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From Deposit to Concentrate: The Basics of Tungsten Mining

Part 2: Operational Practices and Challenges

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Figures 1 - 4: *Wolframite in quartz vein, San Finx; blasthole drilling, loading and hauling at Los Santos Sur (both in Spain), stripping of overburden and packaging of scheelite concentrate at Tasmania Mines' Kara operation, Australia.*

Part 1 of this article, Project Generation and Project Development, was published in the Newsletter of June 2012. It covered the basics of tungsten geology and deposit types and then followed the way from exploration methods, resource calculation and Feasibility Studies through to economic constraints and funding of project development.

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.

Mining and Beneficiation

Mining - General Considerations

All mining of primary tungsten ore is hard-rock mining, a process comprising various sequential operations, either in an open pit or underground environment:

The ore (and its encasing waste rock) has to be:

- Drilled,
- Charged (loading with explosives),
- Blasted,
- Mucked (loaded from the face or stope into a truck or railcar), and
- Hauled to the plant.

There are a number of preparatory and support operations, which might or not be required, depending on mining method and other circumstances, including:

- Waste drifting or stripping to reach the ore,
- Stope development,
- Ground support (to stabilise the rock after excavation),
- Backfilling of mined-out areas, and
- Reclamation in open pit environment.

Technical services like surveying, grade control sampling and geotechnical investigations ensure that extraction follows the mine plan, the contact between ore and waste is correctly followed and pit walls or underground openings remain stable. Geologists and engineers work hand in hand to optimise the day-to-day production, explore for new resources replacing mined tonnages and plan future mining operations.

Over the years, a large number of different mining methods have been developed to allow the most appropriate and economically most advantageous extraction of the given ore.

Figure 5: Maoping Tungsten & Molybdenum Mine, Jiangxi Province, China.

Classic set-up of a major underground mine with headframe (background, right), crushing and screening (background, left) and the mill building in the front with the latter being built on a slope to facilitate gravity flow throughout the process.

The selection of a suitable mining method including the question whether to opt for open pit or underground mining depends on numerous governing factors, including the following parameters

- Ground conditions (physical properties of the ore and the encasing rock mass - e.g. massive or broken);
- Size of the deposit and proposed annual production;
- Ore value (high grade versus low-grade deposits - this governs the money that can be spent to extract the ore); and
- Economic, environmental, legal and regulatory considerations.

These are general parameters, valid for any commodity. In principle, a tungsten mine might use any mining method used for other hard rock mines, but as a niche commodity, moderate-sized mining projects are more likely to be developed, and application of capital-intensive high-capacity methods such as block caving is unlikely.

Some examples of considerations in choosing the appropriate mining method:

- Is the orebody large and near the surface (open pit) or narrow and steeply dipping or in greater depth (underground mining)?
- There are methods, where detailed knowledge of the orebody is required from the onset (example: block cave), while others can easily be adapted during production (example: cut & fill).
- There are methods which require simple straight ore contacts (sublevel stoping with large sublevel spacing), while others can follow the orebody perfectly around any bend (narrow vein open stoping).
- There are methods where the blasted tonnage is available immediately but pillars have to be left due to safety concerns (open stoping). Other methods use ore temporarily to stabilise the ground, but this ore remains blocked until the end of a certain mining phase (shrinkage stoping).
- If tailings placement on the surface is difficult, the required volume can be reduced by underground placement: tailings can be part of the backfill design. This would necessitate sublevel mining with either consolidated or unconsolidated fill, but is not an option for sublevel caving.
- If ore values are high, it is better to choose a mining method that optimises extraction rather than cost (eg., cut & fill or sublevel stoping with cemented fill and secondary pillar recovery).
- If ore values are low, mass mining methods allow production at low unit value, but these methods incur high loss and/or dilution.

Open Pit Mining

Most active tungsten mines are of moderate scale (production of a few 100,000t of ore per year), and thus the few operations that use open pit mining techniques are of a much smaller scale than for example copper or iron ore mines

Currently, open pitting is used for example at Los Santos (skarn, Spain), at Kara (skarn, tungsten is by-product, Australia), for part of the production at Cantung (skarn, Canada) and in various Chinese operations. Most of the currently promoted tungsten mining projects would also be using open pitting.

Some proposed tungsten mining projects call for mining rates of some 20,000t per day of low-grade ore and would be using large-scale loading and hauling equipment.

Figures 6 - 7: Open Pit Mining: Los Santos, Spain

Above: Aerial photograph of the Los Santos tungsten operation near Salamanca in Spain, showing various open pits, large terraced waste rock deposals and the beneficiation plant;

left: loading and hauling with medium-scale open pit machinery; blast hole drill rig in background.

Figures 8 - 10** (left and above)**: Technical Service: Los Santos, Spain
Examples of Technical Services in an open pit environment.
Top left: Use of remote-controlled helicopter for 3D photography of pit walls for geotechnical assessment; Bottom left and above: grade control sampling of blast holes and delineation of the ore zone ahead of blasting.

