Monitoring global flows of hazardous substances from mines and smelters

Iván Valenzuela Rabí, CEO
Ricardo Pezoa Conte, Strategy & Development Engineer

EcoMetales Limited
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Global Trends
Challenges to achieve sustainable development

- **Energy consumption** (CO$_2$ emission)
  - Fe, Al, Ti, Mg, Mn

- **Environmental Problems**
  - Hg, As, Cd, Tl, Be, Se, B, I, F, Br

- **Supply Risk**
  - Au, Ag, PGM, Bi, Co,
  - RE
  - W, Mo, Ta, Nb, Ga
  - Zn
  - Cu, Pb, Sb, Ni, In

- **Health, Biological effects**

- **Climate change**

Source: Voisin L. et al. Todaiforum 2018
Overall flows of hazardous impurities

Anthropogenic Impurities cycles related to Intentional uses

Mining → Concentrator → Imports (Exports) → Smelter/Refinery → As commodities (Imports) (Exports) → As products (manufacturing) → Use → In-use stock → EOL management and recycling

Lithosphere
- Metal ores
  - Cu ores, Zn ores, Sn ores, Au ores, Complex ores

Fossil Fuels
- Trace impurities

Atmosphere
- Fossil fuels mining
- Fossil fuels combustion
- Construction
- Metal production
- Waste incineration
- Miscellaneous other activities

Hydrosphere

Lithosphere Pedosphere

Anthropogenic Impurities cycles related to Unintentional uses

Adapted from J Clean Prod 139 (2016) 328-336
Mining (Copper) is increasing the generation of waste

Mass flow within processing to generate 1 t of cathodic copper

Mine material 327 t / 700 t

Waste rock 210 t / 480 t

Ore 116 t / 220 t

Tailings 113 t / 215 t

Cu cons 3.1 t / 4.5 t

Slag 1.9 t / 2.7 t

Cathode 1.0 t / 1.0 t

Others 0.2 t / 0.8 t

Close to twice more waste generated

Source:
- Mudd & Werner, T. G. (2019). Solid waste in base metals mining, smelting and refining: A comprehensive synthesis (prepared for ICSG)
Global Copper production in 2018 from mineral sources (kMT Copper Content and % of the World)

World Copper Production from Minerals by 2018 (kMT of Cu content)

15% 3.055 Oxide ore HYDROMETALLURGY

Agglomeration

Leaching

Solvent Extraction

Electro-winning

Pure copper cathode, 99.99% Cu

85% 17.797 Sulphide ore PYROMETALLURGY

Crushing

Milling

Froth Flotation

Thickening

Smelter

Electro-refining

Source: COCHILCO / Chilean Copper Commission, based on company reports
As anthropogenic flows in China

Figures in ktpa 2000/2010

More than 50% increase in the handling of As within Non-ferrous metallurgical facilities between 2000-2010

DOI: 10.1021/acs.est.6b01669
Arsenic mines, projects and complex concentrate treatment facilities

High arsenic concentrate as a percentage of total concentrate supply

- 2018: 8%
- 2028 Base: 9%
- 2028 Full Potential: 13%

Key
- Current High As operation
- Future High As project
- High arsenic smelter
- Concentrate blending facility

Modelled complex ore processing

Industry Base Case Flotation
- Base case + roasting and blending
- Base case + leaching
- Blend ore + Base case + roasting
- Base case + roasting

SOURCES: MineSpans by McKinsey; Copyright © McKinsey & Company, August 2019
As environmental regulations become increasingly stringent, arsenic looks set to pile even more pressure on copper producers. Arsenic is increasingly a threat to many copper mines, as a consequence of processing and smelting operations. It is a naturally occurring element that is often found at high concentrations in copper deposits, and its presence can impact the environmental and health risks associated with copper production. Different processing methods yield different forms of arsenic, with some more toxic than others.

The largest copper supply region in the world, Latin America, has high arsenic content in many of its ageing copper mines. With many of the upcoming projects also having high arsenic content, the volume that needs to be treated becomes more acute as the in-situ grade increases. The largest copper supply region in the world, Latin America, has high arsenic content in many of its ageing copper mines. With many of the upcoming projects also having high arsenic content, the volume that needs to be treated becomes more acute as the in-situ grade increases.

Latin America, the world's largest copper supply region, is home to many copper mines that have high arsenic content. This is due to the natural occurrence of arsenic in copper deposits, which can make it difficult to completely remove during processing. As a result, copper produced in Latin America may contain high levels of arsenic, which can have environmental and health impacts if not properly managed.

In response to these challenges, copper producers are investing in advanced treatment technologies to remove arsenic from their concentrates. This includes a range of processes, from physical separation to chemical precipitation, each with its own set of advantages and disadvantages. The choice of treatment technology depends on factors such as the concentration of arsenic in the feedstock, the desired level of arsenic removal, and the availability and cost of processing equipment.

To address these challenges, copper producers are investing in advanced treatment technologies to remove arsenic from their concentrates. This includes a range of processes, from physical separation to chemical precipitation, each with its own set of advantages and disadvantages. The choice of treatment technology depends on factors such as the concentration of arsenic in the feedstock, the desired level of arsenic removal, and the availability and cost of processing equipment.

