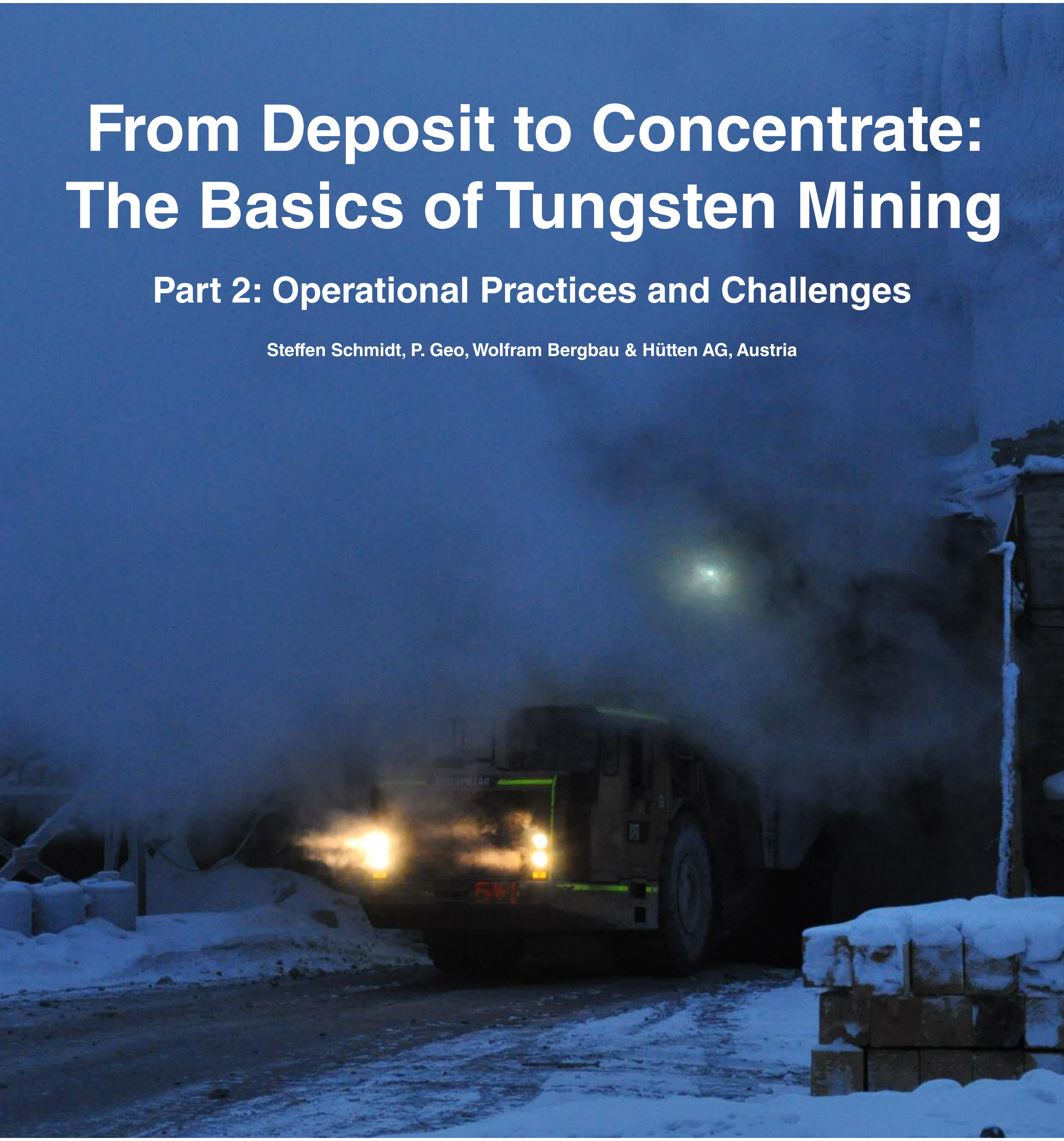

From Deposit to Concentrate: The Basics of Tungsten Mining

Part 2: Operational Practices and Challenges

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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 environments.

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 1)**.

The selection of a suitable mining method including 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. soft, hard, 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 each tonne of 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, moderately 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.