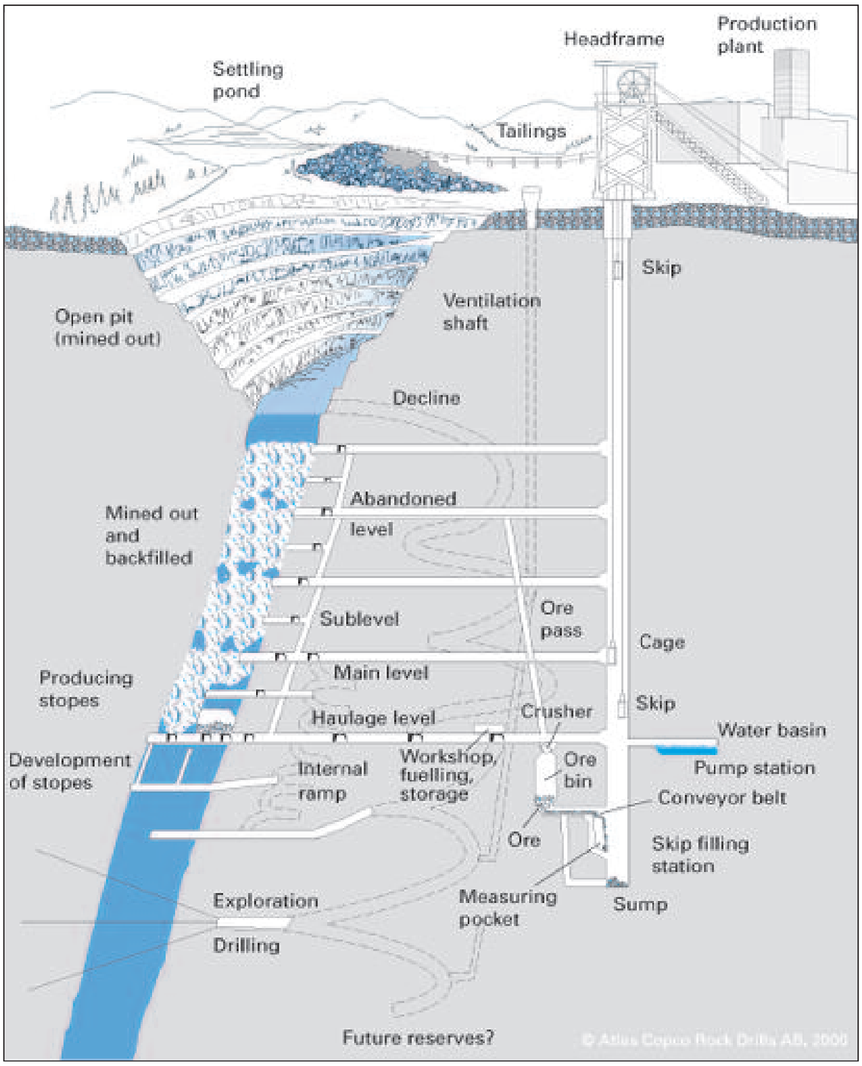


***Figure 11** (right)**: Basic infrastructure of an underground mine.** From SMITH M (Ed) [2008]*

Underground Mining

Underground Mining Methods

Over the centuries, many different underground mining methods have been developed to face the challenges of highly variable ground conditions, geometry and production rate.

The basic infrastructure of a typical underground mine is shown in figure 11. The most iconic building of many underground mines is a head-frame. However, many underground operations are nowadays developed solely by ramping, i.e., access to the underground workings is via a portal.

Figure 12: Head-frame: *Maoping Mine, Jiangxi Province, China. Shaft access for personnel and material to the underground workings and transport of ore to surface by skip.*

Figure 13: Mine Portal: *Mittersill mine, Austria. Access of personnel and material through ramps; ore transport to surface in this case by conveyor belt through a 3km-long tunnel directly to the mill.*

Underground mining methods commonly used in, or considered for, tungsten mining include:

- Best suited for steeply dipping veins or narrow well-delineated skarn orebodies
    - Narrow-vein open stoping [example: Chollja, Bolivia]
    - Shrinkage Stoping [example: Pasta Bueno, Peru]
    - Cut & Fill with resuing fill
    - Cut & Fill [historic: Springer, USA]
- Best suited for flatly dipping veins or flat tabular skarn orebodies
    - Room & pillar mining [example: Panasqueira, Portugal]
- Best suited for thicker tabular or lense-shaped orebodies with medium to steep dip (or very thick flat orebodies)
    - Cut & fill
    - Post pillar mining [historic: Dolphin, Australia]
    - Sublevel stoping with delayed fill [example: Mittersill, Austria]
    - Sublevel stoping with cemented fill and secondary pillar recovery [example: Cantung, Canada]
    - Vertical Crater Retreat
    - Sublevel caving [example: Mittersill, Austria]

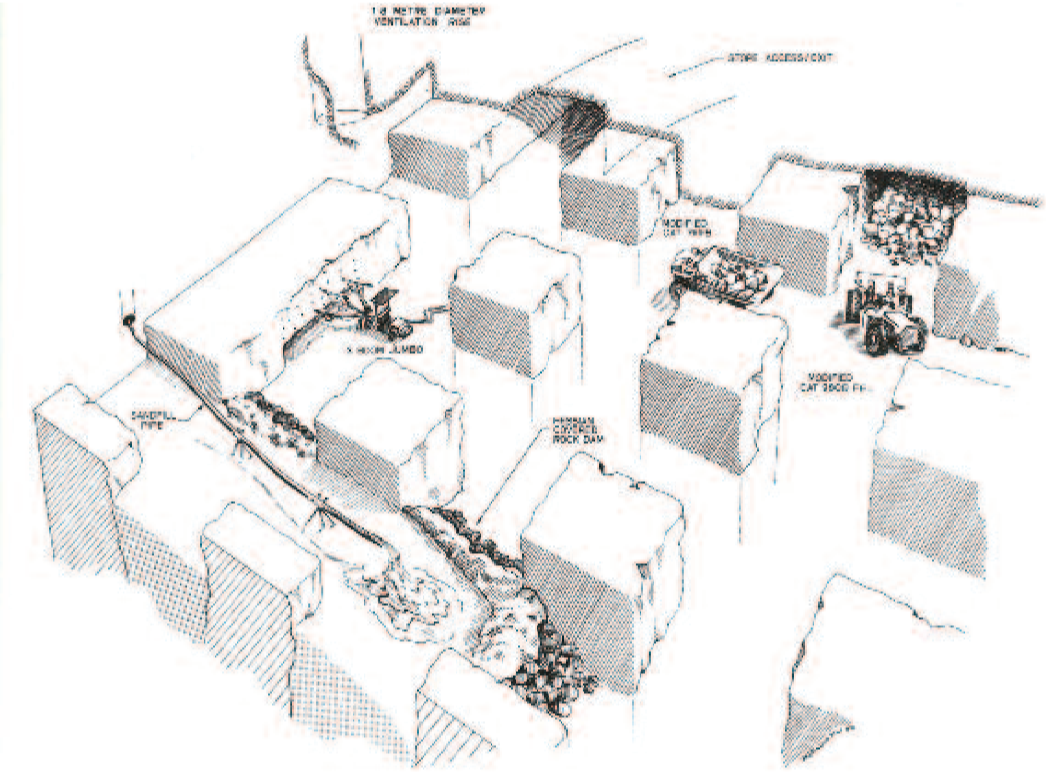
The various underground mining methods are explained in detail in HUSTRULID, WA & BULLOCK RL (Eds) [2001]. In the following, some selected aspects of these methods are shown in sketches and photos from tungsten mining operations.

