifurwe mine, Rwanda. Narrow quartz veins (white/orange) with very irregular wolframite mineralisation criss-cross grey graphitic schist. Quartz veins are mainly too narrow to be mined individually.





**Figure17:**

Stockwork deposit: Mittersill scheelite deposit, Austria. Geological sketch of level 1175, Western Ore Zone, showing the extension of quartz-scheelite stockwork veining in basic and ultramafic rocks in the surrounding of a small granite intrusive (K1-Gneiss).



**Figure18-19:**

Quartz-scheelite stockwork veining at Mittersill under normal light (left) and UV light (right). Scale = 10 cm.

## PROJECT DEVELOPMENT

The path from discovery to production is complex and time-consuming: It is rare that production occurs within the first ten years

### Economic constraints

*The tungsten market has been less cyclic than that of major metals, but there have been major fluctuations in price over time: Two price peaks occurred in the mid- to late 20th century: the first in the 1950s, due to strategic stockpiling programs around the Korean War and in the 1970s, due to capacity constraints during a growth cycle.*

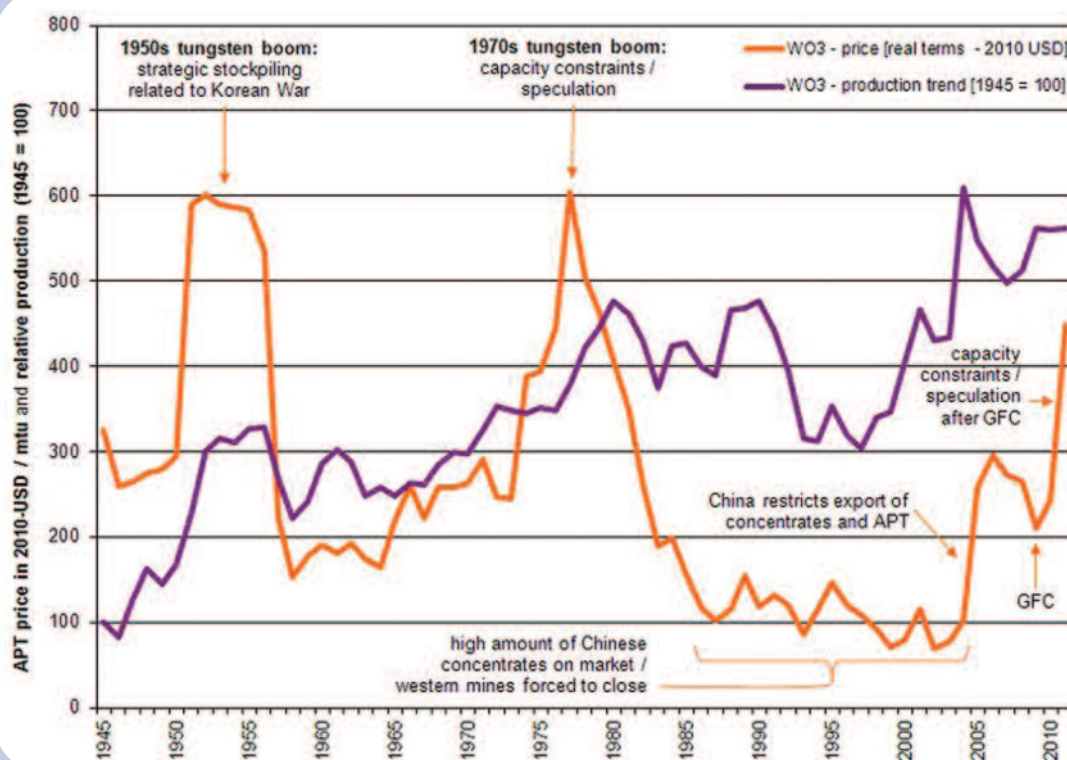
*The boom of the 1970s was followed by a prolonged period of depressed prices, due to flooding of the western market by Chinese concentrates (and later Chinese APT). When China imposed an export ban for concentrates and quotas for export of APT in the mid-2000s, prices went up swiftly, causing renewed interest in development of tungsten operations.*

*Most of the tungsten projects now under consideration were originally discovered or had even already been mined in the mid to late 20th*

*from initial discovery. Besides a “good” deposit, the right economic environment is needed to trigger interest in project development.*

*century before depressed prices from the 1980s onwards forced most western producers to mothball their mines or halt exploration and development projects. Many of these projects have passed through the hands of various owners since.*

*Junior Resource companies own most tungsten projects, and these need to raise specific interest in a given project to assure project funding, as financing from own funds is not possible. This means, the project itself does not need to be only economically interesting, but adequate promotion is required: A good “story” is needed, and to this end, the classification of tungsten as a critical raw material by the European Union and the US is helping to raise interest*



**Figure 20:**

*Relative mine production and prices in real terms for tungsten between 1945 and 2011, based on data from USGS. GFC stands for Global Financial Crisis.*











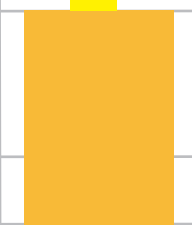


Once a deposit has been discovered, various studies are undertaken with the ultimate goal to establish a mine. This is a multi-phase process, in which each phase is designed to justify further expenses for the increasingly detailed and thus costly stages in the process leading to a Bankable Feasibility Study.

At the beginning, this is largely aimed to better understand the geological inventory through exploration and resource modelling,

always keeping in mind the economic potential. At later stages, engineering of extraction and beneficiation, environmental considerations, market studies and cost modelling are the main focus.

PINCOCK, ALLEN & HOLT (2005, 2009) provide an excellent overview over the engineering study requirements at the individual study level (conceptual (=scoping), pre-feasibility and feasibility level) in issues 70 and 95 of their Pincock Perspectives series of newsletters.



Stage	Operations, techniques, important issues	Relative risk	Relative costs
Production	Start-up, optimisation, routine operation, ongoing exploration to replace mined tonnages.		
Construction	Mine development, construction of mill, tailings facilities and other infrastructure.		
Pre-Construction	Financing, permitting, off-take negotiations, final engineering, tender & selection of contractors.		
● Positive Outcome of Feasibility Study-Go-Ahead Decision			
Feasibility Study	Advanced engineering, detailed mine plan for first few years, Proven Mineral Reserves, Metallurgical testwork might include pilot plant processing, Environmental Management Plan, social studies, marketing studies, detailed calculation of operation and capital costs.		
Pre-Feasibility Study	Basic engineering, selection of mining method and basic mine plan, metallurgical testwork, Probable Mineral Reserves, Environmental Baseline Study. Additional detailed exploration to further upgrade resource/reserve classification.		
Resource Definition and scoping	Extensive staged drilling campaigns leading initially to Inferred Resources and then to Indicated Resources at least for the central portion of the deposit; preliminary metallurgical testwork, Scoping Studies to define scale and economic merit of a possible operation (Preliminary Economic Assessment). Could include underground development and test mining.		
● Discovery			
Grass-root exploration	Regional prospection, mapping, geochemistry, limited drilling, possibly geophysics.		
Exploration concept	Data research and desktop review and so on to formulate targets.		

**Figure 21:** Typical steps of project generation and development from grass-root exploration through discovery and technical studies to production. Distribution of relative costs varies from project to project and depends on risk assessment and approach to feasibility work.