Note: 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.

Figure 1: 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.

Open Pit Mining

Most active tungsten mines are of moderate scale (production of a few 100,000t of ore per year), and thus the 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 the stockwork deposits of Barruecopardo, Spain **(Figure 2)** and Mt Carbine, Australia, and at the skarn deposit Dolphin, also in Australia, as well as in various Chinese operations. At Los Santos, a skarn deposit in Spain **(Figures 3** and **4)**, mining was recently completed.

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.

Figure 2: Aerial photograph of the Barruecopardo tungsten operation near Salamanca in Spain, showing the open pit, landscaped and gradually recultivated waste rock and tailings deposals, various water storage ponds and in the background, the beneficiation plant.

Figure 3: Open pit mining, Los Santos, Spain. Loading and hauling with medium-scale open pit machinery; blast hole drill rig in background.

Figure 4: Examples of Technical Services in an open pit environment, Los Santos, Spain. Use of drone for 3D photography of pit walls for geotechnical assessment (top left); grade control sampling of blast holes and delineation of the ore zone ahead of blasting (bottom left and above).

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 5.** 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.

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, San Finx, Spain]
  - Shrinkage Stoping [example: partly at Resguardo de la Tempestad, Bolivia]
  - Cut & Fill with resuing fill
  - Cut & Fill [example: partly at Gifurwe, Rwanda]
- Best suited for flatly dipping veins or flat tabular skarn orebodies
  - Room & pillar mining [example: Panasqueira, Portugal, several mines in the Serido scheelite province, NE Brazil]

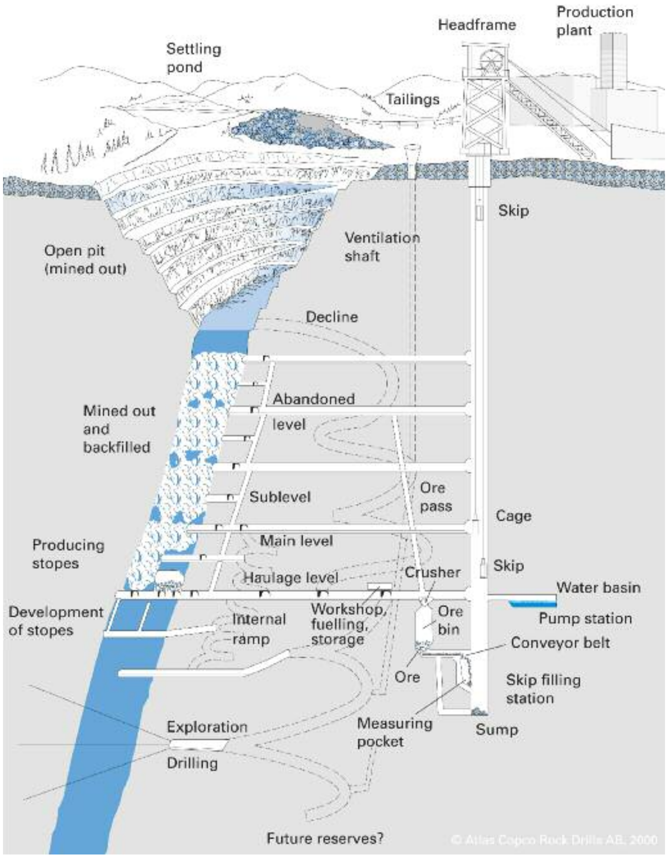


Figure 5: Basic infrastructure of an underground mine. From SMITH M (Ed) [2008]

Figure 6: Head-frame: One of the shafts for ore haulage at the Barra Verde / Boca de Laje operation in NE Brazil. Ore is transported in a skip, discharged into a small bin and loaded into a truck for transport to the beneficiation plant. In this case, access to the mine for personnel is through a separate shaft.

Figure 7: Mine Portal at Mittersill mine, Austria. Access of personnel and material through ramps; ore transport to surface in this case by conveyor belt through a 3 km-long tunnel directly to the mill.

- 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 [historic: 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 **(Figures 6 – 14)**.

Figure 9: Narrow-vein open stoping, using small pillars as support, San Finx, Spain.