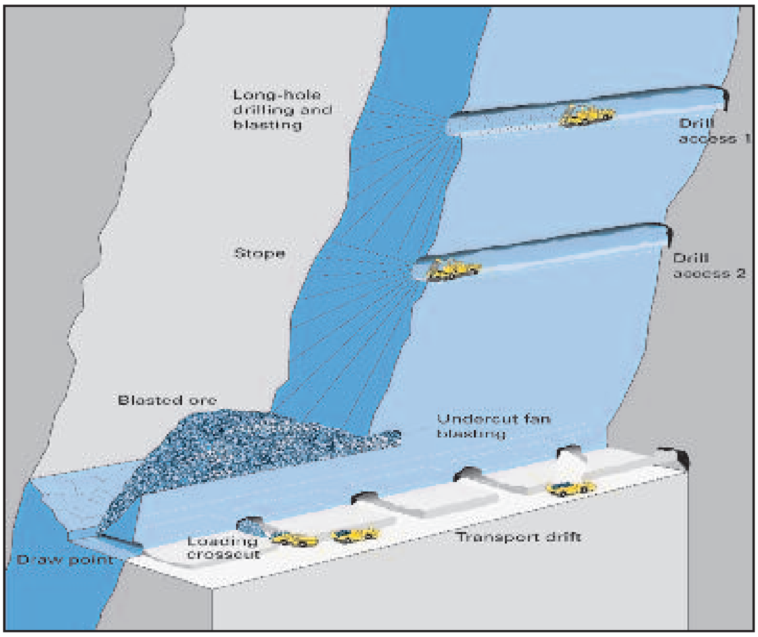
Figure 14: Narrow-vein open stoping, *using timber props as support. Chollja, Bolivia. Vein zone is less than 1m wide.*

Figure 15 *(above)****: Narrow-vein open stoping,*** *using small pillars as support, San Finx, Spain.*

Figures 16 - 17 *(right)****: Room & pillar mining*** *at Panasqueira, Portugal. The narrow flat-dipping orebody (quartz vein with wolframite, visible in bottom picture) is extracted in stages, leaving first 11x11m pillars and then 3x3m-pillars only, giving an overall recovery of 84%.*

Figure 18 *(below)****: Post-pillar mining*** *in the historic Dolphin mine, Australia. Sand fill by tailings (bottom left) is used as floor for subsequent lifts (drill jumbo is set-up in centre left), making this a combination of cut & fill and room & pillar mining.*
From HUGHES FE (Ed) [1990]





Figures 19 - 20: Sublevel stoping: *left mucking of a sublevel stope by remote-controlled scooptram in the Mittersill mine, Austria; above a sketch depicting the set-up of large-scale open stoping using draw-point, from SMITH M (Ed) [2008]*

Track-bound versus rubber-tyre equipment

There are two fundamentally different techniques in underground mining:

- "conventional" / track-bound (electric drives for haulage, pneumatic (compressed air) for semi-stationary tasks): pneumatic drills (often hand-held), pneumatic over-head loaders, haulage with locos and mine carts.
- Rubber-tyre equipment (diesel-powered plus electric for semi-stationary tasks): drill jumbos, diesel-driven scooptrams (LHD – load/haul/dump), underground trucks.

The entire mine is usually planned around the fundamental up-front decision between track-bound and rubber-tyred equipment. Therefore it is also difficult and costly to change the set-up at a later stage, for example by introducing scooptrams in a conventional mine. Nowadays, the so-called "conventional" approach is often considered outdated, while rubber-tyred becomes standard. However, many tungsten deposits are comparatively small or orebodies very narrow, and conventional track-bound mining might still be the most economical choice.

"Rule-of-thumb" characteristics of track-bound mines versus operations using rubber-tyre equipment are shown in table 1.

In practice, the narrower the orebody and the lower tonnage per vertical metre, the better suited is probably the "conventional" approach. In contrast, large-scale mining is generally undertaken with rubber-tyre equipment.

Loading and partly drilling / blasting in large open stopes requires remote controlled equipment: the machine operator remains in the secured area of the mine and (either with direct sight or via cameras) directs the loader (or other equipment) with a remote-control unit using joy-sticks.

It is important to highlight that one system is not better than the other, but the right system needs to be selected depending on the deposit, economic constraints and mining approach in question.

Some mines apply also a combined approach, often using LHD near the face (active working) and rail haulage for longer distances. One example would be the Panasqueira tungsten mine in Portugal.

Related and overlapping to the selection of the mining equipment is the question of haulage to the mill: shaft versus ramp; haulage by truck, train or conveyor belt.

Development drifting to access the orebody and to provide the required infrastructure for mining might be a significant factor of the overall underground work. Semi-permanent openings need to be supported to allow safe access. This applies especially to the large-section drifts required for LHD mining. The overall work cycle in drifting comprises drilling, charging of explosives, blasting, scaling (to remove lose rock from the backs), mucking and ground support (installation of rock bolts and wire-mesh and/or shotcrete).

It is not untypical that mining operations struggle to keep up with development drifting: ore production by stoping is often far easier – and it is this operation that gives immediate cash flow.

Table 1: Comparison between conventional and rubber-tyre approach to underground mining.

	"conventional" / track-bound	rubber-tyre equipment / LHD
"iconic equipment"	jack-leg drill, overhead loader, locos & mine carts	drill jumbos, scooptrams (LHDs = load-haul-dump), mine trucks
access	horizontal adits (requires suitable topography), shaft	ramps (straight or decline)
drift size	generally small (2 x 2m)	generally large (>4 x 4m), requires much higher degree of ground support (bolting, screening, shotcrete).
selectivity	high - leads to low dilution	low - better suitable for larger orebodies.
mine layout	rather inflexible: only horizontal development at regular intervals (plus shafts/raises)	flexible, as various gradients possible; no fixed sublevel system required.
power supply	compressed air, electricity for haulage (can be batteries)	diesel, electricity for drilling
productivity	low - many active stopes required	high - individual stopes provide high daily tonnage
capital costs	capex for equipment low (but: many units required); small-section development has low cost per metre of advance; but: shafts are expensive, pre-production development might be extensive.	capex for equipment high; large-section development costly (per meter); but: often no shaft required, pre-production development can be optimised.
operation costs	high - especially high labour cost per tonne of ore.	low - especially low labour cost per tonne of ore.

Figures 21- 25

(from top left, counter-clockwise):

Underground mining equipment

Left and bottom: drilling with pneumatic jack-leg drill, loading with air-driven overhead loader and rail haulage with battery loco at the Pasta Bueno tungsten mine, Peru (narrow-vein mining).

Top centre and right: electro-hydraulic twin-boom jumbo, loading with 15t scooptram and truck haulage at the Mittersill mine, Austria (large-scale stockwork mineralisation).

Beneficiation ("Ore Dressing")

Other than mining, beneficiation is highly dependent on commodity and ore minerals. In the case of tungsten, the specific properties of the tungsten minerals govern the design of appropriate beneficiation flow-sheets.

