Examples of New Technologies in Extractive and Process Metallurgy

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Introduction

• **Mineral Processing** has been practiced for a long time (Georgius Agricola from Saxony wrote the first real technical text).

• **Liberation** to free the valuable constituents from the waste (gangue) materials, followed by **separation** through using the differences in physical and chemical properties have been the guiding principles from the beginning.

Georgius Agricola – De Re Metallica (1556)
Mineral Processing/Extractive Metallurgy - Challenges and Opportunities

The following topics will be discussed:

- Current State of Mineral Processing/Extractive Metallurgy
- Water, Dry Stacked Tailings and Dry Processing
- Energy Efficiency & Modeling
- Automated Mineralogy
- Example New Extractive Metallurgy Technology
- Critical Materials – Ores, By-products and Recycling
Introduction – Current State

- Mineral processing/Extractive metallurgy technology continues to advance at a rapid pace.
- This is due to the need to produce materials essential to modern society.
- This need continues to expand as more countries throughout the world begin to require more modern conveniences.
- Modern mineral processing/extractive metallurgy benefits from many decades of fundamental and applied research.
- This has greatly enhanced our ability to perform processing by more scientific and well-engineered methods.
Introduction – Current State

There have been several significant advances that have improved our ability to:

- Treat larger tonnages,
- Treat lower grade ores,
- Treat ores with more problematic and/or by-product impurities,
- Meet stricter environmental regulations,
- Economics is always the bottom line.
Among the principal recent advances in comminution are:

- semi-autogenous grinding (larger and better controls)
- high pressure grinding rolls
- automated mineralogy
- Innovations in screening, thickening and filtering methods
- models for ore breakage (population balance models) and for other unit operations
- Fundamental models and software used for design and flow sheet development.
Among the recent advances in separations are:

- improved magnetic separators
- ore sortation
- column flotation
- improved gravity separation devices
- improved understanding of surface chemistry and flotation kinetics
- improved large scale mechanical flotation machine
- modeling of particle behavior and material flow in unit operations.

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Among the advancements in chemical processing methods for extraction and separation are:

- Excellent chemical thermodynamic screening methods for heterogeneous systems (gas/solid, molten metal/slag and aqueous systems).
- Improved extraction methods based on increased understanding of chemical kinetics, reactor design and transport phenomena.
- Improved understanding of solution purification techniques, such as solvent extraction and ion exchange.
- Improved models and software for chemical reactor and flow sheet design.
Metal Reduction and Refining

There have been several significant advancements in metal reduction and refining technology.

- Excellent thermodynamics screening methods.
- Improved reduction and refining methods based on increased understanding of chemical kinetics, reactor design and transport phenomena.
- Improved understanding of the high temperature chemistry and electrochemistry in metal recovery systems.
- Improved materials of construction.
Introduction

These advances have been driven by:

- The desire to produce more metals and minerals, at the lowest cost possible, to meet societies needs.
- Stricter environmental regulation
- The desire for engineers, and companies, to continue to make things work better and more efficiently.
- The desire to make money.
Introduction

We will discuss a number of the challenges and opportunities that are being addressed in the field of mineral processing/extractive metallurgy

- **Water** (this is fast becoming a scarce resource)
- **Energy** (the major economic factor in grinding circuits)
- **Modeling**
- **Critical materials.**
Water

Social License to operate (Dunne 2010)

Community focused issues around water include:

- Concerns about the impacts of mining and processing on the local water quality.
- Rerouting of watercourses.
- Mining and processing reducing availability of water for other uses valued by the community.
“Water management strategies address these concerns by:

- Greater efficiency in waste water usage, increased water recovery and recycle with reduced demand on external freshwater supplies.
- Reduced impact on local water resources by reduced discharge of excess waste water from the mine.
- Compliance with regulatory commitments.”
• Good management would include a mine site water balance.
• This schematic includes dewatering in a thickener and water recovery from the tailings.
• New water is 20%.
• Reduced losses can be identified (seepage, evaporation, etc.)

FIG 2 - Generic mass balance for a mineral processing flotation plant (Turcotte, 1986).
Mine Sites with a Positive Water Balance

- This becomes a problem due to constraints on the amount and quality of water discharged outside (EPA and local authorities).
- This is a moving target and compliance will require new technology as the requirements change.