Figure 10: Cut & fill mining in a narrow vein environment at Gifurwe, Rwanda: the mined-out void is layer-by-layer filled with waste rock, so that the miners are always close to the fresh vein exposure above them.

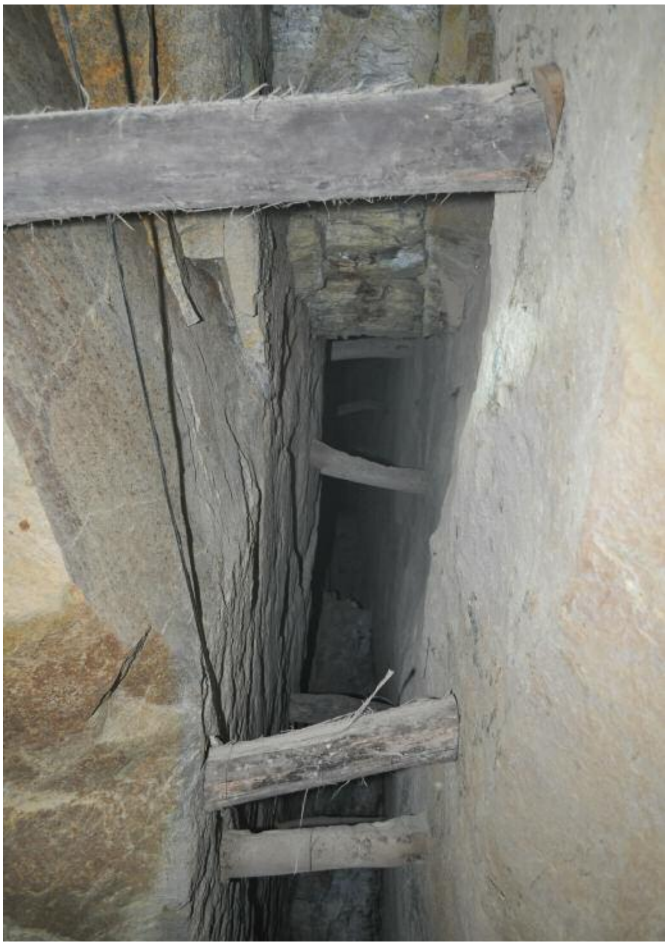


Figure 8: Narrow-vein open stoping at Chollja, Bolivia, using timber props as support. Vein zone is less than 1m wide.

Figure 11: Room & pillar mining at Panasqueira, Portugal. The narrow flat-dipping orebody (quartz vein with wolframite) is extracted in stages, leaving first 11 x 11 m pillars and then 3 x 3 m-pillars only, giving an overall recovery of 84%.