Both scheelite and the wolframite series have a high density and are brittle. Only scheelite is readily amenable to flotation (however, flotation properties are less pronounced than those of common sulphide minerals). Wolframite, in contrast to scheelite, is paramagnetic.

Thus beneficiation techniques focus on high density and/or flotation (scheelite) or magnetic separation (wolframite).

Figures 26 - 27: Primary and secondary crushing *in a large underground cavern at Mittersill mine, Austria. Jaw crusher (top) and two cone crushers and sieving plant (bottom).*

Comminution: Crushing and Milling

Due to the brittle character of the tungsten minerals, comminution, (staged size reduction to liberate the individual grains of the ore mineral from the surrounding waste) has to be careful to avoid overgrinding. The term "overgrinding" signifies that the mineral particles following the given stage of crushing, grinding or milling are finer than required to liberate the particles and to recover them in the current stage. This leads inevitably to losses as, with decreasing grain size, it becomes increasingly difficult to recover the ore mineral.

Thus, at every stage of size reduction, appropriate sizing techniques will endeavour to minimise formation of fines and the following concentration step will endeavour to recover the maximum of the liberated grains. Size reduction will always be only to a diameter, where a significant amount of the ore mineral is liberated. The only exception is pre-concentration of run-of-mine ore: visual (hand-picking), optical or radiometric methods intend to upgrade the material without reaching final concentrate grade.

As for the comminution technique itself, there are certain techniques that are more sensitive than others. For example, roll milling is superior to the other methods, but has higher unit costs due to high wear. Rod mills are still better than ball mills.

Figure 28: Secondary crushing to grinding *in an artisanal operation in Bolivia, using a so-called quimbalete.*

Figure 29 *(left)*: **Milling:**
Staged rod and ball mills and spiral classifiers at the Vostok-II mine, Far-East Russia.

Sorting and Pre-Concentration

At some tungsten projects, pre-concentration methods are used to discard a portion of the run-of-mine ore to increase the head grade prior to traditional beneficiation methods.

- *Hand-picking*

  In case of large grade contrasts or good visual distinction, hand-picking is a very effective way of up-grading, although in countries with high labour costs, the latter might be prohibitive. Used in several tungsten deposits in China and world-wide as part of the upgrading chain in artisanal mines.

- *Optical sorters*

  Optical sorting can be used where a strong brightness contrast exists between higher-grade portions of the overall run-of-mine ore, and dilution. At the historic Mt Carbine operation, optical sorting was used in the 1970s and 80s to separate the wolframite-bearing quartz-veins (white) from the sterile host rock (grey). Hence, despite the actual ore mineral being black, the positive search property was "white".

- *X-ray sorters*

  The most advanced approach, because it actually allows looking "inside" the individual rock fragments. Tungsten minerals are strongly X-ray-resistant, and thus, appear "black". This, however, is also the case for many sulfide minerals, and sorting of sulphide-rich ore is less efficient.

  In the sorter, fragments of a certain grain-size bandwidth are individualised on a small conveyor belt, pass the x-ray unit, and then, depending on the percentage of "black", are either shot out or not by a short blow of compressed air through a row of fine nozzles at the end of the conveyor belt.

Figure 30-31: Hand picking:

Hand-sorting at the Taoxiken mine, Jiangxi, China.

Large wolframite (reinite) crystal with porous (honeycomb) texture – will disintegrate into fine powder when crushed. Hand-picking is important to improve overall recovery. Gifurwe mine, Rwanda

Depending on the grain size of the tungsten minerals and the use of narrow grain-size bands, up-grade factors for the sorted fraction of 1:2 to 1:10 are achievable with minimal loss.

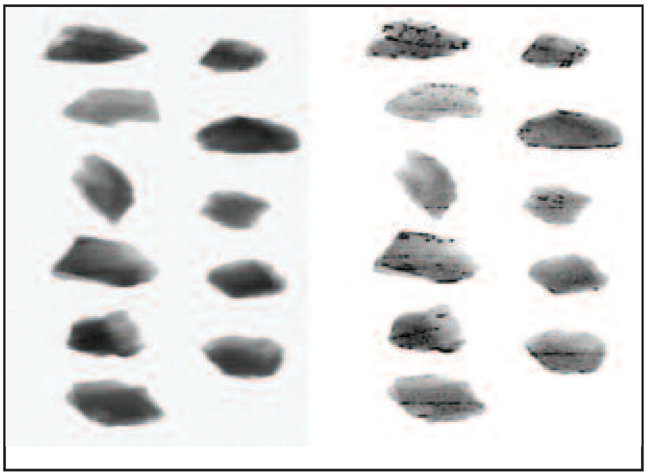


Figure 32: X-ray sorting: *ore fragments (2 - 3 cm length) translucent (left) and x-rayed (right). Mittersill mine, Austria.*

- *Gravitational Pre-concentration*

  Several gravitational methods, as described further below can also be used for pre-concentration. However, these methods will be ineffective in case of disseminated ore or to upgrade material with only little density contrast.

Gravity Enrichment

Upgrading techniques based on the density contrast between valuable mineral and the waste material have been employed since the onset of mining, several thousand years ago. Valuable minerals (e.g., gold) have often a much higher density than the surrounding rock, and this is also true in case of tungsten. Panning for gold is probably the best-known application of density contrasts to enrich the target mineral.

Density methods can be highly effective, leading to recoveries well above 90%, and they can be both very simple and highly sophisticated. Common to gravity enrichment is that it works best with well-sorted materials (narrow band of grain-sizes).

- *Artisanal methods*

  Artisanal miners “feel” the density of reddish pebbles from lateritic sources in their palms to distinguish between wolframite and waste. Or they use wind to remove light-weight fines before washing. Panning, of course, is wide-spread in artisanal mining, but access to water is a problem in many areas.

  The first step to more elaborate processes is the use of sluices, which might be simple ground sluices (dug in the ground) or various types of wooden sluices, or, at the opposite end of the grain size spectrum, corduroy sluices which allow material to be caught at grain sizes of less than 50μm.

  While traditional panning can produce final concentrates with more than 60% WO_3 content, sluicing is generally used as pre-concentration, followed by either panning or more elaborate methods like jigging and tabling.

Figures 33- 35: Artisanal methods: *from left to right: traditional panning of alluvial wolframite; manual jig and wooden sluice leading to corduroy sluice (downstream of a ground sluice); both at the Gifurwe mine, Rwanda. Wooden sluice boxes designed to minimise water consumption at an artisanal site in Bolivia.*

- *Dense-media separation (DMS)*

  The dense medium is a thick suspension of a heavy medium (e.g., magnetite) in water, which behaves like a heavy liquid with a well specified density: rock particles with lower density will float and can be removed. DMS is widely used when density segregation already occurs at coarse grain size. One example is the wolframite mineralisation at Panasqueira, Portugal. DMS concentrates are usually only pre-concentrates, which require further comminution and upgrading.