Mine Sites with a Negative Water Balance

- This requires make up water (rain, river or ground water) and varies during water scarcity.
- Water storage, water recovery and minimizing waste are central to water management.
Dewatering and Water Recovery

- Methods include: screening, conventional and paste thickening, lamella separators, filtration and sedimentation.
- Chemicals are used for coagulation and flocculation to enhance separations.
- Technology for thickeners has improved significantly over the past twenty years with increased discharge densities and ability to treat difficult ores.
- Paste or High density products have numerous advantages: recover more process water, decreased time for drying, and mine back fill.
Reducing water usage

- Recycling of water is a desirable practice, if possible.
- This might also allow the recycle of unused reagents (if they are not detrimental to the process).
- Reducing evaporation from ponds – various covers
- There are numerous examples of mines utilizing recycled process water. Numbers vary for 25 to 80% recycle.
Dry Stacked Tailings

An option that arises from pressure from regulators and the public for alternatives to large tailing impoundments.

- Large capacity vacuum and pressure filters advances provide an opportunity to store tailings in an unsaturated state.
- Filtered tailings can be transported by conveyor or truck and stacked in a stable, dense form.
- This process has become fairly common (up to 20,000 tpd) as is shown on the next slide.
List of some mines with dry stacking (after AMEC 2008)

<table>
<thead>
<tr>
<th>Mine</th>
<th>Raglan</th>
<th>La Copia</th>
<th>Green Creek</th>
<th>El Sauzal</th>
<th>Alamo Dorado</th>
<th>Pogo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country</td>
<td>Canada</td>
<td>Chile</td>
<td>Alaska</td>
<td>Mexico</td>
<td>Mexico</td>
<td>Alaska</td>
</tr>
<tr>
<td>Commodity</td>
<td>Ni, Cu</td>
<td>Au</td>
<td>Pb, Ag, Zn, Au</td>
<td>Au</td>
<td>Ag, Au</td>
<td>Au</td>
</tr>
<tr>
<td>Daily treatment (t/d)</td>
<td>2400</td>
<td>16000</td>
<td>2000</td>
<td>5300</td>
<td>4000</td>
<td>2500</td>
</tr>
<tr>
<td>Filtration method</td>
<td>Pressure</td>
<td>Vacuum belt</td>
<td>Pressure</td>
<td>Vacuum belt</td>
<td>Pressure</td>
<td>Pressure</td>
</tr>
<tr>
<td>Stacking method</td>
<td>Truck</td>
<td>Truck</td>
<td>Truck</td>
<td>Truck</td>
<td>Truck</td>
<td>Truck</td>
</tr>
</tbody>
</table>

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Recycling of Process Water to Mills

- Work has been done on the effects of recycling process water back to mills due to increased regulation on discharge and water conservation.
- In many cases this would require chemical treatment to reduce deleterious elements.
- Recycled reagents or decomposition products can have a negative effect on complex flotation and leaching circuits.
- In some recent developments, certain leaching process waters have been subjected to treatments that regenerate required reagents (acids and bases) using EDU or salt splitting technology.

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Generic treatment alternatives may be divided into broad categories:

- Neutralization of acidity with lime.
- Removal of metals by precipitation (i.e. hydroxides or sulfides).
- Treatment by membrane technology
- Removal of specific target compounds (As, Hg, Se, Cd, Tl, etc).
- A generic list is shown in the following figure.
# Minerals industry water treatment technology (after Van Niekerk et al. 2006)

<table>
<thead>
<tr>
<th>Neutralization</th>
<th>Metals removal</th>
<th>Desalination</th>
<th>Specific target removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lime/limestone process</td>
<td>Hydroxide precipitation</td>
<td>Biological sulfate removal</td>
<td>Cyanide destruction</td>
</tr>
<tr>
<td>Sodium based alkali’s</td>
<td>Carbonate precipitation</td>
<td>Membrane-based processes</td>
<td>Radioactive nuclides removal</td>
</tr>
<tr>
<td>Ammonia</td>
<td>Sulfides precipitation</td>
<td>Ion exchange processes</td>
<td>Arsenic removal</td>
</tr>
<tr>
<td>Biological sulfate removal</td>
<td>Wetland oxidation ponds</td>
<td>Electrochemical processes</td>
<td>Others</td>
</tr>
<tr>
<td>Others</td>
<td>Reactive Barriers</td>
<td>Others</td>
<td></td>
</tr>
</tbody>
</table>
Reverse Osmosis

Reverse osmosis membrane separation is now well established technology. The goal is to maximize water recovery and minimize brine for subsequent treatment.