## Exploration

During the tungsten booms of the 1950s and 1970s, numerous deposits have been discovered world-wide which since have not or only partly been mined. This means that there is little incentive for grass-root exploration (the search for new deposits in virgin terrain), except in China, where the industry actively undertakes exploration to replace mined-out deposits.

More important than early-stage exploration is detailed exploration to better understand known deposits, bring them to Feasibility stage to attract financing and to extend the resources of active mines.

Exploration methods have to take the particularities of tungsten deposits into account, for example the low concentration of the valuable mineral and its often highly erratic distribution.

Besides specific tungsten exploration campaigns, for example during the tungsten boom in the 1970s, many deposits have rather been discovered by chance, or as “by-product” of the exploration for deposits of other commodities. Historically, tungsten was even an unwelcome constituent of multi-element ore deposits – hence the name Wolfram (mineral that is “wolfing” away the tin).

## Way to discovery

With exception of well-developed vein deposits, tungsten deposits tend to be inconspicuous: ore grades and thus the concentration of the ore mineral are low, there are no colourful oxidation zones (gossans) and generally no magnetic or gravity anomalies that would aid geophysical prospection.

Moreover, scheelite is “just” a whitish or pale-coloured mineral perfectly camouflaged by carbonates, quartz and feldspar. However, the mineral has a very strong fluorescence, and this property is used for exploration: field work is often undertaken as night prospection with UV lamps or by checking heavy mineral concentrates from stream sediments under UV light for scheelite content.

Thus, the main avenue to discovery is:

1. Selection of a prospective area (for example in one of the known deposit clusters, and near granites).
2. Geochemical prospection, for example, testing stream sediments for tungsten content (or scheelite) and then tracing the way of an anomaly back up-stream.



3. In case of scheelite: night-prospection with UV light. An example for successful systematic grass-root exploration was the discovery of the Mittersill deposit in the Austrian Alps in 1967.

This is also an example for two other issues:

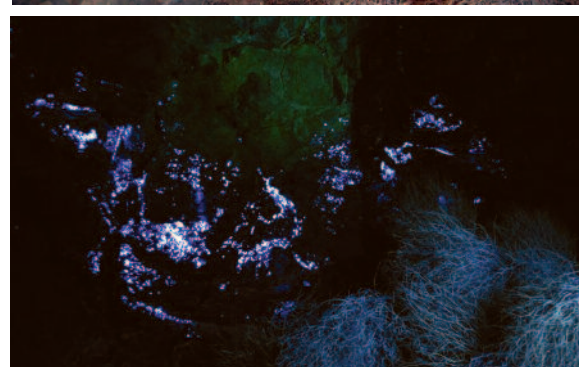
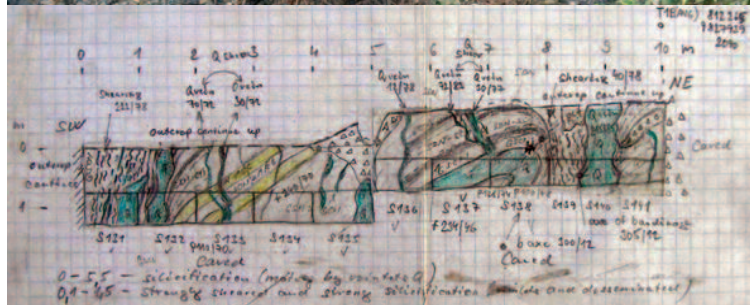
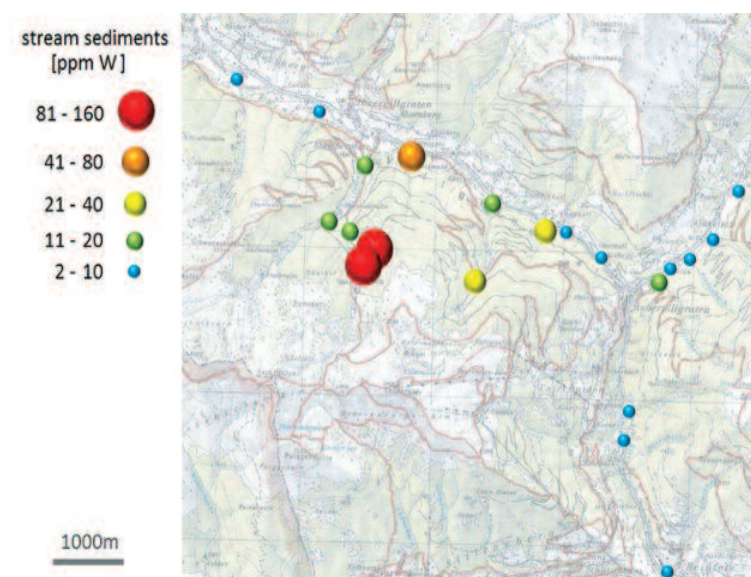
- Scheelite is easily overlooked, unless specifically explored for: the Mittersill deposit is a world-class high-grade deposit, directly outcropping, in a densely populated area: for any common commodity (such as iron, copper or lead-zinc), a deposit of this size, in such a setting, would have been discovered centuries earlier.
- Discovery of a deposit based on a specific scientific theory does not prove that the deposit is indeed of the envisaged deposit style.

#### Figures 22 - 27: Exploration field work.

Stream sediment sampling (top right) and an anomaly map (top left) for regional tungsten exploration in Austria.

Mapping of a trench in Rwanda (middle left) and an excerpt of the geologist's field book; (bottom left).

Breccia-hosted scheelite during night prospection at Darwin in the Californian desert (middle right flash light, bottom right UV light).





## Detailed Exploration

Once the deposit is discovered, staged exploration aims to provide the base for increasingly reliable estimates of the resource inventory: in order to plan mining, a reliable model of shape, tonnage and grade distribution within the deposit is required as well as information about the ground conditions (rock quality, geotechnical parameter).

The staged drilling campaigns are often the single most expensive item prior to mine development. In a typical case, the deposit would have been found by sparse randomly oriented drill holes, and detailed exploration would tighten this to a regular grid. For example, in the initial phase of resource definition, one hole every 200m might suffice, while determination of Proven Reserves at the same deposit requires holes in less than 25m spacing.

The principal method of detailed exploration is drilling, in general diamond core drilling: in contrast to destructive drilling methods such as employed during exploration of hydrocarbons, core drilling allows the retrieval of an intact sample of the intersected ground, in the form of a drill core. This permits examining in detail mineralogy, lithology and ground conditions of the ore zone and assures that no contamination occurs. While advancing the drill hole, the core is recovered in a core barrel, which then is retrieved with help of a wire-line.

Another common exploration drilling method is reverse circulation (RC) drilling. Drill chips are recovered by compressed air blown down the rods through the centre void of the drill string. In the case of tungsten, the high density contrast between ore minerals and host rock and their high friability pose risks of biased results, and RC drilling is rarely used for detailed tungsten exploration.

Many tungsten deposits are “nuggety” and the problem of a high nugget effect (refer to info box **“Nuggety Ore” and the Nugget Effect**) is exacerbated by the comparatively small sample volume recovered during diamond core drilling. In general, for a very coarse-grained mineralisation, one would aim for the highest possible sample volume to assure representative results for individual samples.

Trenching, underground channel sampling and test mining of small ore blocks provide better results, but might be prohibitively costly. Trenching is only possible along the surface outcrop, and results might be influenced by weathering and supergene enrichment.

Limitations and constraints of the sampling have to be taken into consideration during the subsequent stage of the investigation, notably for resource modelling.