- *Spiral Concentrators*

  In a spiral concentrator, the ore particles flow spirally down-wards, and denser / heavier and less dense / lighter-weight particles are separated by the combined effect of centrifugal force and differential settling rates. Grain size and density-effects overlap, and spiral separation is most effective if used in narrow grain-size bands. There are no motors and no moving parts involved, which makes spiralling a very economic method.

- *Jigs*

  The idea behind a jig is that particles are introduced to a jig bed (usually a screen) and then thrust upward within a water column. The particles are thus suspended within the water and once the pulse dissipates, the particles settle again, those with higher density faster than the ones with low density. The repeated jigging action leads thus to a separation of the higher and lower-density particles on the jig bed, from where the density concentrate can be removed.

  There is a large variety of different jig types, from the basic Pan-African jig with bicycle drive to highly sophisticated circular jigs such as the Knelson, Kelsey and Falcon concentrators.

- *Shaking tables*

  Shaking tables are probably the metallurgically most efficient means of density separation, and they are commonly used to produce final concentrates from pre-concentrates obtained by jigging and spiral concentration.

  The sorting method combines a water film and rapid strokes, which make the particles crawl along the surface of the table and separate into larger, lower-density and finer, higher-density grains, which are then captured separately at the edge of the table.

  Various types and brands have been developed, such as Wilfley, Deister and Holman tables, specialising in the recovery of specific grain size bands.

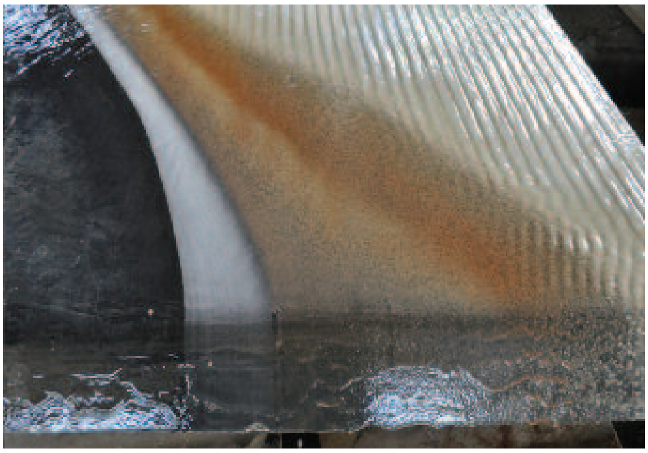
  A special type of shaking table are flotation tables, usually used to remove sulphides from density concentrates: the addition of a flotation reagent renders the sulphides hydrophobic and thus, they react like very low-density material and are discharged with the tailings.

Flotation

Froth flotation is a process taking advantage of differences in the hydrophilic or hydrophobic properties of the individual minerals. The ore is finely ground and mixed with water and selected reagents and then aerated to form bubbles. The hydrophobic minerals attach to the bubbles and can be skimmed off, while hydrophilic particles remain in the liquid phase and are discharged as tailings. Flotation reagents are used to selectively enhance (collectors) or decrease (depressants) the hydrophobic properties of minerals.

Figure 36: Gravity methods:

Gravity plant at San Finx mine, Spain (wolframite vein deposit). In background different spirals and jigs (right), in middle different shaking tables, in foreground flotation table.



Figures 37- 38: Gravity methods:

Top: Tabling section in the beneficiation plant of the Brejui mine, Brazil (scheelite skarn deposit) Bottom: distinct bands of scheelite (white), sulphides (narrow grey streak), and various silicates (red and greenish) on the tables at Brejui.

There have been attempts to float wolframite but, so far, only flotation of scheelite is common practice, using fatty acids as the collector. Unlike many flotation agents used in base metal beneficiation, fatty acids are uncritical for the environment.

Whole rock flotation means that the run-of-mine ore (possibly after pre-concentration by x-ray sorting or similar) is subjected to "positive" flotation of the scheelite content. In contrast, combined methods often produce first a high-grade concentrate by tabling. Lower-grade flotation concentrates are then produced from gravity tailings to increase overall recovery.

Another approach would be to use gravity to remove the low-density fraction before "positive" flotation of scheelite. This is of particular interest when calcite or fluorite are present that are activated with the same flotation reagents as scheelite and thus would lead to undue dilution of the concentrates.

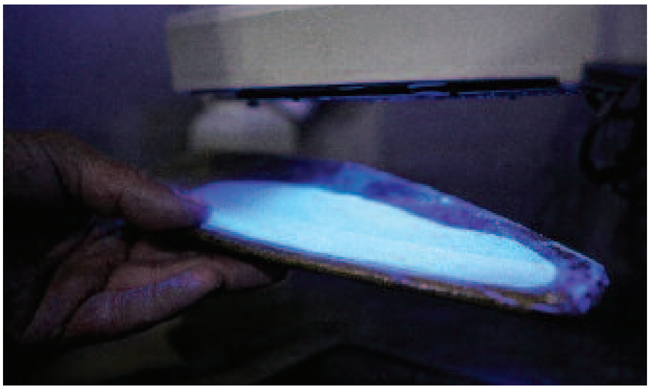
In the case of the Petrov process, flotation with fatty acids is undertaken at elevated temperatures which increase selectivity.

A modification of the Petrov process is the "Chinese" whole-of-ore flotation, where higher temperatures are only used in the collector cycle of cleaner flotation. This modification, together with the use of a severe reagent regime, including sodium silicate, leads to effective depression of Ca-bearing minerals other than scheelite. This process allows the production of high-grade concentrate from skarn ores but results in higher operation costs than conventional scheelite flotation.

Flotation is frequently also used to remove sulphides, including the critical contaminants arsenopyrite and galena, at various stages of the beneficiation process.

Figures 39: Froth flotation:

Flotation section in the Vostok-II process plant, Far-East Russia. Cells with dark froth (foreground left and centre) are for first-stage sulphide flotation, while scheelite is floated in the cells with white froth (background and right).



Figures 40 - 41: Foth flotation:

Top: Detailed view of the scheelite flotation at Vostok-II, Far-East Russia. Bottom: Fine-grained final scheelite flotation concentrate skimmed off from the cleaner flotation cells is inspected under UV light, Mittersill mine, Austria.