• Low pH reverse osmosis is a new development.

The following steps are used for acid mine drainage:

• Limestone/lime neutralization.
• Softening and excess gypsum crystallization
• Micro-ultra-filtration to remove fine particles
• Antiscale additions to prevent membrane fouling
• Reverse Osmosis
Brine Treatment

- Brine solutions generated through reverse osmosis requires additional treatment to remove and stabilize precipitated metals prior to disposal.
- The requires chemistry that will allow the reduction of metals to regulatory limits for disposal.
- Sludge generated from brines is either stored in plastic lined facilities on site or sent to an external permitted land fill.
- Disposal can be a significant portion of the water treatment costs.
Biological Treatment of Water

- Biological sulfate reduction is one of the successful methods developed to treat waste waters.
- Using reducing and anaerobic conditions, in the presence of organic nutrients, sulfate reducing bacteria can convert acid mine drainage sulfate to sulfide.
- Carbon dioxide is generated as a respiration product and produces bicarbonate alkalinity to increase the pH, while sulfides form insoluble metal complexes.
Other Applications

- **Sea Water** - Various mills have operated using sea water, many without deleterious effects.
- **Sewage Water** - There are many examples where treated sewage water has been used in milling operations.
- **Desalination Water** – reverse osmosis is used in Australia and Chile.
- **Electro Dialysis Reversal (EDR)** – has been used in South Africa and the Czech republic. This is a niche technology which only out performs reverse osmosis under certain circumstances. It has high water recovery (95%) and can treat high silica.
### Mining operations using or considering using seawater (after GWI Research 2011)

<table>
<thead>
<tr>
<th>Company</th>
<th>Operation</th>
<th>Capacity (m³/d)</th>
<th>Type</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Citic Pacific</td>
<td>Sino Iron Magnetite Project</td>
<td>139,726</td>
<td>Seawater desalination</td>
<td>Started 2011</td>
</tr>
<tr>
<td>BHP Billiton</td>
<td>Olympic Dam (expansion)</td>
<td>280,000</td>
<td>Seawater desalination</td>
<td>Awaiting approval</td>
</tr>
<tr>
<td>Minara Resources</td>
<td>Murrin Murrin nickel operation</td>
<td>15,000</td>
<td>Borehole water desalination</td>
<td>Since mid-1990’s</td>
</tr>
<tr>
<td>BHP Billiton</td>
<td>Coloso plant at Escondida</td>
<td>45,360</td>
<td>Seawater desalination</td>
<td>Since 2006</td>
</tr>
<tr>
<td>++ Minerals</td>
<td>Michillla Mine</td>
<td>6,500</td>
<td>Direct seawater for leaching</td>
<td>Since early 1990s</td>
</tr>
<tr>
<td>Antofagasta Minerals</td>
<td>Esperanza</td>
<td>62,200</td>
<td>Seawater used for copper flotation</td>
<td>Started 2011</td>
</tr>
<tr>
<td>CAP</td>
<td>Cerro Negro Norte</td>
<td>17,280-34,560</td>
<td>Considering Desalination (RO)</td>
<td>Mid 2012</td>
</tr>
<tr>
<td>Anglo American Chile</td>
<td>Mantoverde</td>
<td>10,368</td>
<td>Considering Desalination (RO)</td>
<td>2012</td>
</tr>
<tr>
<td>Aguas de Barcelona</td>
<td>Copiapo (expansion)</td>
<td>86,400</td>
<td>Considering Desalination (RO)</td>
<td>2012-2013</td>
</tr>
<tr>
<td>Freeport McMoRan</td>
<td>Candelaria (expansion)</td>
<td>25,920</td>
<td>Considering Desalination (RO)</td>
<td>2012</td>
</tr>
<tr>
<td>Xstrata/Barrick</td>
<td>El Morro</td>
<td>64,000</td>
<td>Desalination</td>
<td>Feasibility approved</td>
</tr>
<tr>
<td>BHP Billiton</td>
<td>Escondida (expansion)</td>
<td>276,480</td>
<td>Desalination</td>
<td></td>
</tr>
<tr>
<td>Quadra FNX</td>
<td>Sierra Gorda</td>
<td>65,664</td>
<td>Direct Seawater</td>
<td>2013-2014</td>
</tr>
</tbody>
</table>
Screen-Bowl Centrifuge