### **“Nuggety Ore” and the Nugget Effect**

*Nuggets are known from gold deposits, and the term describes the occurrence of comparatively large grains of the valuable mineral in an overall very low-grade deposit, such as in the case in many tungsten deposits, especially vein-type deposits. A deposit with the said characteristics is described as “nuggety”.*

*In practice, this means that a given sample (for example, a drill core) might or might not contain one of these larger grains, and thus does not give a valid estimate for the mineralisation as such (it is either – in most cases – too low, or – in rare cases – much too high).*

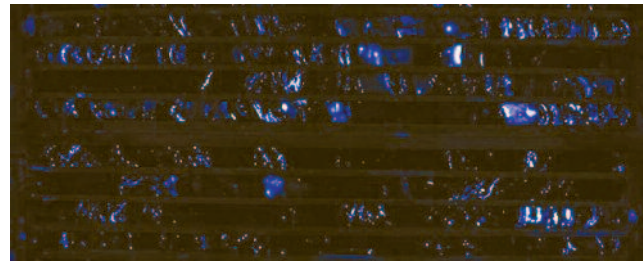
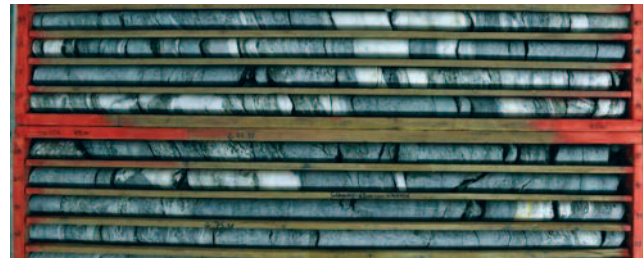
*In geostatistics, the nugget effect describes the variance between two samples taken at (virtually) the same position – this might also be due to sampling errors. The higher the individual sample volume, the lower the nugget effect.*



**Figure 28:**

*Nuggety wolframite ore at the Panasqueira mine, Portugal. Visual estimates (surface of black wolframite in white quartz) are used to determine the grade. Note: a 2mm thick “continuous seam” of wolframite would account for a grade higher than the average production grade of the mine.*





**Figures 29 - 32: Detailed Exploration.**

Underground channel sampling (top left) and surface diamond core drilling (bottom left) at the Rudnik mine, Serbia, testing scheelite mineralisation.

Drill core from the Mittersill scheelite mine, seen at normal (top right) and UV light (bottom right).



## Mineral Resources and Ore Reserves

In the wake of the Bre-X scandal, a massive gold mining fraud that unravelled in 1995 (DANIELSON V & WHYTE J [1997]), rules for reporting of mineral resources and reserves by public companies were tightened in most jurisdictions. Several different resource reporting codes exist, but the main definitions were standardised in the late 1990s. The most wide-spread codes used are JORC (Australasian), CIM (Canadian) and SAMREC (South African). Somewhat different codes exist in Russia, other states of the former Soviet Union and China.

Companies listed on the principal international stock exchanges are generally obliged to follow the guidelines defined by these codes.

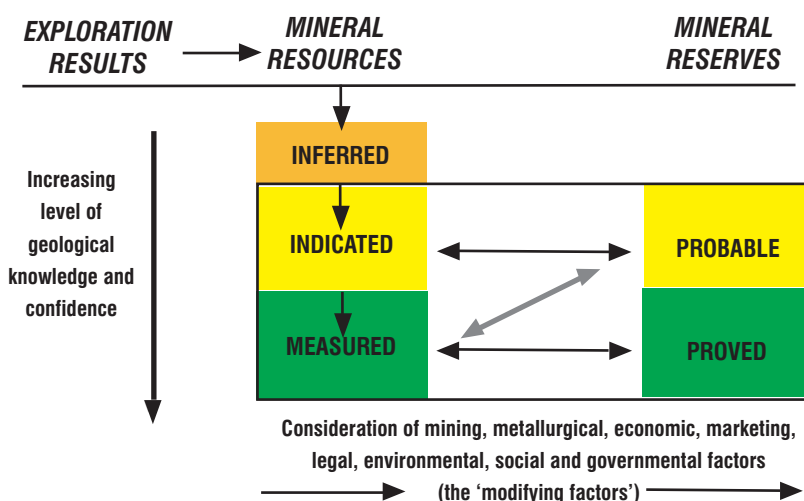
These codes all distinguish between resources and reserves as follows:

- Resource: the estimate of the quantity and quality of the mineralised material in-situ that has **potential to be mined**; and
- Reserve: the **under current conditions economically mineable portion of the resource**, including adjustments for dilution and mining losses and the application of modifying factors.

All these codes include the concept of Competent Persons. A Competent Person is a suitably experienced professional who has a minimum of five years' experience which is relevant to the style of mineralisation and scope of the report. The Competent Person must also be a member of a recognised professional association

**Figure 33:**

Relation between Mineral Resources and Mineral Reserves showing classification with increasing quality of data. Redrawn after CIM [2011]



## Resource / Reserve Modelling

Determination of the (at the given time best possible) estimate for the quantity and quality of ore that can be mined from a given deposit is probably the most important parameter for the economic assessment of a proposed mining project (and justification to spend money on a mineral property, at any stage). These estimates and their reporting in the public domain generally follow certain industry standards (refer to info box **Mineral Resources and Ore Reserves**).

The estimate is based on “hard facts” (like assay values and density measurements at sample points) and a diligent interpretation and interpolation how the ore grades are distributed in the three-dimensional space between these measurement points. It is important that continuity of the mineralisation can be assumed between the individual sample locations points. Therefore, a sound understanding of the deposit type is required. Subsequently, statistical and geostatistical methods are used to describe the data distribution and assess whether sample spacing is sufficiently tight within the given domain.

Traditional (“paper-based”) estimates have now been largely replaced by computerised block models, which allow not only global estimates but provide insight into the local grade distribution and thus aid mine planning and production scheduling. However, there are a number of risks attached to computer-aided modelling:

- Black box: the operator relies too much on the data processing of the computer without being able to follow-up step-by-step.
- Misinterpretation of the deposit model; lack of continuity between neighbouring samples; risk of modelling across “hard boundaries” (like geological contacts).
- In general, there is a tendency to model “unconstrained” if the morphology of the deposit is complex.
- Over-reliance on local estimates: other than in paper-based models, it is easy to forecast production in small increments: however, even if the global estimate is indeed correct, local estimates might be completely erratic. Blocks are filled with information, but the information might be nonsensical.

A computer-aided resource model can only be as good as the geological understanding. If individual quartz vein intersections in a stockwork deposit are interpreted as continuous quartz veins and modelled as a high-grade narrow vein deposit, the estimate is meaningless even if all statistical parameters indicate the opposite.

The finer-grained and more homogeneous a mineralisation is, the easier it is to provide reasonable grade estimates. In case of skarn deposits, the often complex shape has to be modelled due to the strict lithological

control of the mineralisation: grades are not allowed to “float” across boundaries as in unconstrained models.