Magnetic Separation

Differences in magnetic susceptibility are often used to clean concentrates: low-intensity magnetic separation is used to remove magnetite and other ferromagnetic materials, while high intensity magnetic separation allows the collecting of wolframite and its separation from diamagnetic dilution and, most importantly, cassiterite.

Pre-concentrates might also be subjected to a “magnetising roast”, transforming hematite into magnetite prior to magnetic separation.

Contaminants in Tungsten Concentrates

Common contaminants and deleterious elements in tungsten mining are radiation, arsenic, lead, molybdenum and fluoride. The first three of these factors are of particular interest as they might have legal implications. For example, allowable radiation levels for the import of concentrates into the European Union are far below that of naturally occurring radiation in many commercially available concentrates. Critical levels of radiation are caused by U/Th content in the range of a few 10ppm, and it is often difficult to detect (and even more to separate!) the U/Th-bearing mineral phases.

Tight legal limits exist also for arsenic and lead levels in tungsten concentrates, otherwise the concentrates have to be treated as dangerous goods. Usual specifications of downstream producers are around 0.1% As and 0.25% Pb. In unoxidised status, arsenic (in the form of arsenopyrite) and lead (as galena) can be removed by sulphide flotation. In the case of weathered or oxidised ore, for example near the surface, due to hydrothermal alteration or in the case of tailings re-treatment, oxide arsenic and lead minerals might pose a far bigger challenge.

Depending on the downstream use of tungsten concentrates, molybdenum content as little as 0.2 – 0.5% Mo might lead to reduced capacity or recovery of APT production. Many deposits contain some molybdenum in the form of molybdenite. Here, cleaning of the concentrates is comparatively straightforward, due to the excellent flotation properties of molybdenite. In contrast, if the molybdenum occurs as powellite in solid solution with scheelite, separation by physical (ore dressing) means is not possible. Fluorite, which is activated with the same reagents as scheelite is another unwanted mineral in tungsten concentrates.

Secondary Tungsten Minerals

In general, scheelite and wolframite are fairly resistant to chemical weathering. However, especially in tropical climates or during hydrothermal alteration, secondary tungsten minerals might replace a part of the primary scheelite or wolframite mineralisation. Most secondary tungsten minerals are of extremely friable (powdery) nature and easily washed out during traditional ore dressing. This leads to reduced recovery.

Another problem in deposits that have undergone lateritic alteration is the occurrence of diffuse iron-oxide/hydroxide phases with elevated tungsten content, often replacing the original wolframite. Spongy wolframite-hematite intergrowth is also known from hydrothermally altered greisen. Analysis of apparently intact wolframite crystals might return tungsten content as low as 50% WO_3. This material will lead to either low recovery and/or low concentrate grade.

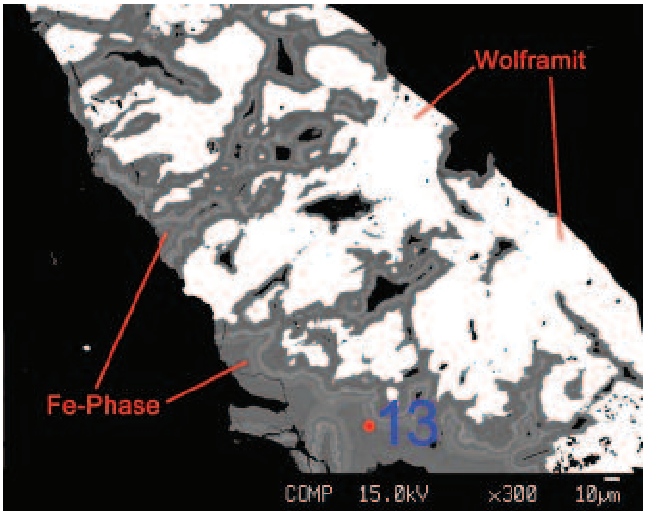


***Figure 42: Secondary replacement** of wolframite by W-bearing iron oxide phases, Gifurwe mine, Rwanda.*

Synthetic Scheelite

Historically (until the 1980s), especially for skarn deposits with high fluorite content or deposits where the scheelite contains a high powellite component, the classic ore dressing circuit was designed to produce a low-grade concentrate only, which was then used to produce synthetic scheelite, directly on the mine site. This is a complex energy-intensive chemical process, requiring digestion of the concentrate and subsequent staged precipitation, adding significant process risk, capital and operation costs. Essentially, synthetic scheelite could be seen as the precursor to APT and it is now considered more effective to adapt the APT process directly to specific concentrates, if a sufficiently large resource base exists.

Flow Sheets of Tungsten Beneficiation Plants

Industrial beneficiation plants at scheelite mines often combine gravity enrichment of the coarse-grained fraction and flotation of finer-grained material to optimise recovery. Flow sheets can become quite complex, especially at multi-commodity operations or when contaminants have to be removed. An example is given in figure 43.

Environmental Challenges and Solutions

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

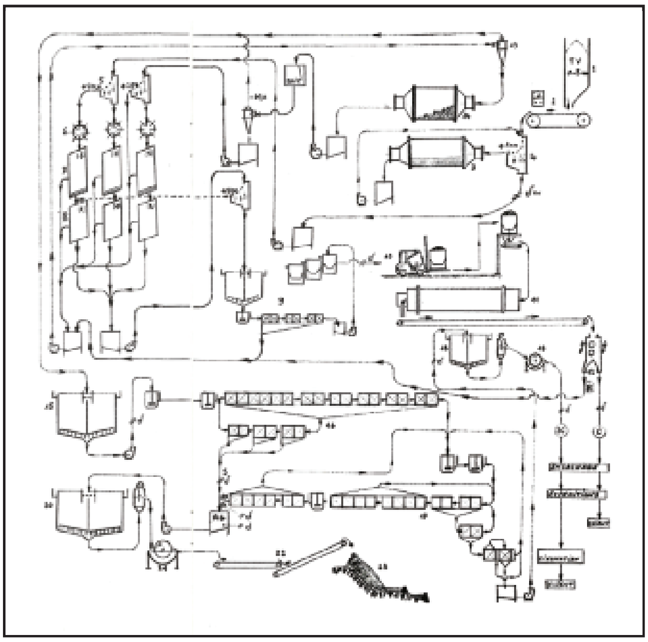


***Figure 43: Flow sheet of a combined gravity and flotation scheelite plant:** Historic Anglade mine in France, from* SOCIÉTÉ MINIÈRE D'ANGLADE [1980]

Beside the mining operation itself (buildings and in the case of open pitting the "hole in the ground"), the most significant impacts are waste rock dumps and deposals of tailings (mill rejects). Tungsten deposits have typically a grade of less than 1% WO_3 and together with the swell factor (blasted rock takes up a far larger volume than in-situ material), tungsten mines produce volume-wise more waste than has originally been mined – in addition to the waste rock that has to be removed to access the tungsten ore.