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Dry Processing of Ores

• If it were possible to grind and process ores in dry form, rather than in water, then the water dilemma is partially obviated.

• Ore sorting is one type of water free process, but for many ores this would typically be used for upgrading prior to subsequent wet processing.

• Dry grinding is practiced at some mines were roasting is used as a subsequent treatment step.

• Research has been going on to develop dry gravity and/or size separators.

• Research is needed to develop new dry processes that can treat large tonnages efficiently at reduced energy costs.

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Examples of Dry Processing

Dry Grinding – Carlin Mill

Dry Shaking Table, Wire Chopping Plant – Cu Recovery
Fine Grind Flow Sheet - Newmont

Primary Crushers

Secondary crushing

- 50 mm

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Conclusions - Water

- Fresh water sources will continue to become more scare and tensions will increase between potential users.
- Discharge from mines will see ever increasing regulation to improve the quality of the discharges.
- The focus will continue to be on recycle (reuse) and reduction of water, along with utilization of alternative sources.
- This will lead to research and development on new, or improved, technology for water treatment for mining and milling purposes.
- Alternative dry comminution and concentration processes will be developed
Energy in Mineral Processing

• Another major concern for mining operation is the cost of energy in mining and mineral processing.

• Energy audits are just as important as the water audits discussed in the previous section. This is demonstrated for a gold operation in the following figure.

• Evaluation of this example mining and processing operation will shows that the major energy costs are related to excavating/trucking and grinding.

• This indicates that the operating costs are very sensitive to the cost of diesel and electricity.
Fig. 1 Energy Use by Activity

Musa et al

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Methods to reduce energy costs

• Mining excavation/haulage is not part of this discussion; but is an area of active development.

• In milling operations, one can break down the various energy costs as shown in the next Figure as an example.

• As can be seen, the major cost is related to the grinding operations.

• This step is most important, as the ore must be ground fine enough to liberate the valuable constituents.

• Various studies have been performed to evaluate how increased blasting might reduce overall comminution costs.
## Energy and costs for stages in comminution (Workmann and Eloranta 2003)

<table>
<thead>
<tr>
<th>Operation</th>
<th>Feed size (cm)</th>
<th>Product size (cm)</th>
<th>Work input (kwh/ton)</th>
<th>Energy costs ($/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explosives</td>
<td>Infinite</td>
<td>40</td>
<td>0.24</td>
<td>0.087</td>
</tr>
<tr>
<td>Primary crushing</td>
<td>40</td>
<td>10.2</td>
<td>0.23</td>
<td>0.016</td>
</tr>
<tr>
<td>Secondary crushing</td>
<td>10.2</td>
<td>1.91</td>
<td>0.61</td>
<td>0.042</td>
</tr>
<tr>
<td>Grinding</td>
<td>1.81</td>
<td>0.0053</td>
<td>19.35</td>
<td>1.35</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>20.43</td>
<td>1.50</td>
</tr>
</tbody>
</table>
Example comminution circuit
Improving Energy Efficiency in Milling

There are four general aspects for energy efficiency in milling operations;

- Improving energy efficiency in operating mills.
- Developing flow sheets for new milling operations that weigh energy (operating cost) versus capital costs by evaluating various forms of grinding equipment (i.e. high pressure grinding rolls versus SAG mills).
- Fundamental research to understand how changes may effect overall energy efficiency in grinding (i.e. lifter design and configuration and other operating parameters).
- Developing completely new methods to grind ores.

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Energy efficiency in operating mills (Musa et al)

• Optimization to increase plant throughout by eliminating process bottlenecks.