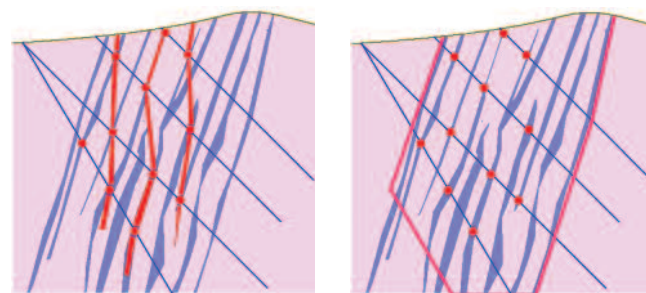
The grade distribution of vein-type deposits is particularly difficult to model, due to the erratic (“nuggety”) distribution of the ore minerals. Reliable data can often only be obtained from underground development, not from drilling. Vein-type deposits are often operated with very little Ore Reserves “on the books”, but long-term experience shows that mined resources will be replaced in the course of day-to-day mining by newly defined resources.

In case of vein-type deposits, required sample volumes to obtain reliable grade values might be prohibitive, and graphical methods (measuring the surface of ore minerals per square meter) are used instead. There might be also rule-of-thumb relations between vein thickness and mineral endowment, which aid in resource estimation.

Vein deposits can be seen as two-dimensional features, and, depending on their orientation, are still often shown in “traditional” VLP (vertical longitudinal projection) or horizontal projection.

Once the geological inventory is determined with the required level of detail, modifying factors have to be applied to convert resources to reserves, i.e., to estimate the “mineable” portion of the geological (in-situ) inventory. These comprise mainly planned and an adequate allowance for unplanned dilution (where waste is taken instead of ore) and planned and unplanned losses (ore left behind in pillars or after blasting in stopes). The parameter take ground conditions, mining method and legal requirements into account.

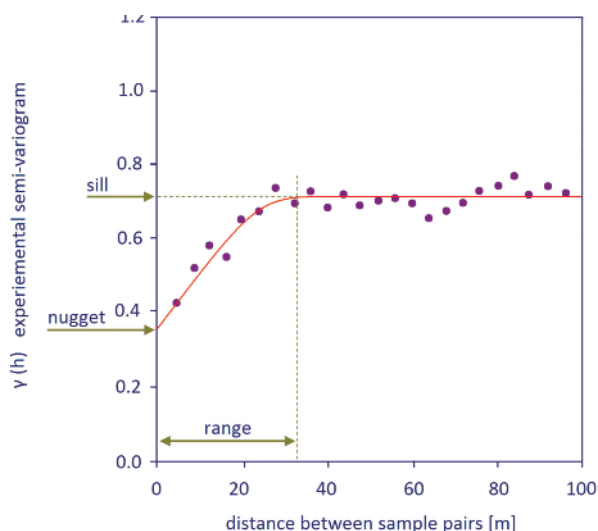
Where valid 3D block models exist, pit optimisation programmes allow establishing the most economic open pit outline, based on input parameters like operation costs, revenue and slope angle.



**Figure 34-35:**

*Erroneous interpretation of a stockwork as deposit comprising individual continuous high-grade quartz veins that could be mined in an underground mine (left, red dots = individual intersections above cut-off, assumed “orebodies” = red); valid interpretation of the same results as bulk mineable deposit suitable for open pitting (assuming average diluted grade is sufficiently high – resource estimate would encompass all material within purple outline, right).*



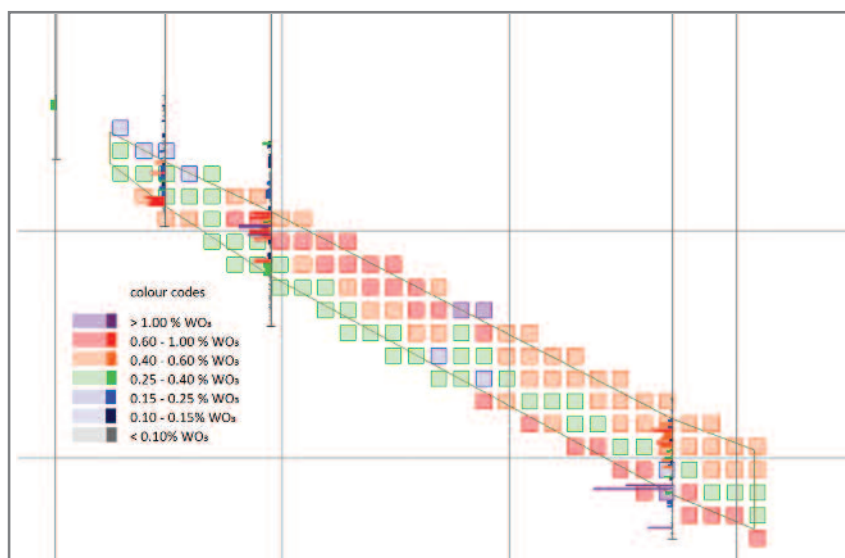
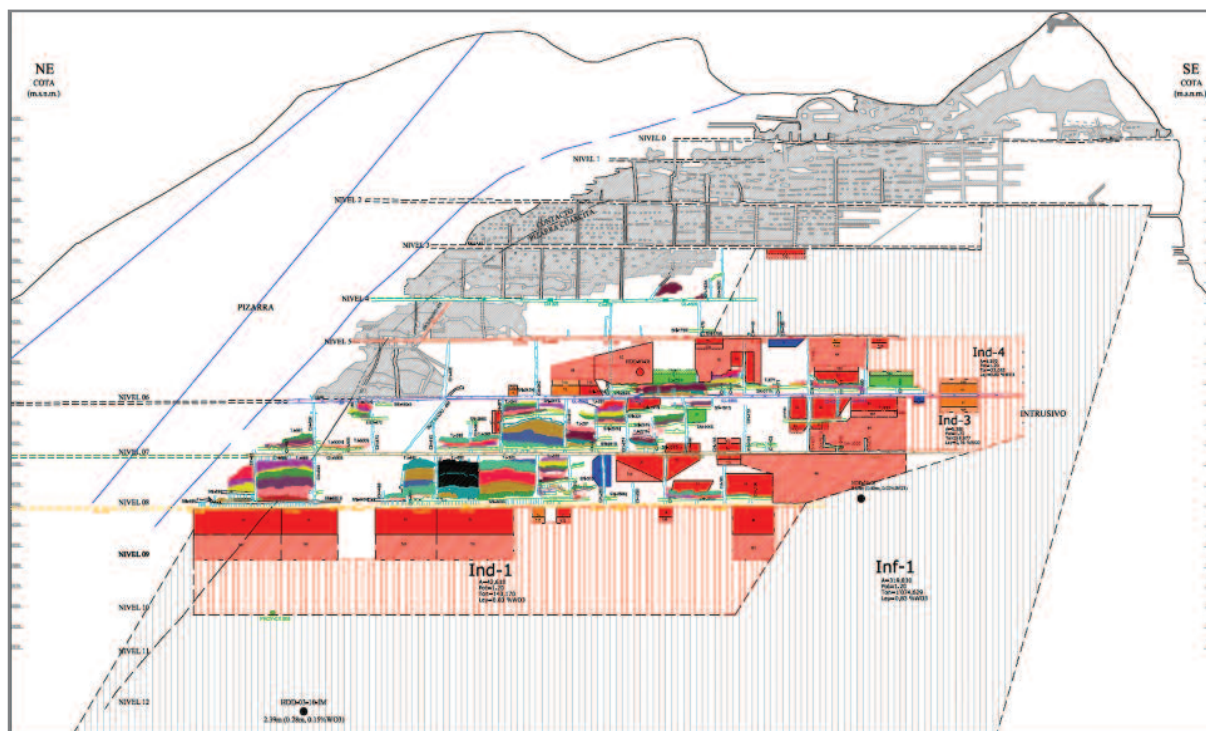


**Figure 36 (Left):**

Semi-variogram (short: variogram), an important tool for the geostatistical interpretation of orebodies. Simply speaking, the range indicates the maximum acceptable drillhole spacing; at this spacing, the sill is reached, which means that sample results are independent of each other. The sill value equals the variance of the data set. The nugget describes the expected discrepancy of the result for drillholes drilled at (almost) the same place. Tungsten deposits, especially vein-type deposits have typically a high nugget effect.