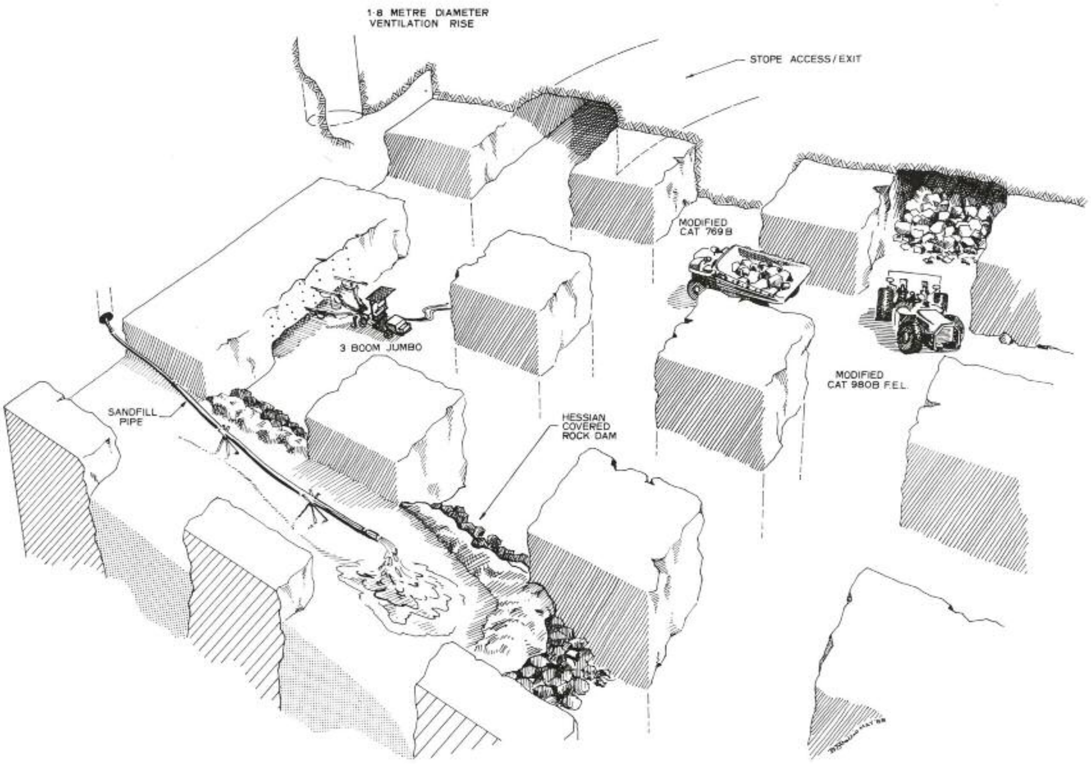


Figure 12: Post-pillar mining in the historic Dolphin mine, Australia. Sand fill by tailings (bottom left) is used as floor for subsequent lifts (drill jumbo is set-up in centre left), making this a combination of cut & fill and room & pillar mining. From HUGHES FE (Ed) [1990]

Figure 13: Mucking of a sublevel stope by remote-controlled scooptram in the Mittersill mine, Austria.

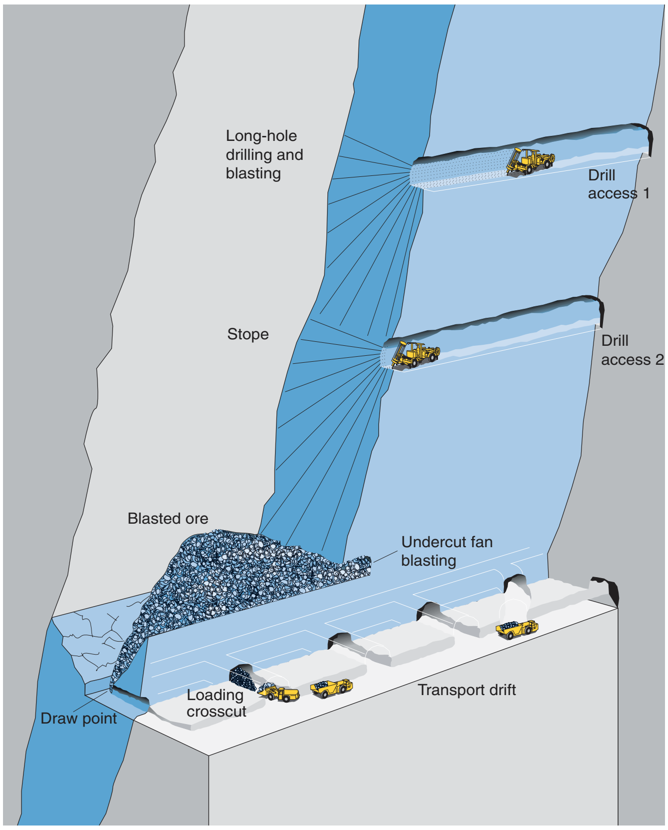


Figure 14: Sketch depicting the set-up of large-scale open stoping using draw-point, from SMITH M (Ed) [2008]

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-tire 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-tire 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-tire becomes standard, and where diesel is now slowly replaced by electric drives. 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 **(Figure 15)**. In contrast, large-scale mining is generally undertaken with rubber-tire equipment **(Figure 16)**.

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.

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 spiral)
drift size	generally small (2 x 2 m)	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 (but recently also moving to EV/battery systems), 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.

Figure 15: Underground mining equipment for track-bound narrow-vein mining. Drilling with pneumatic jack-leg drill, Pasta Bueno tungsten mine, Peru (left). Pneumatic overhead loader at a mine in Bolivia (right). Train haulage at Nyakabingo, Rwanda (below).