Landscaping of waste piles is a common approach, and there have been examples where the original landscape has been enriched by the heritage of mining. However, in many cases, at least a part of the waste material needs to be backfilled into the void created by mining. In the case of underground mines, this can be a continuous process, while for open pits, adequate funding has to be kept to complete this task after mining has been completed.

***Figure 44: Continuous rehabilitation and re-vegetation of a tailings pond,** Mittersill tungsten mine, Austria.*

As mentioned before, tailings of many tungsten projects are benign as they do not contain chemical reagents (or just minor quantities of fatty acids) and low levels of heavy metals. This allows projects being classified as non-class A facilities in the context of the EU Mining Waste Directive. Still, these tailings facilities constitute large engineered structures containing often millions of tonnes of fine-grained material and require adequate supervision and long-term stability planning. Many underground mining methods allow or require backfilling of voids, and depending on the grain size distribution and other physical properties, tailings may constitute a significant portion of the backfill material. However, the high amount of slimes in many tailings need to be removed, if stability of the backfill is of concern, especially if consolidated backfill is generated by mixing of the tailings with a binder such as cement and /or fly-ash.

As much as mining operations impact on their environment, the natural environment can also pose extraordinary challenges for the mine itself. In remote areas, infrastructure might be totally absent and the mine operator might find it challenging (or very costly) to attract qualified personnel. In contrast, in densely populated areas, there might be virtually no place for the mine, or it would need to be completely concealed to be accepted.

Examples for special challenges include

- NATC's Cantung Mine in Northern Canada, where personnel need to be flown in and out, leading to very high labour costs and all electricity is generated on site from fuel oil trucked in over hundreds of kilometres, even in the Arctic winter;
- Malaga's Pasta Bueno Mine in the high Andes, where steep topography makes tailings placement an extraordinary challenge; or
- WBH's Mittersill mine located in an nature reserve a few kilometres from Austria's foremost National Park and passed by thousands of tourist and hikers each year. All mine infrastructure including work shops, changing rooms and offices, is located underground, and the mill is connected by means of a three kilometre long tunnel to avoid any sign of the operation being seen in the touristic area. At the same time, the set-up guarantees year-round accessibility in a valley cut off every winter by avalanches.

Figures 45 – 47: Challenges of remote and sensitive locations:

Top left: Pasta Bueno in the foothills of the Andes, Peru, where tailings placement on the steep slopes is particularly challenging.

Bottom left: Cantung, a fly-in fly-out operation in the Canadian North-West Territories.

Top right: At Mittersill, in the heart of the Austrian Alps, thousands of hikers on route to the Hohe Tauern National Park pass each year one of the biggest underground mining operations in Central Europe without hardly noticing it. All infrastructure is located underground (arrow indicates the portal that is also shown in figure 13) and the mill is located 3km further away in a far less sensitive location along a main highway. Ore is transported by conveyor through a tunnel to the mill.

Special Cases

Artisanal Mining

Artisanal and small-scale mining accounts for an estimated 6% of the annual primary mine production of tungsten. Artisanal mining for tungsten is found for example in South America, SE Asia and Central and Western Africa. During WW2, more than 10,000 artisanal tungsten miners were active in Portugal and Spain. Many of the deposits extracted by artisanal miners would be far too small to justify industrial mining.

In some developing countries, artisanal mining including that for tungsten provides livelihood for a large portion of the population, and might constitute a first stage of development for the local economy. In contrast to artisanal mining of gold, environmental damage is limited. Governments promote gradual formalisation of the artisanal mining sector, for example by the formation of cooperatives and issuing of small-scale mining permits. Cooperation with Geological Surveys, private-public partnerships and off-takers aims to provide training, improve safety and promote more sustainable mining practices without having a negative impact on the social fabric and employment.

Figure 48: Artisanal tungsten mining *in lateritic alteration above primary vein-type mineralisation, Burundi.*

Normally artisanal mining remains at a shallow depth, either as small open pit or narrow underground working, partly taking advantage of weathering and supergene enrichment. Extraction might be purely by manual digging (pick-axe, hammer, chisel) or in more advanced operations, aided by compressors, pneumatic tools and explosives.

Principal methods of beneficiation are hand-picking, ground-sluicing and panning. The transition to semi-industrial operations with (manual) jigs and shaking tables is gradual. Artisanal processing methods are shown in figures 28 and 32 - 35.

Alluvial Mining

Only few alluvial (placer) deposits of economic importance are known for tungsten, due to the friable nature of the main tungsten minerals. One example is the Zakamensk area in Siberia, where a placer is exploited in a valley a few kilometres down-stream of a large low-grade stringer deposit formerly exploited in an open pit. High-grade fossil placers are also known in narrow channels immediately downstream of Central African stockwork deposits.

Figure 49 - 50: Alluvial mining: *Artisanal panning concentrate. of subrounded wolframite "gravel" from fossil placer at the Gifurwe deposit, Rwanda (top). Gravel deposit at Zakamensk, Burjatia, Russian Federation: Wolframite is contained in the sand fraction of the gravel beds in a valley downstream of the primary deposit (bottom).*

Figure 51: Alluvial mining *: Compact modular gravity plant for seasonal operations in the Siberian summer at the alluvial wolframite deposit near Zakamensk, Burjatia, Russian Federation.*

Figure 52: Tailings Retreatment: Rehandling and homogenisation of tailings at the historic Sritorranee mine near Chiang Mai ahead of transport to the flotation plant at Lampang Mineral and Metal (Thailand) Ltd.

Tailings Retreatment

Some tailings ponds of historic tungsten operations contain significant tungsten grades and appear an attractive target for re-treatment. Yet, the remaining grades are often a function of very high feed grades of the original plant, grain sizes are largely reduced, and "the best is gone". There is normally a valid reason for the tailings grades being high, thus only if a clearly advanced or new beneficiation method is available, re-treatment is likely to return good results. If treatment was originally aiming for coarse mineralisation only, but the deposit contains also a significant portion of fine-grained mineralisation, or in the case of "primitive" artisanal to semi-industrial first-pass treatment, retreatment with more sophisticated methods will be successful. Weathering, oxidation and/or coating with reagents might be further challenges.