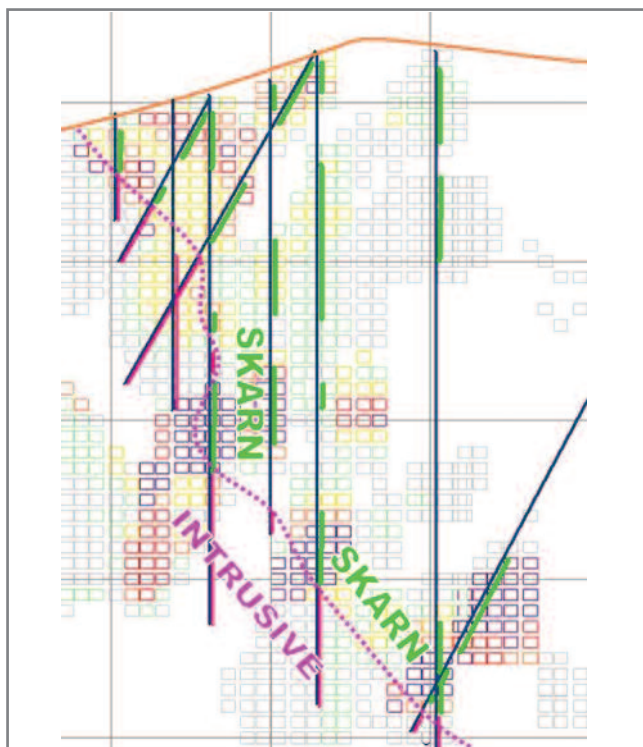
**Figure 37 (Below):**

Classic presentation of the resource inventory of a narrow vein quartz-wolframite deposit on a VLP (vertical longitudinal projection), Pasta Bueno mine, Peru. From company documentation of Malaga Inc., Canada, prepared by Pincock, Allen & Holt in 2012. Grey areas = historic mining; solid blocks in red & orange = Proven Reserves; dense hatch pattern in orange & red = Probable Reserves, vertical wide hatching = Inferred Resources. Various colours in stoped areas = recent production in shrinkage stopes. Level spacing = 50m.



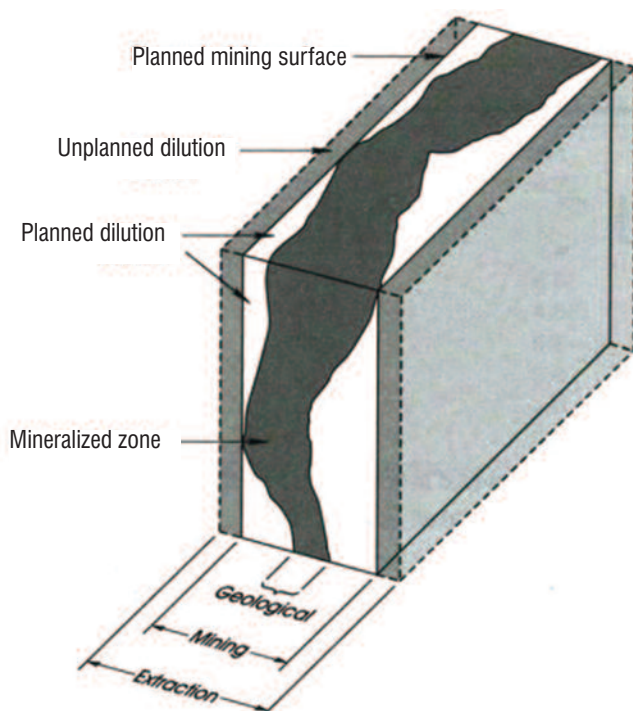
**Figure 38 (Left):**

Resource estimation with three-dimensional block model, sectional view of grade interpolation between widely-spaced drillhole intersections, grid spacing = 50m. This shows the relation between measured data along the drillholes and data interpretation in the block model.



**Figure 39:**

*Erroneous interpretation of a skarn mineralisation due to unconstrained block modelling, not taking lithological boundaries into account: grades are allowed to “float” into the granite domain, which is completely sterile. Grid spacing = 50 m*



**Figure 40:**

*Conceptual view of planned and unplanned dilution when mining a tabular deposit: The planned layout for mining includes an irregular geological body and expected dilution by host rock; in reality, there will be likely some further overbreak into the sterile rock – so real extraction includes both, planned and unplanned dilution, both of which has to be accounted for in a realistic ore reserve estimate. From SINCLAIR & BLACKWELL [2002].*

## Engineering Studies

From initial scoping to Bankable Feasibility Study, increasingly detailed engineering studies are required to provide a solid foundation for financial decisions. Initially, rule-of-thumb estimates might suffice, but in the later stages of the process, design, scheduling and cost estimation of mining methods, beneficiation techniques, the set-up of the entire infrastructure including tailings management and water supply and so on do require a vast specialist knowledge. Except in the largest international mining houses, this knowledge is not available in-house.

The engineering studies are therefore generally undertaken by specialist consultancy groups, and often outsourced to various specialists, especially where knowledge of such particular matters as flotation of scheelite is required. Mining and infrastructure of tungsten mines are not specific to the commodity, but beneficiation is highly sensitive, especially with respect to concentrate specifications. It might prove almost impossible to overcome certain ore dressing challenges, and in-depth metallurgical testwork, using representative samples from the deposit, is a must for a robust design of the beneficiation plant – and the overall economic model.

Together with resource definition drilling, metallurgy is the most expensive part of the engineering studies. Essentially, resource definition and metallurgy go hand-in-hand: by definition a mineralisation is only a resource if potential economic extraction can be demonstrated. And the drilling and sampling of the orebody required to estimate the inventory are also the principal source of feed material for the metallurgical test work.

Given the low tenor of tungsten deposits, only a small quantity of concentrates can be produced per tonne of sample. Therefore, test mining or bulk sampling are likely to be required to supply additional material to supplement initial testwork based on drill core samples.



**Figure 41:**

*Engineering Studies: Pilot plant equipment at the Aachen Mining University, Germany used to undertake metallurgical studies for tungsten mining projects. In foreground a laboratory concussion table.*



## Environmental and Social Studies

Environmental and social impacts of any mining operation are extremely sensitive issues, and they are not specific to tungsten mining. In fact, tungsten operations have often a smaller environmental impact than the more common base metal (lead, zinc, copper) or gold mining operations: beneficiation requires generally much lower or no usage of chemicals, and the levels of hazardous metals as arsenic and lead in the deposits are often low.

Mining projects have often a significant impact on the local communities. It is important to minimise negative impacts on one side, but promote reasonable and sustainable projects on the other side. Critics of mining in many industrialised countries are pushing the problems to less developed countries, which have lesser control on the possible impact management. It is important to assure the right balance between environmental impact, impact mitigation, social advantages (creation of employment) and possible disadvantages (eg, relocation), tax revenue, regional development opportunities and the economic benefit for the mine owner.