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.

Figures 16: Underground mining equipment for large-scale skarn and stockwork mining. Stope drilling with electro-hydraulic long-hole jumbo at Vostok-2, Far-East Russia (above). Loading of 50t underground haul truck with 17t scooptram at Mittersill, Austria (left).

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).

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 **(Figures 17, 18, 19)**. 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 aim 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. An exception is pre-concentration of run-of-mine ore: visual (hand-picking), optical or x-ray 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.

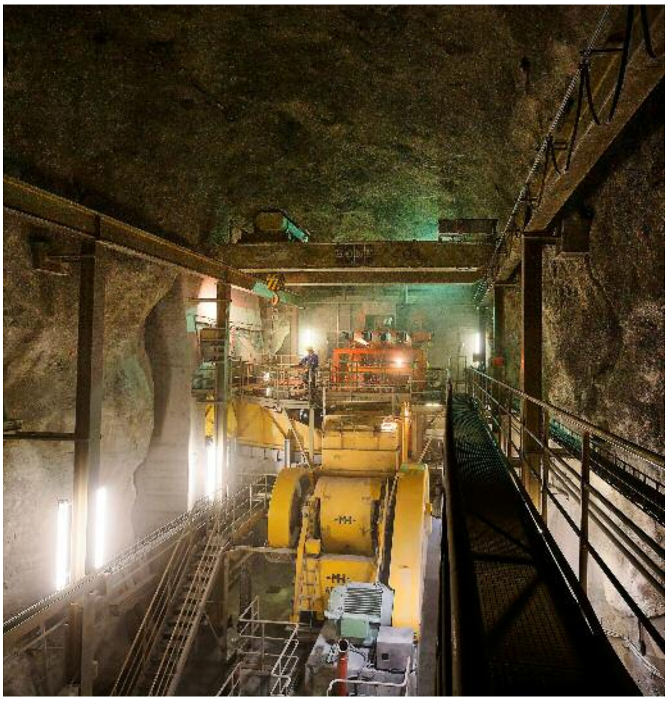


Figure 17: Primary and secondary crushing in a large underground cavern at Mittersill mine, Austria. Jaw crusher (top) and two cone crushers and sieving plant (bottom).

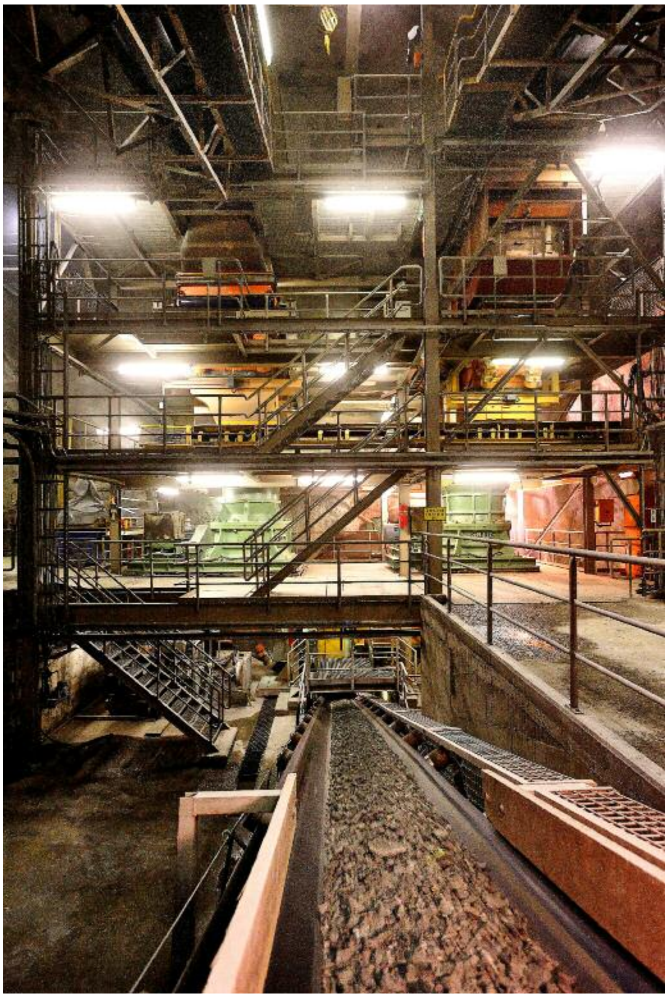


Figure 18: Secondary crushing to grinding in a small-scale operation in Bolivia, using a so-called quimbalete.

