Industrial Water Use and Reuse Workshop
Strategies for Sustainable Water Management for Mining

Patrick R. Taylor, Ph.D., P.E.
Director, Kroll Institute for Extractive Metallurgy
Colorado School of Mines
“KIEM - Excellence in Education and Research for the Mining, Minerals and Metals Industries”

- **History:** The Kroll Institute for Extractive Metallurgy was established at the Colorado School of Mines in 1974 using a bequest from William J. Kroll.

- **Over the past 42 years,** the Kroll Institute has provided support for a significant number of undergraduate and graduate students who have gone on to make important contributions to the mining, minerals and metals industries.

- **Objectives:** The objectives of KIEM are to provide research expertise, well-trained engineers to industry, and research and educational opportunities to students, in the areas of: minerals processing, extractive metallurgy, recycling, and waste minimization.
Kroll Institute for Extractive Metallurgy

Patrick R. Taylor
Director, KIEM
G.S. Ansell
Distinguished
Professor of Chemical
Metallurgy
EXPERTISE
• Mineral Processing
• Extractive Metallurgy
• Recycling
• Waste Treatment & Minimization
• Thermal Plasma Processing

D. Erik Spiller
Research Professor of Metallurgical and Materials Engineering
EXPERTISE
• Mineral Processing
• Leaching
• Project management: feasibility, engineering, construction management, operations

Corby G. Anderson
Harrison Western Professor of Metallurgical and Materials Engineering
EXPERTISE
• Extractive Metallurgy
• Mineral Processing
• Recycling
• Waste Treatment & Minimization

Edgar E. Vidal
Research Associate
Professor of Metallurgical and Materials Engineering
EXPERTISE
• Extractive and process metallurgy
• Pyrometallurgy
• Recycling
• Waste treatment and minimization.

Judith C. Gomez
Research Assistant
Professor of Metallurgical and Materials Engineering
EXPERTISE
• Extractive and process metallurgy
• Materials synthesis
• Recycling
• Waste treatment and minimization
Industry Funded Projects - Current and Recent

✓ Magnetic separation of a Peruvian vanadium containing titaniferrous magnetite;
✓ Beneficiation of a Colombian iron ore (oolite);
✓ Recovery of titanium from casting pickling solutions;
✓ 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;
✓ Development of a new laboratory scale mill for energy efficiency in milling operations.
✓ Fundamental study of commercial gold roasting operation.
Industry Funded Projects - Current and Recent

✓ Ion exchange separation technologies for rare metals;
✓ Metal reduction technologies for rare metals;
✓ Controlled oxidative roasting of enargite concentrates.
✓ CFD Modeling and slag chemistry for secondary lead processing

Center for Resource Recovery and Recycling - Industry consortia

✓ CR³ – Beneficiation of Photovoltaic Coatings;
✓ CR³ – Recovery of Rare Earth Metals from Phosphor Dust;
✓ CR³ - Recycling of Bag-house Dust from Foundry Sand;
✓ CR³ – Zinc Removal from Galvanized Scrap
✓ CR³ – Indium and Rare Earth Recovery from Used Plasma Display Panels;
✓ CR³ – Recycle of Rare Earth Magnets;
✓ CR³ – Red Mud Recycling.
✓ CR³ – Recycling of Fines
Government sponsored projects - Current

✓ Surface Chemistry and Flotation of Rare Earth Minerals – Office of Naval Research - ~$300,000 over 3 years.

✓ Critical Materials Institute – DOE - ~$8.5 million over 5 years to research mineral processing and extractive metallurgy for recovery and recycling of critical metals. ~$1 million in new mineral processing – extractive metallurgy and analytical equipment.
Projects at Colorado School of Mines

- Project 1.1.1: Advanced Beneficiation Techniques
- Project 1.2.2: Conversion to Metals, Alloys and Materials
- Project 3.1.1: Recovery and Reuse of Rare Earth Metals from Phosphor Dusts
- Project 3.1.3: Cost Effective Recycling of Rare Earth Containing Magnets
- Project 3.1.4: Beneficiation of Photovoltaic (and other) Functional Coatings
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.
- **Extractive Metallurgy** is used to recover metals from minerals.

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

The following topics will be discussed:

- Wont recycling take care of our needs for metals?
- Current State of Mineral Processing & Extractive Metallurgy
- Water in mineral processing and extractive metallurgy
- Reagent regeneration technologies
Economics - Iron Ore and Steel Production – The Easiest Metal to Recycle

- Steel is the most recycled metal, usually after many decades or even centuries.
- Recycling can not keep up with the increased demand from developing countries.
- If all the steel produced in 1980 was recycled it would not meet half the current demand.
- New mines and mining are essential to the USA and world economy.