Plant surveys yield mill throughput, operating hours and mill power

• Better control and balancing of the circuit

• Circuit redesign and changing flow paths for example removing undersize from feed streams

• Integrating mill requirements into mine operations and blasting
There are a wide variety of modeling efforts going on in the mineral processing field and we will discuss some of them here.

There are several types of mineral processing models:

- Models that attempt to simulate flow sheets.
- Models to attempt to predict particle breakage (population balance models).
- Models that attempt to predict material flow and behavior in unit operations.
- Models that utilize discrete element modeling and/or computation fluid dynamics to simulate unit operations.
Simulates steady state flow sheet behavior using models for each unit operation.
Example MinOOcad Mill Flow Sheet Simulation

Simulates dynamic flow sheet behavior using models for unit operations

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Metso KIEM
Models for Particle Behavior in Milling

- Various models have been developed to predict grinding in tumbling mills.
- Most include population balance models with breakage and selection functions.
- They also may include discrete element models and predictions of impact energy (magnitude and frequency).
- Several examples are shown in the next few slides.
- We have been using a program called “MillSoft” to determine scale up factors for data generated in smaller laboratory mills (1 m diameter).
“MillSoft” Simulation Results at KIEM

Charge motion of different diameter mills. Ball load: 35\%, speed: 70 \% critical
Variation of power draw with mill diameter
Speed: 60% critical, mill load: 50%

\[ y = 322.43e^{2.5151x} \]
\[ R^2 = 0.9945 \]
DEM impact energy spectra.

- A simplified picture of collision phenomena in a grinding mill is shown.

- $E_k$ is the energy of the collision in Joules, and $\lambda_k$ is the frequency of the $k^{th}$ level collision in collisions per second.

- When the coarse size or feed material enters the mill, it is subjected to a number of different levels of collisions in the tumbling body at each time interval until it exits the mill.

**Fig. 1.** Illustration of collisions occurring in a grinding mill.

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Tuzcu & Rajamani
New Grinding Methods

• There have been many attempts to find alternative methods to reduce solids to fine “liberation” sizes in more energy efficient ways (water jets, electrical discharges, rotary and air impingement methods, etc.)
• To date, there have been no breakthroughs that can replace conventional tumbling mills for the final stages of size reduction.
• One new concept is the use of HPGR for dry, fine grinding.
• There will be a break through someday, and this could be a very fruitful topic for fundamental research.
Conclusions - Energy and Models

- The high operating costs in both energy and wear of balls and liners is seen as the cost of doing business.
- Efforts are primarily on ways to improve the energy efficiency of conventional mills by understanding how things like lifter design and operating parameters effect this through both modeling and experimental evaluation.
- Flow sheet simulations can be used to compare and contrast various alternatives during design.
- These simulations are only as good as the models (and data) that are used and work is continuing world-wide to improve both.
Automated Mineralogy

- Various types of automated mineralogy systems are available (MLA, QEMSCAN, etc.)
- They are typically scanning electron microscopes with one or more EDS systems to detect elements, coupled with a computer and data base for mineral identification.
- These work best when coupled with an experienced mineralogist to help define and interpret the results.
- This tool is extremely useful in defining liberation, minerals and mineral associations, in testing, and losses in operations through plant audits.
Automated Mineralogy

• Two examples of iron ores are presented from our research. Both are lower grade and too high in impurities (primarily phosphorus).

• The objectives in both are to increase the iron grade (at acceptable recoveries) and reduce the P content.

• In the first study, the ore turned out to be oolitic with a liberation size less than 5 microns. The only method found to meet the objectives was a magnetizing roast followed by fine grinding and low intensity magnetic separation (expensive).