Figure 19: Milling: Staged rod and ball mills and spiral classifiers at the Vostok-2 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 upgrading, although in countries with high labour costs, the latter might be prohibitive. Used in several tungsten deposits in China **(Figure 20)** and world-wide as part of the upgrading chain in artisanal mines **(Figure 21)**.

- **Optical sorters (historic)**
  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 1980s to separate the wolframite-bearing quartz-veins (white) from the sterile host rock (dark-grey). Hence, despite the actual ore mineral being black, the positive search property was “white”.

Figure 20: Hand-picking: Hand-sorting at the Taoxiken mine, Jiangxi, China.

Figure 21: Hand picking: 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.

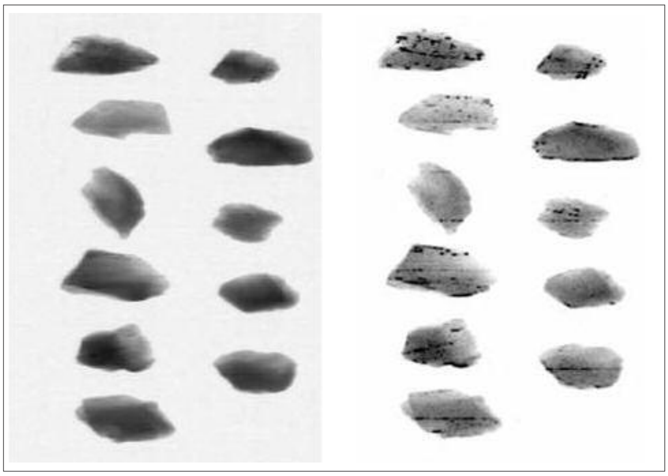


Figure 22: X-ray sorting: ore fragments (2–3 cm length) normal light (left) and x-rayed (right). Mittersill mine, Austria.

- **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" **(Figure 22)**. 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.

  Depending on mineralisation style, 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.

- **Gravitational Pre-concentration**
  Several gravitational methods, especially sluicing and jigging, 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 50 µm.

Figure 23: Artisanal methods: Wooden sluice boxes designed to minimise water consumption at an artisanal site in Bolivia (above). Traditional panning of alluvial wolframite, Gifurwe mine, Rwanda (top right). Manual jig and wooden sluice leading to corduroy sluice (downstream of a ground sluice), Gifurwe mine, Rwanda (bottom right).

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 **(Figure 23)**.

- **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 **(Figure 24)** 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.

Figure 24: Gravity methods: Gravity plant at San Finx mine, Spain (wolframite vein deposit). In the background are different spirals and jigs, in middle different shaking tables, in foreground flotation table (above). Tabling section in the beneficiation plant of the Brejui mine, Brazil (scheelite skarn deposit)(top right). Distinct bands of scheelite (white), sulphides (narrow grey streak), and various silicates (red and greenish) on the tables at Brejui (bottom right).

Figure 25: Froth flotation: Flotation section in the Vostok-2 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) (left image). Detailed view of the scheelite flotation (right image).

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 **(Figures 25** and **26)**.

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.

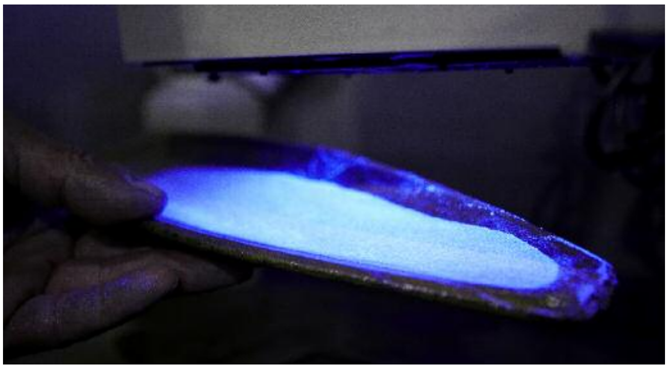
Whole rock flotation means that the run-of-mine ore (possibly after pre-concentration by x-ray sorting or similar) is subjected to “positive” flotation of the scheelite content. In contrast, combined methods often produce first a high-grade concentrate by tabling. Lower-grade flotation concentrates are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