Tailings retreatment is currently undertaken for example in Russia (Zakamensk), NE Brazil (area around Currais Novos) and Australia (historic Mt Carbine mine).

On the other hand, tailings re-treatment might go hand-in-hand with the reclamation of abandoned mines and lead to an improved environmental performance.

Conclusion: Commodity and Deposit - Related Challenges in Tungsten Mining

Although tonnage-wise, the combined capacity of the tungsten mining industry is just of the size of one single copper mine, tungsten operations are found on all continents, extracting deposits in highly variable geological settings and facing diverse challenges and constraints.

Development of additional tungsten concentrate capacity is important for a balanced supply to the downstream industry. Significant progress has been made at various promising projects. However, a number of specific challenges have to be mastered to avoid economic failure. Due to the overall small market size, the impact of individual projects might be significant, and a deficit scenario can swiftly turn into a phase of excess capacity.

Broadly speaking and as a rule-of-thumb, tungsten projects can often be classed into one of the three following groups, each with its own deposit-related challenges:

Classical vein deposits

- Small size, low capex, high operation costs.
- Nugget effect makes reserve definition very difficult. Not attractive for companies eyeing public reporting.
- Radiation and arsenic are common contaminants.

Skarn deposits

- Medium-size, capex can be significant (metallurgy!).
- Occasionally complex shape and problematic continuity.
- Often complex metallurgy; molybdenum and fluoride are common contaminants.

Bulk mineable deposits: greisen, porphyry, stockwork

- Very high capex and high production rates – financing, marketing and overall impact on supply balance have to be considered.
- Variable metallurgy and contaminants, often multi-commodity.
- Radiation and arsenic are common contaminants.

In summary, potential developers have to consider:

- Reasonable project size and due care for marketing.
- Ensure that impact of nugget effect, lithological control and continuity concerns are adequately addressed (minimise resource risk).
- Careful selection of the process route.

Co-operation between miners and downstream companies is of mutual benefit. In a market without trading on a metal exchange, this allows securing both off-take and supply and many quality concerns can be solved by collaboration between the APT manufacturers and concentrate producers.

Given the number of promising deposits available for development, adequate supply of tungsten concentrates depends mainly on the willingness of the industry players to commit to project development and the ability to attract funding.

Acknowledgements

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All photos are from the archives of Wolfram Bergbau & Hütten AG or from the author, except where noted in the caption and

- figures 5 & 12 courtesy Jiangxi Yaosheng Tungsten Company Ltd, (Maoping Mine),
- figures 6 & 8–10 courtesy Almonty Industries (Los Santos Mine),
- figures 21–23 & 45 photos courtesy to Malaga Inc, Montreal (Pasto Bueno Mine) and
- figure 30 courtesy Dr. B. Zeiler (ITIA)

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The 25th Anniversary Annual General Meeting, 17-20 September, Beijing

Stephen Leahy, the ITIA President and CEO of North American Tungsten Corp, welcomed 270 delegates from 24 countries to the 25th AGM, in particular the representatives from eight companies which had joined the Association during the year. In his opening address, he warmly thanked Minmetals for generously sponsoring this historic event and the China Tungsten Industry Association (CTIA) which had provided strong support.

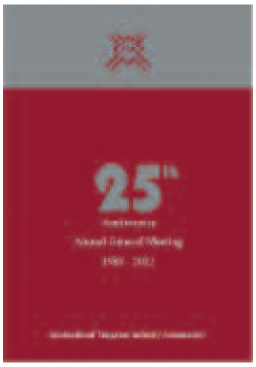
He said that it was entirely appropriate that the venue was Beijing as the capital city of the world's largest tungsten producer and consumer, China; and that the host was one of the most famous names in the industry – China Minmetals.

Leahy, who was presiding over his last meeting after serving for two years, congratulated the new Secretary-General, Burghard Zeiler, for ensuring a smooth and successful transition in the ITIA leadership in 2012. He also thanked his colleagues on the Executive Committee for their devotion to ITIA's activities and to the HSE Committee for managing it's work programme so efficiently. He expressed the hope that members would give the same strong level of support to Claude Lanners, the new President, as he himself had received.

Zhou Zhongshu, CEO of China Minmetals Corp, addressing delegates at the AGM

A Booklet – ITIA History and its Members

To celebrate the 25th Anniversary AGM, the Association published a Booklet "ITIA History and its Members". It contains a brief history of ITIA, tributes from former Presidents to Michael Maby on his retirement early this year and a page devoted to each ITIA member company profiling its products and activities.



Readers who would like to receive a copy, please contact the Secretariat (info@itia.info). Copies will be allocated on a "first come, first served" basis as stocks are limited.

Election to the Executive Committee

The AGM unanimously approved the election as new members of the Executive Committee of:

- William Hanna (Director, Metallurgical Operations, Integrated Supply Chain & Logistics, Kennametal Inc)
- Hu Qiming (Vice-President, Zhuzhou Cemented Carbide Group)
- Ulf Lundahl (Chief Purchasing Officer, Sandvik Machining Solutions AB)
- Karlheinz Reichert (Senior Vice-President, Business Unit TMR, HC Starck GmbH)

Election of the President

The AGM unanimously approved the election of Claude Lanners (General Manager, Purchasing & Human Resources, CERATIZIT SA) to serve as President in 2013 and 2014.

Claude Lanners, newly elected President

Welcome as an ITIA Member in 2013 to:

Tikomet Oy, a hardmetal recycling company specialising in the zinc process.

ITIA's 26th AGM, 23 to 27 September 2013, Australia

Global Tungsten & Powders Corp and Wolfram Camp Mining Pty Ltd will jointly host the ITIA's 26th Annual General Meeting in Australia (in Cairns or Sydney) and the provisional outline programme is as follows:

Date	Meeting / Function
Monday 23 Sept	• Tungsten Consortium Technical Committee • ITIA HSE Committee
Tuesday 24 Sept	• Tungsten Consortium Steering Committee • Joint ITIA Executive and HSE Committees • ITIA Executive Committee • ITIA Reception and Dinner
Wednesday 25 Sept	• AGM • Tungsten Consortium Committee • Dinner hosted by Global Tungsten & Powders and Wolfram Camp Mining
Thursday 26 Sept	• AGM
Friday 27 Sept	• Optional Mine Visit

Further details of this annual event, at which the worldwide industry gathers, can be found on our website - www.itia.info. Details will be updated to include the expanded programme and registration form in May. Companies which are not ITIA members may attend the AGM (there is a fee) and receive presentations on a variety of industry and general topics.

Dr Burghard Zeiler
Secretary-General