• In the second study, the apatite was seen to be liberated at 74 microns, implying that a form of froth flotation could be the best approach.
QEMSCAN KIEM Example – Apatite Liberation

Fig. 4: QEMSCAN images of representative particles showing liberated Fe Oxide/Hydroxide and apatite grains as well as both minerals cementing quartz. Scale bar = 300 μm.
Automated Mineralogy

- There will be continued advancement in this technology including better data bases, better fine resolution and less expensive platforms.
- Operating plants will benefit from having near real time data on the performance of each unit operation.
- This might be coupled with on line XRF (or other) systems to provide detailed process information for control purposes.
Examples from Extractive Metallurgy

- Fundamentals
- Ore preparation – induration and roasting
- Smelting
- Reduction
- Leaching
Fundamentals

- Heat and Mass Balances
- Chemical Kinetics and Reactor Design
- Heat, Mass and Momentum Transfer
- Gibbs Energy Minimization
- Computational Fluid Dynamics

Slag Fuming in Top Submerged Lance Smelting Furnace

Temperature profile inside the furnace (a) molten slag only (b) gas phase only (Huda et al 2010)
Iron Ore Induration

The future of methods to treat fine iron ore concentrates will require new technological innovations. If certain countries decide to impose a tax on carbon emissions, then induration of iron ore pellets could become much more expensive. The innovative approaches that may be taken might include:

- Alterative heat sources during induration (electricity in place of fossil fuels).
- Development of cold bonded pellets.
- Development of iron making technology that would use the iron ore fines directly.
- Use of hydrogen as a reductant to convert iron ore fines.

Schematic of a Grate-Kiln Induration System (Trescot 2004)
• This process uses iron ore fines, coal instead of coke, is air based.
• Coal is injected through bottom tuyers into the molten bath.
• Carbon is dissolved and reacts with the oxygen from incoming iron ore to form carbon monoxide and iron.
• This reaction is endothermic and additional heat has to be supplied.
• To provide this needed heat, carbon monoxide released from the bath is reacted with oxygen from top injection of air.
• The reacted hot gasses exit the vessel and are used in a fluidized bed to pre-heat and pre-reduce incoming ore.

HIsmelt Process (Goodman 2007)
Roasting

Innovation is occurring in roasting:

• Evaluating methods to treat ores with higher amounts of problematic elements, either by capture in the calcine during roasting (lime roasting), selective volatilization (Oudenne 2006) or by improved gas treatment systems.

• Continued design and scale up improvements.

• Continued development and application of recirculating fluidized beds. The higher operating gas velocities provide for a greater difference in slip velocity and enhance heat and mass transfer rates and thus the kinetics of heterogeneous reactions.

Schematic for a two stage fluidized bed for refractory gold ores (Smith 1990)
Smelting

- A major copper and lead smelter converted to the treatment of complex concentrates and recycled materials.
- Hoboken plant, where besides precious metals, copper, and a large variety of base and special metals are recovered.
- State-of-the-art off-gas and waste water purification installations, the plant has been developed to be the most advanced full-scale processor of secondary materials such as automotive catalysts and electronic-scrap, generating optimum metal yields at increased productivity.
- Circuit boards, mobile phones and metal hydride batteries etc are treated.

Flow sheet for Umicore's integrated metals smelter and refinery (Hagelüken)
As an alternative to traditional roasting technology, Rio Tinto’s Kennecott facility at Bingham Canyon, Utah has patented an alkaline pressure oxidation process for the recovery of molybdenum and rhenium from molybdenite concentrates. In this process, the molybdenite flotation concentrate is leached with either sodium or potassium hydroxide at elevated temperature (150-200°C) and pressure to form soluble MoO₄²⁻.
The insoluble molybdenum tri-oxide is brought into solution using soda ash leaching via the following reaction.

\[
\text{MoS}_2 + 3\text{H}_2\text{O} + 5\frac{1}{2}\text{O}_2 \rightarrow \text{MoO}_3 \cdot \text{H}_2\text{O}_{(\text{solute})} + 2\text{H}_2\text{SO}_4
\]

\[
\text{MoS}_2 + 2\text{H}_2\text{O} + 5\frac{1}{2}\text{O}_2 \rightarrow \text{MoO}_3_{(\text{insoluble})} + 2\text{H}_2\text{SO}_4
\]

\[
2\text{CuFeS}_2 + 8\frac{1}{2}\text{O}_2 + \text{H}_2\text{SO}_4 \rightarrow 2\text{CuSO}_4 + \text{Fe}_2(\text{SO}_4)_3 + \text{H}_2\text{O}
\]