Figure 26: Froth flotation: Fine-grained final scheelite flotation concentrate skimmed off from the cleaner flotation cells is inspected under UV light, Mittersill mine, Austria.



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

Magnetic and Electrostatic 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. Electrostatic methods are used to separate scheelite and cassiterite in mixed concentrates.

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 below that of naturally occurring radiation in many commercially available concentrates. Critical levels of radiation are caused by uranium content in the range of a several 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.

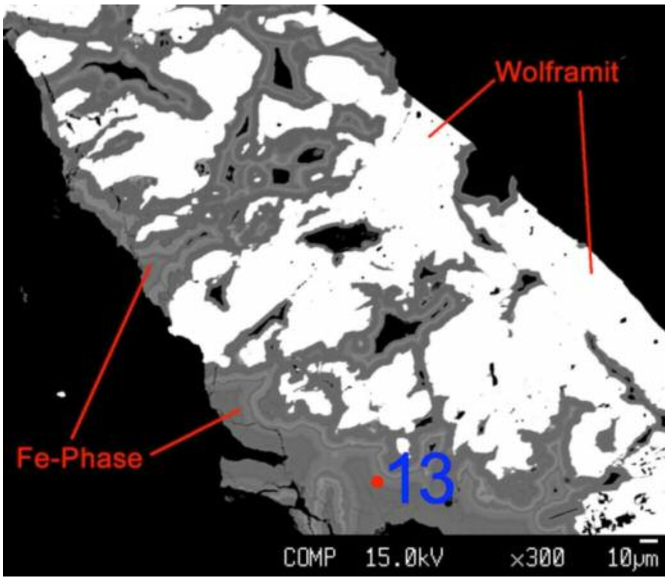
Depending on the downstream use of tungsten concentrates, molybdenum content as little as 0.2 – 0.5% Mo might lead to reduced capacity or recovery of APT production. Many deposits contain some molybdenum in the form of molybdenite. Here, cleaning of the concentrates is comparatively straightforward, 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 **(Figure 27)**. 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 27: 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 28**.

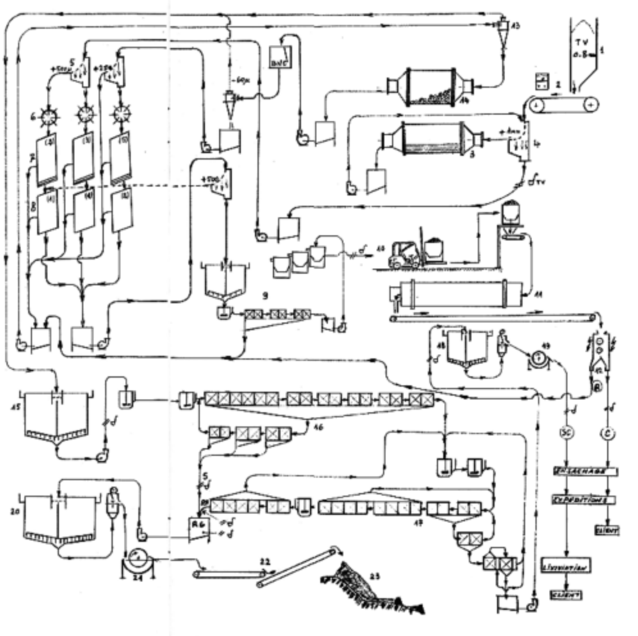


Figure 28: Flow sheet of a combined gravity and flotation scheelite plant: Historic Anglade mine in France, from SOCIÉTÉ MINIÈRE D'ANGLADE [1980]

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.

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.

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 **(Figure 29)**. 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

Figure 29: Continuous rehabilitation and re-vegetation of a tailings pond, Mittersill tungsten mine, Austria.