Source: UNCTAF Trust Fund on iron ore information

Source: Professor David Matlock
Introduction – Current State

- Mineral processing and 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 and extractive metallurgy benefit from many decades of fundamental and applied research.
- This has greatly enhanced our ability to perform extracting metals 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.
Separations

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.

G. S. ANSELL DEPARTMENT OF METALLURGICAL & MATERIALS ENGINEERING
Extractive Metallurgy

There have been several significant advancements in our understanding of chemical processing methods for extraction and separation:

- 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 one of the challenges and opportunities that is being addressed in the field of mineral processing and extractive metallurgy.

- **Water** (this is fast becoming a scarce resource)

Others are:

- Energy, and
- Improved fundamental understanding of unit operations

Reverse Osmosis

G. S. ANSELL DEPARTMENT OF METALLURGICAL & MATERIALS ENGINEERING
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

“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.
- Greater consideration of long-term mine closure needs.”
Water Resources

Water might be obtained from:

- Ground water, run-off water, mine dewatering, acid mine drainage, recycled process water, rainwater, sewage water, or seawater.

- Each potentials source has different characteristics that may limit it’s utility or require treatment prior to use.
Water use in the Mining Industry

- Generally, the majority of use is for mineral processing, smelting and refining applications.
- Most of this is for flotation.
- Use may be reduced by water management strategies, recycling process water, reducing evaporation, and seepage and dry stacking.
- Another option might be the use of alternative water sources, i.e. saline, seawater and/or sewage.
• 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.)
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>
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, chlor alkalie or salt splitting technology.
Salt to HCl and NaOH

Fig. 1. Three liquid compartment electrolysis cell to produce hydrochloric acid and sodium hydroxide from sodium chloride and the main transfers in the system.
Sodium Sulfate to NaOH and Sulfuric Acid

Figure 1. Three compartments electro-electrodialysis to produce $\text{H}_2\text{SO}_4$ and NaOH
Chlor Alkali

G. S. ANSELL DEPARTMENT OF METALLURGICAL & MATERIALS ENGINEERING
Thermal Hydrolysis of Iron Chloride to make HCl

• The hydrolysis of FeCl$_3$ is a reversible reaction.
  \[2\text{FeCl}_3 + 3\text{H}_2\text{O} \rightleftharpoons \text{Fe}_2\text{O}_3 + 6\text{HCl}\]

• Increasing initial HCl concentrations will, therefore, reduce the extent of hematite precipitation and sufficiently high initial acid concentrations will solubilize part of the added hematite seed.
Mine Water Treatment Technologies

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>

Dunne

G. S. ANSELL DEPARTMENT OF METALLURGICAL & MATERIALS ENGINEERING
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>Michilla 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

G. S. ANSELL DEPARTMENT OF METALLURGICAL & MATERIALS ENGINEERING

KIEM
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.
Examples of Dry Processing

Dry Grinding – Carlin Mill

Dry Shaking Table, Wire Chopping Plant – Cu Recovery
Primary Crushers

Secondary crushing

- 50 mm
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.
Ball Mills

SAG Mill

G. S. ANSELL DEPARTMENT OF METALLURGICAL & MATERIALS ENGINEERING
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.
Example JK SimMet Mill Flow Sheet Simulation

Simulates steady state flow sheet behavior using models for each unit operation.
Example MinOObcad Mill Flow Sheet Simulation

Simulates dynamic flow sheet behavior using models for unit operations.
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 Oolite

Mineral Name
- Goethite: 45.9
- Fe Al Silicate - (Chamosite?): 35.9
- Apatite: 6.2
- Fe-Apatite Boundary: 5.1
- Hematite/Magnetite: 5.7
- Quartz: 0.8
- Background: 0.0
- Others: 0.2
- Fe-sulphides: 0.2

Fe-Deposition
- Goethite: 28.8
- Fe Al Silicate - (Chamosite?): 10.6
- Hematite/Magnetite: 4.1
- Fe-Apatite Boundary: 2.2
- Fe-sulphides: 0.1
- Others: 0.1
- Quartz: 0.1
- Apatite: 0.0

Total: 45.9

G. S. ANSELL DEPARTMENT OF METALLURGICAL & MATERIALS ENGINEERING
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.
Primary References for the Presentation

- Agricola, G., 1556, De Re Metallica, 1950 Hoover Translation, Dover, New York
- Dunne, R., 2010, Water recycling and Frugal Water Use, XXV International Mineral Processing Congress (IMPC), 2010 Proceedings, Brisbane, Australia
- GWI, (2011), Water in Mining, Media Analytics, Oxford UK
- JKMRC Commercial Division, (2009) JK SimMet, Australia
- Metso, MinO0cad, (2003), Colorado Springs, CO
Hill Hall, home of KIEM
Colorado School of Mines
Please come see what we’re up to.

The Kroll Institute for Extractive Metallurgy
George S. Ansell Department of Metallurgical and Materials Engineering
Colorado School of Mines
www.mines.edu