The level of environmental studies required to advance a mining project are often prescribed by legislation. In addition, funding of projects is often dependent on the adherence to the Equator Principles (refer to info box [Equator Principles](#)).

Environmental studies can be divided into three overlapping areas: baseline studies that describe the current status, the assessment of the impact of the mine on the natural environment, and a management plan to mitigate the impact. An important issue is timing: the baseline studies require generally to record data covering an entire annual cycle of climate, ground water and natural habitat in the surrounding of the mine. Therefore, baseline studies are often started early in the evaluation process, in order to collect the required data without undue time pressure.

Social impact depends largely on the scope and location of the proposed mine. In the case of a medium-scale underground mine in an industrialised country, social impact might be almost nil, while a larger-scale open pit mine in an area with an indigenous population having a traditional life-style might have a huge social impact: relocation, loss of ancestral values, alcohol-related problems and similar, which need to be minimised and offset by adequate management systems and significant efforts in direction of training, schooling, improved health care and regional development (respecting cultural heritage).

In the end, a mine will only then be fully successful, when it obtains a “social licence” – all stakeholders, and especially the local population,

need to be convinced that benefits offset (and ideally exceed) the detriments of mine development.

While engineering studies are often undertaken by consultancy groups in the main mining countries, social and environmental studies require local knowledge and in their best case are developed jointly by experienced expatriates together with local or regional experts, and thus promote knowledge transfer.

### Equator Principles

*The Equator Principles (EPs) are a set of standards to assess and manage environmental and social risk in project financing. They were elaborated in 2003 by a group of leading banks, in collaboration with project developers, NGOs, the International Finance Corporation (IFC) and the World Bank. A revised set of the EPs has been in force since 2006. While the standards are voluntary for the project developer, financial institutions that subscribe to the EPs will not commit loans for financing projects that are unable to comply with these standards. Around 70 of the most important international project financiers have adopted the EPs, which makes them a de-facto standard to assess major developing projects world-wide, including mining projects.*

## Permitting

Permitting can be a very time-consuming and frustrating process for the prospective operator. While the original exploration permits are clearly issued with the intention to progress a discovery to an operating mine, authorities outside of the traditional mining countries are sometimes taken by surprise when this actually happens. The historically often poor track record of the mining industry (numerous abandoned mine sites require public funding because the operators simply “disappeared” and a number of well-publicised environmental disasters related to mining) caused understandably a sceptical approach to new mining applications, and the permitting authorities try to play safe by imposing very stringent regulations.

It is a must for the potential miner to involve from the outset all stakeholders and good communication is invaluable to build trust and obtain support from the local population and regional governments. This mutual trust and the feeling that the operation is actually beneficial for the region can help to overcome unspecific opposition by anti-mining groups.

In general, permits are required from various authorities, and beside the actual “mining” cover issues like construction, water supply and discharge, environmental compliance, explosives and might involve tricky issues like employment of expatriates and knowledge transfer.

There is also a tendency to oblige operators to strive for value adding by not exporting concentrates, but going further down-stream. In the case of tungsten, a significant annual capacity and long lifetime of the resources is required to justify downstream upgrading to APT. This needs to be communicated.

Permitting is a staged process, and while many permits can be obtained rather early in the process, final permits might only be available after construction, and thus a residual risk remains throughout financing and construction. Permitting risks are also detrimental to off-take commitments, which rely on prompt delivery according to a pre-approved schedule. It is thus of the utmost interest to the mining company to handle the entire permitting process with greatest care – and that might prove to be particularly challenging to inexperienced Junior Resource companies as typical for the tungsten sector.

## Marketing, Financing and Construction

Tungsten is not traded on a metal exchange, and it is not possible to hedge concentrates. Most concentrate is traded directly between mines and APT / down-stream producers. Therefore, the market is fairly opaque, which makes it difficult for a newcomer to get a good idea of the expected revenue for his product. However, various journals (London Metal Bulletin, Metal Pages, Ryan's Notes,...) publish price indications for APT and concentrate.

Due to the small size of the market, it is difficult to assure off-take – even if the price is right. For example, during the Global Financial Crisis in 2009, the APT quotation did not decrease as much as the prices for more common metals; however, not because the market remained intact but rather due to the absence of any market.

The tungsten mining sector is a playground for Junior Resource companies – major mining companies are generally not interested in this market. This, and the limited understanding of the tungsten market by investors, makes financing even more challenging. Preliminary Economic Assessments and Feasibility Studies recently completed for a number of projects show very favourable economic indicators (Internal Rate of Return, Net Present Value), but this is based on the assumption of guaranteed off-take of the entire production – which is illusory if several of the large-scale projects would be developed contemporaneously. Projects currently under consideration have planned capital investments of up to several USD 100M.

At the same time, there is persistent hesitation of the downstream companies to go upstream and look for backward integration.

In summary, these factors limit access to financing, which will minimise the risk of sudden oversupply followed by yet another wave of renewed mine closures. However, the development of some additional tungsten concentrate capacity is a must to balance the supply of the downstream industry. The most likely approach is that a few promising projects will collaborate closely with the downstream industry and by having solid off-take contracts in place will be able to obtain financing.

In most cases, once a larger-scale mining project obtains financing, construction will still take two to three years before initial production commences.

**Part 2** of this article will look into operational practices in tungsten mining and features with many examples from the worldwide industry. Due to be published in the next ITIA Newsletter – December 2012.

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*The ITIA is most grateful to Mr Steffen Schmidt and to Wolfram Bergau-und Hütten AG for this comprehensive report "From Deposit to Concentrate: The Basics of Tungsten Mining" written especially for this Newsletter. The first part appears in this Newsletter and the second part will follow in the December issue.*



## Nickel-tungsten Tapes Support the Second Generation of High Temperature Superconductors

*W.D. Schubert;  
Vienna University of Technology*

When certain materials are cooled below a characteristic critical temperature, their electrical resistance becomes exactly zero. This phenomenon is called Superconductivity, and was described for the first time for mercury in 1911 by Heike Kamerlingh Onnes [1]. However, as the critical temperature for most metallic materials is well below 10 K ( $-263.15^{\circ}\text{C}$ ), cooling must be performed below this temperature, which is costly and usually done with liquid Helium (boiling point: 4.22 K, resp.  $-268.93^{\circ}\text{C}$ ). For many applications in the energy sector this high operating expense is a clear disadvantage. Nevertheless, so-called low-temperature-superconductors (LTS), based on NbTi or Nb<sub>3</sub>Sn have become attractive solutions for high end applications, such as superconducting magnets, MRI/NMR machines or particle accelerators (for example at the Particle Collider at CERN) [2]. In 1986, it was demonstrated that certain ceramic materials have a critical temperature above 90 K ( $183.15^{\circ}\text{C}$ ). This discovery became a breakthrough for a new generation of superconducting materials, called high temperature superconductors (HTS) due to the fact that these ceramics become superconducting already on cooling them down with liquid nitrogen which has a boiling point of 77 K ( $196.15^{\circ}\text{C}$ )<sup>1)</sup>.

So far, two HTS ceramics have achieved technical importance: Bismuth-strontium-calcium-copper-oxide (BSCCO) and Yttrium-barium-copper-oxide (YBCO) with critical temperatures of 110 K and 92 K, respectively [2].