Figures 30: 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.

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

- WBH's Mittersill mine **(Figure 30)** is located in a 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 workshops, change 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.
- At NATC's Cantung Mine **(Figure 31)** in Northern Canada personnel needed to be flown in and out, leading to very high labour costs and all electricity was generated on site from fuel oil trucked in over hundreds of kilometres, even in the Arctic winter. High costs for transport of supplies and flights for the staff eventually led to bankruptcy despite extraordinarily high ore grades.
- Challenges at many Andean deposits **(Figure 32)** include general accessibility and especially tailings placement in the very steep terrain. At the Pasta Bueno Mine in the Peruvian Andes, the challenges and costs around tailings placement led eventually to the failure of the project.

Figure 31: Cantung, a past fly-in fly-out operation in the Canadian North-West Territories.

Figure 32: Urania, at 3900 m elevation at the foothills of the Illimani (6400 m), Bolivia.

Special Cases

Artisanal Mining and the concepts of Conflict Minerals and CAHRAs

Artisanal and small-scale mining accounts for roughly half of the tungsten production outside of China, Russia and North Korea, i.e., it is significant importance for the supplies of smelters worldwide. Artisanal mining for tungsten is found for example in Latin America, SE Asia and Central 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. Other than artisanal mining of gold, the risk for environmental damage by tungsten extraction is limited. In contrast to general perception, artisanal mining is per se not illegal. 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.

There is a gradual transition between fully artisanal mining **(Figure 33)**, semi-industrial methods **(Figure 34)** and truly modern small-scale mining. 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.

Figure 33: Artisanal tungsten mining in lateritic alteration above primary vein-type mineralisation, Burundi.

Figure 34: A very different impression of artisanal mining: Haulage by compact loader ("bobcat") and timber support at Rufungo, Rwanda.

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 Figure 23.

Artisanal mining of tantalum, tin, tungsten and gold (called 3TG) mainly in the Great Lakes' Region of Central Africa came into the focus of the general public through reports of rebel financing and grave human rights violations in the early 2000-years ("the blood in your gadgets"). The term "Conflict Minerals" was defined in the US Dodd-Frank Act (2010). Multi-stakeholder conferences organised by the OECD tried to provide guidance to address the risks and avoid a de-facto boycott. The term Conflict-Affected and High-Risk Areas was coined to show that not only Central Africa is affected.

In the meantime, the OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict Effected and High-Risk Areas (OECD, 2016) became de-facto industry standard, and it forms the basis of audit schemes and recent EU legislation. The OECD Guidance does also highlight the positive effect artisanal mining can have for local development, while offtakers have to take care that the mineral supply chains do not support adverse effects like human rights violations.

Access to the international market requires willingness of the miners to follow strict rules and of the smelter industry to undertake due diligence and risk mitigation rather than simple risk avoidance. "Upstream mechanisms" like ITSCI provide training and support traceability from reviewed mine sites, for example through "bag & tag" **(Figure 35)**.

Figure 35: Registration of daily production of an artisanal operation in the framework of the ITSCI scheme, South Kivu, DR Congo.

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 **(Figures 36** and **37)**. High-grade fossil placers are also known in narrow channels immediately downstream of Central African stock-work deposits **(Figure 38)**.

Figure 36: Compact modular gravity plant for seasonal operations in the Siberian summer at the alluvial wolframite deposit near Zakamensk, Burjatia, Russian Federation.

Figure 37: 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.

Figure 38: Artisanal panning concentrate of subrounded wolframite "gravel" from fossil placer at the Gifurwe deposit, Rwanda.

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), while in Australia, it was the initial stage of the re-activation of the historic Mt Carbine mine.

On the other hand, tailings re-treatment might go hand-in-hand with the reclamation of abandoned mines **(Figure 39)** and lead to an improved environmental performance.

Figure 39: 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.

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. Since publishing the first edition of this paper in 2012, significant progress has been made at various promising projects; on the other hand, several operation went into receivership, including newly developed ones. The specific challenges of tungsten mining (especially beneficiation) should not be underestimated. 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 and assuring that adequate beneficiation tests are done using representative samples.

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.

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