This aqueous molybdenum species is then recovered using solvent extraction and is stripped with an ammonium hydroxide eluent via the following reaction.

\[
\text{Na}_2\text{MoO}_4 + \text{H}_2\text{SO}_4 \rightarrow \text{Na}_2\text{SO}_4 + \text{MoO}_3 \cdot \text{H}_2\text{O}_{(\text{solute})}
\]

The rhenium present in the molybdenite concentrate is recovered, as ammonium perrhenate, in the loaded strip solution. Rhenium present in the strip solution is then recovered using a selective ion exchange resin. This resin typically contains quaternary amine functional groups as found in Amberlite IRA-400.
Critical Materials – a mineral processor’s perspective

Monazite

Bastnasite
Criticality Matrices for Clean Energy – the DOE Perspective

Figure ES-1. Short-Term (Present–2015) Criticality Matrix

Figure ES-2. Medium-Term (2015–2025) Criticality Matrix
Critical Materials

• In recent years there have been several elements that, through scarcity, or other constraints, appear to be limited in supply.

• These might be broken down into two primary types of scarce elements.

• There are those that are primarily a minor byproduct of the recovery of another primary metals (rhenium, indium, tellurium, gallium, germanium, etc.)

• And, there are those that occur as a separate deposits or as mineral by-products; but may require significant effort to economically beneficiate and refine (rare earth elements, platinum group elements, lithium, etc.)
Critical Materials – Minor By-Product Impurities

• For the first group, there is very little than can be done unless the primary ore deposits are expanded.
• In some cases, i.e. rhenium, alternative treatment methods for the primary metal can lead to increased recoveries. Pressure oxidation of molybdenite concentrates instead of roasting is an example.
• In all cases, development of recycling technology can help to alleviate some of the demand, if developed in an economic manner. Recycling of CdTe PV panels, Plasma display panels (ITO), etc. may be examples.
Critical Materials - Ores

• Deposits that contain rare earth elements are not very rare; but deposits with significant ore grades are apparently rare. These higher grade ores will most likely be developed if the demand stays high.

• Rare earth elements are also a fairly common occurrence as by-product in ores such as: some phosphate ores, some iron ores, some heavy mineral sands, etc. These may be exploited if demand stays high.

• Some consideration of problematic impurity elements requires research for safe processing and disposal in some of these deposits.

• Recycling can also play an important role in these elements’ availability.
Challenges and Opportunities in Critical Materials

- Understand the current state of the technology available for critical materials resource processing.

- Do research on those aspects that could be improved utilizing new mineral processing, extractive metallurgy and metal refining technology; both on ores and recycled materials.

- Address the ultimate disposition of problematic elements in the solid and aqueous discharge.

- Develop a trained engineering work.

- Understand that economics is always the bottom line in any resource recovery operation.
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Industrial Projects - Current and Recent

- Magnetic separation of a vanadium containing titaniferrous magnetite;
- Beneficiation of iron ores (oolites);
- Extraction of titanium from pickling solutions;
- Methods for treatment of electronic scrap for feed to a copper smelter;
- Molten Salt Electro-reduction of Boron Oxide
- Controlled Pressure Oxidation of Enargite Concentrates
- Rare Earth Recovery from Thermal Spray Powder Wastes
- Development of an improved method for measuring and predicting abrasive wear in milling operation
Industrial Projects - Current and Recent

- Develop a new laboratory scale mill for energy efficiency in milling operations
- Ion exchange separation technologies for rare metals
- Metal reduction technologies for rare metals
- CR\(^3\) – Beneficiation of Photovoltaic Coatings
- CR\(^3\) – Recovery of Rare Earth Metals from Phosphor Dust
- CR\(^3\) - Recycling of Bag-house Dust from Foundry Sand
- CR\(^3\) – Zinc Removal from Galvinized Scrap
- CR\(^3\) – Indium and Rare Earth Recovery from Used Plasma Display Panels
- CR\(^3\) – Recycle of Rare Earth Magnets
- Surface Chemistry and Flotation of Rare Earth Minerals
Thank you for inviting me to
X Seminario Minero Internacional
Hermosillo, Sonora, Mexico
Hill Hall, home of KIEM
Colorado School of Mines
Please come see what we’re up to.