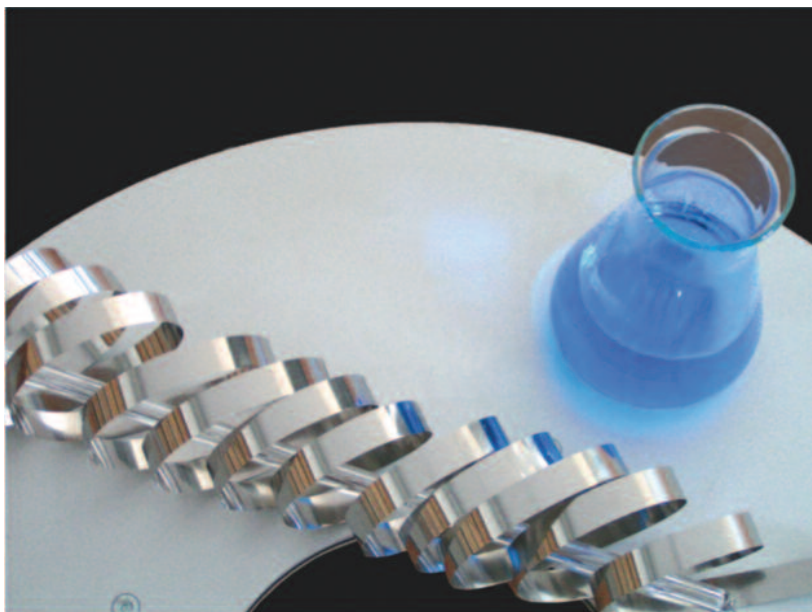
To be usable for electric devices, these ceramics must be formed into wires or tapes. In the case of the so-called first generation of HTS (1G) this is done by packing the ceramics into silver tubes and drawing the tubes into wires or flattening them into tapes (Powder-in-Tube process). The ceramics are then transformed into the superconductive state by a series of thermo-mechanical treatments which lead to an alignment of the BSCCO grains [2]. The drawback of these wires is the use of silver as cladding material, which makes the solution rather expensive, and the fact that a complete alignment of all crystal axes is not possible during processing, which significantly lowers the maximum reachable current densities for application. In addition, other than in the case of YBCO, BSCCO's performance drops in the presence of a magnetic field [3].

In 2007, the first industrial application of HTS materials was demonstrated at weseralu GmbH in Germany for the magnetic heating of extrusion billets [2]. Since then, several HTS cable projects have been established worldwide, including a 600-meter-long 138 kV cable system with a rated power of 574 MVA, which was put into operation in the grid of the Long Island Power Authority [2,4]; **Fig. 1**.



**Figure 1:**

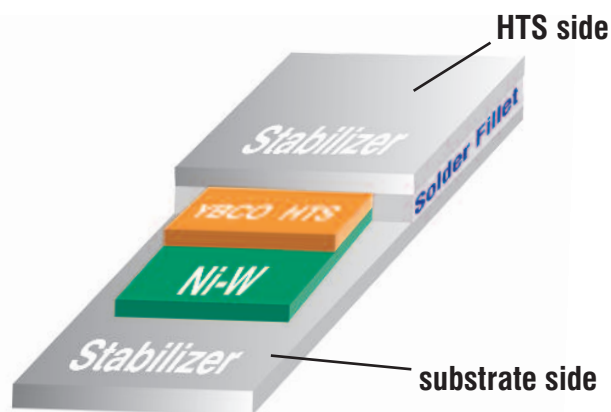
*Long Island Power Authority HTS cable project; the cable system (600-metre-long, 138 kV) was put into operation in 2008 with a rated power of 574 MVA; courtesy of AMSC [4].*



**Figure 2:**

*Cube textured Ni-5at%W strip formed by standard rolling and annealing processes; cube texture sharpness of the strip is an important property for the aligned growth of the superconducting layer (grains) and its optimal performance; courtesy of Deutsche Nanoschicht GmbH, Germany.*

<sup>1)</sup> Note: liquid nitrogen is 50 times less expensive than helium [3]

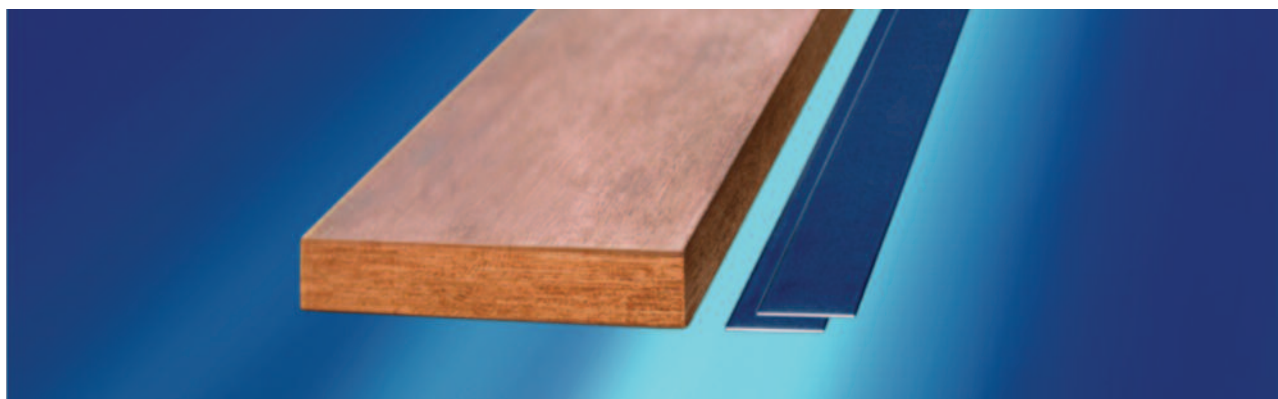


**Figure 3:**

Layer architecture of an Amperium® Wire; the YBCO ceramic film is deposited on an oxide-buffered Ni-5at%W alloy strip that is laminated and soldered between two metal strips (stabilizers) which provide physical protection and electrical stability for the very thin HTS layer: source: AMSC. [5]

Several techniques were applied for the coated tape architecture, such as reactive sputtering or pulsed laser ablation, but chemical solution deposition (dipping, slot-die coating, or even ink-jet processing [8]) is widely considered to be the most promising route for scaling up the production of HTS tapes [2].

American Superconductor (AMSC) is offering a high temperature superconductor (HTS) wire designed and engineered for use in large-scale power applications such as generator coils, current limiters and power cables (Amperium® wire). The layered structure is laminated and soldered between two metal strips, which may be copper, brass or stainless steel, and which provide a physical protection and electrical stability for the HTS layers [5]. The HTS insert is encapsulated in a thin silver coating. The critical current performance is enhanced by “flux pinning” features in HTS materials by adding small amounts of secondary materials (rare-earth oxides) during processing.



**Figure 4:**

Current density of copper vs. HTS wire; the size comparison refers to the same ampacity; in the cross section this means a reduction of 100 to 500 times depending on application; by courtesy of Dr. Bäcker, Deutsche Nanoschicht GmbH, Germany, source: AMSC.

Today it is clear that the first generation of HTS will not fulfill the demand of a cheap solution for the future. The production of low cost coated conductors is the main prerequisite for the spreading of the use of superconductivity in power applications [2, 5]. Therefore, new ideas had to be developed. In the second generation (2G) of high temperature superconductors, textured metallic strips are used for the aligned growth of a buffer layer (to avoid contamination of the superconductive layer by nickel) and an overlying very thin layer of superconducting yttrium-barium-copper oxide (YBCO). Such strips are manufactured in long lengths by standard rolling and annealing processes (Fig.2). Currently, the most promising solution is designed on a metallic Ni-5 at% W (13.7 m% W) strip (RABiTS\*)<sup>2</sup> coated with a La<sub>2</sub>Zr<sub>2</sub>O<sub>7</sub>-CeO<sub>2</sub> buffer structure, and a thin superconducting YBCO top layer [2-6]; Fig.3. Cube texture sharpness and thermal stability of the metallic tape is increased by the alloying of nickel with tungsten [7].

The thickness of the wire is about 0.2 mm (200 μm) with an YBCO layer of 1 μm only. The key for optimal wire performance is how to align the cubic nickel grains already introduced during rolling of the Ni-W parts to form thin sheets or foils. Then this alignment is transferred to a deposited buffer layer and, finally, to the thin YBCO film [3]. The ampacity of HTS wires is up to 100 times higher than of conventional copper wires. The higher the current density, the smaller (thinner) the wire can be (Fig.4). This renders the possibility of fabricating new electric power devices that are more compact, cost less to operate, and use less energy [2,3] (Fig.5).

<sup>2)</sup> RABiTS means: rolling-assisted biaxially textured substrates [6].





**Figure 5:**

HTS wires can lead the way to a more energy efficient future; compared to the weight of 450 tons of a conventional (copper and aluminium based) wind generator which produces up to six megawatt power, a modern HTS arrangement will weigh 120 tons only and produce eight megawatt at a reduced cost of one million Euro [9]; photo courtesy of en.bestpicturesof.com.

**Acknowledgement:** The author would like to thank Dr. M. Bäcker, Deutsche Nanoschicht GmbH, Germany, for discussions and support.

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## ITIA NEWS ITEMS

### ITIA MEMBERSHIP

#### Welcome to:

- **Almonty Industries Inc** Exploration, development and production at the Los Santos Mine, near Salamanca in western Spain. The mine has been in production since 2008 and has an annual output of approximately 225,000 tonnes of ore (at 0.25% WO<sub>3</sub>).
- **Ganxian Shirui New Material Co Ltd** Producers and suppliers of wolframite (14 mines), ammonium paratungstate, tungsten oxides, tungsten powder and tungsten carbide powder, ready-to-press powders and cemented carbide products.
- **Grondmet GmbH Co KG** Trading and stockholding of ferro tungsten, ammonium paratungstate, yellow tungsten oxide, tungsten blue oxide and pure tungsten.
- **Jiangxi Yaosheng Industry and Trade Development Co Ltd** Producer of tungsten concentrate with 5 wolframite mines, ammonium paratungstate, tungsten oxides, tungsten metal, tungsten carbide and ready-to-press powder and cemented carbide products.
- **Tungsten West NL** A tungsten exploration and development company focused on small high grade projects.
- **Wolfram Camp Mining Pty Ltd** A fully-owned subsidiary of Deutsche Rohstoff AG, developing and operating the Tungsten-Molybdenum mine "Wolfram Camp" In Queensland, Australia.

#### And welcome back after a brief absence:

- **Zhuzhou Cemented Carbide Group** Producer of ammonium paratungstate, tungsten trioxide, tungsten blue oxide, tungsten metal, tungsten carbide, fused tungsten carbide, mining / oil field drilling / exploration tools, wear parts and cutting tools.
- **Zigong Cemented Carbide Co Ltd** Producer of ammonium paratungstate, tungsten trioxide, tungsten blue oxide, tungsten metal (powder and wire), tungsten carbides and cutting tools.



Compliance with REACH - a service from the ITIA

The Lead Registrants successfully submitted registration dossiers of the three lower tonnage band substances to ECHA in 2011:

- ammonium metatungstate (100–1,000tpa)
- fused tungsten carbide (100–1,000tpa)
- tungstic acid (10–100tpa)

Thus registration of all the substances currently covered by the Consortium is complete.

Another two companies, Haldor Topsøe A/S (Denmark) and Tejing Tungsten GmbH (Germany) joined the Consortium in 2012.

For further details of the Consortium work programme, a list of members, and conditions for the purchase of Letters of Access etc, please refer to the Consortium websites –

[www.tungstenconsortium.com](http://www.tungstenconsortium.com) and  
[www.sief.tungstenconsortium.com](http://www.sief.tungstenconsortium.com).

## 24th Annual General Meeting, 2011, Nice

Opening the 24th AGM, the President, Stephen Leahy (Chairman & CEO, North American Tungsten), welcomed more than 250 delegates from 27 different countries and in particular the representatives from six companies which had joined the Association during the year.

Leahy expressed the thanks and appreciation of all present to Marc Mounier-Vehier and his colleagues at Eurotungstène-Eramet for their generosity in hosting the event and to Philippe Lavagna of Specialty Metals Trading for kindly supporting the Eurotungstène-Eramet dinner on Wednesday evening.

He had no doubt that everyone would enjoy the wonderful setting of Nice enclosed by an amphitheatre of hills, extending around a beautiful bay, making it indeed the capital of the Riviera. First populated in 350BCE, rich in culture and home to many notable historical figures such as Garibaldi, Matisse and Chagall, Napoleon reclaimed the region for France in the 1860s from the House of Savoy.

### New Secretary-General An End and a Beginning of an Era!

Leahy said that Michael Maby had announced his retirement as Secretary-General in March 2012 after 37 years in the tungsten business and, as one of the founders of the ITIA in 1988, he would be sorely missed. He was being honoured with the lifelong title of Emeritus Secretary-General. His efforts and dedication were legendary and he was a large part of the reason for a healthy, effective and vibrant ITIA today.

The new Secretary-General would be Burghard Zeiler, a man whose credentials were impeccable and whose leadership qualities were second to none. Zeiler had had a distinguished career in tungsten, joining Wolfram Bergbau in 1991 and leading the company through its impressive growth phase over the next two decades. Zeiler had been an active member of the Executive Committee since 1999, serving as President from 2006 to 2008.

Leahy concluded by welcoming three old friends who had come specially to bid Maby farewell (vale) and to hail (salve) Zeiler.



*Stephen Leahy, (left),  
with Marc Mounier-Vehier*



*Michael Maby (left) and Burghard Zeiler*



*Philippe Lavagna*



*Guests Jaap and Alie Koeleman*



*Guests Jocelyn Waller (left) and Shinichi Ogura*

## Celebrating the ITIA's 25th Anniversary Annual General Meeting, 17-20 September 2012, Beijing

China Minmetals Group will kindly host this meeting at the Regent Beijing Hotel with support from the China Tungsten Industry Association. The provisional programme is as follows:

**Mon 17 September** – ITIA HSE Committee Meeting  
– Consortium Technical Committee Meeting

**Tue 18 September** – Joint meeting of ITIA Executive and HSE Committees  
– ITIA Executive Committee Meeting  
– China Minmetals' Reception and Dinner in the Hotel

**Wed 19 September** – ITIA AGM  
– Tungsten Consortium Meeting  
– ITIA Reception and Dinner

**Thu 20 September** – ITIA AGM

Further details of this annual event, at which the worldwide tungsten industry gathers, including presentations and registration forms are available from the Secretariat or can be downloaded from the ITIA website.