Capturing arsenic in early-stage processing has cost advantages compared to processing high arsenic after the ore has been smelted. However, it is crucial to understand the environmental and health impacts of different arsenic treatment methods. The selection of the most appropriate arsenic treatment technology depends on a range of factors, including the concentration of arsenic in the feedstock, the desired level of arsenic removal, and the availability and cost of processing equipment.
Global Copper Mine Production
Production & Participation, last 10 years
(kMT Copper Content and % of the World)

<table>
<thead>
<tr>
<th>Country</th>
<th>Production (kMT)</th>
<th>Participation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chile</td>
<td>5.832</td>
<td>28.0</td>
</tr>
<tr>
<td>Peru</td>
<td>2.437</td>
<td>11.7</td>
</tr>
<tr>
<td>China</td>
<td>1.507</td>
<td>7.2</td>
</tr>
<tr>
<td>DR Congo</td>
<td>1.225</td>
<td>5.9</td>
</tr>
<tr>
<td>USA</td>
<td>1.216</td>
<td>5.8</td>
</tr>
</tbody>
</table>

By 2018

Cu Content (kMT)

Year

Other countries

Source: COCHILCO / Chilean Copper Commission, based on company reports
Arsenic content concentrate output is growing fast

• **El Brocal** (Buenaventura): 5-8% As
• **Cobriza** (Doe Run): 0.4-0.6% As
• **Chinalco**: 0.5-1% As
• **Magistral** (Nexa Resources): 1% As
• **Cañariaco** (Candente Resources): 1% As
• **Other Projects**: La Granja, Galeno

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Sources: Codelco, Cochilco, Anglo American, EcoMetales, ICSG, McKinsey
Copper concentrate market

PRODUCERS

2007
16 Mt

2012
20 Mt

2017
30 Mt

IMPORTS

Source: ICSG

56%
44%
South America
(Chile & Perú)

56%
44%
Others

56%
44%

56%
44%

26%
26%

26%
48%
China

26%
48%
Japan

26%
48%
Others

Source: ICSG
Copper smelters Worldwide

YEAR
2000  2009  2018

USA
KMT  %  Rank
1002  8.5  4°

Chile
KMT  %  Rank
1460  12.3  2°
1522  10.8  3°
1246  7.0  3°

Russia
KMT  %  Rank
758  6.4  5°
850  6.1  4°
897  5.0  4°

China
KMT  %  Rank
1014  8.6  3°
2694  19.2  1°
6357  35.7  1°

Japan
KMT  %  Rank
1481  12.5  1°
1542  11.0  2°
1565  8.8  2°

Zambia
KMT  %  Rank
852  4.8  5°

India
KMT  %  Rank
729  5.2  5°

Chilean Copper Production 1992-2018 and projection 2019-2023 (kMT Copper Content)

Production of Copper in Chile by 2018

<table>
<thead>
<tr>
<th>Route (kMT)</th>
<th>2018</th>
<th>2023</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total from Mine</td>
<td>5.832</td>
<td>6.309</td>
</tr>
<tr>
<td>Hydrometallurgy</td>
<td>1.575</td>
<td>1.130</td>
</tr>
<tr>
<td>Pyrometallurgy</td>
<td>1.246</td>
<td>1.246</td>
</tr>
<tr>
<td>Concentrate</td>
<td>3.010</td>
<td>3.933</td>
</tr>
</tbody>
</table>

Source: COCHILCO / Chilean Copper Commission, based on company reports
Effects of impurities in smelting
More than 20 metals can be recovered except RE, W, Mo, V, Mn, Cr, Nb, Ta and Li

Source: Voisin L. et all. Todaiforum 2018
Necessity to treat more complex ores with higher contents of As and Sb has generally been high.

Amounts of As and Sb in produced metals have far exceeded the demand.

Some ores high in As and Sb have in fact faced a cost penalty at the smelter, or are deliberately avoided during mining.

Elimination of these elements before final refining stage is required.

High arsenic and antimony become a problem at copper smelters.
High Arsenic Concentrate from DMH
A real case at Chuquicamata smelter in Chile

- DMH Concentrates contains large amounts of arsenic and clay gangue minerals causing serious problems during the smelter operation.
- Formation of a molten Speiss even at the Flash Furnace
- Large emission of arsenic gases to the air and bad quality of copper anodes

In 2012, 26 days for maintenance
High As in CuCons: Japanese smelters

<table>
<thead>
<tr>
<th>Regulation</th>
<th>As limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>No limits</td>
</tr>
<tr>
<td>Surface water</td>
<td>0.01 ppm</td>
</tr>
<tr>
<td>Underground water</td>
<td>0.01 ppm</td>
</tr>
<tr>
<td>Slag</td>
<td>Content: 150 g/ton</td>
</tr>
<tr>
<td></td>
<td>Elution: 0.01 ppm</td>
</tr>
</tbody>
</table>

An increase of the As content in concentrate would prevent it from being fixed in the slag.
High As in CuCons: Chinese smelters

Cu concentrate → Smelter → Sulfation roasting → As recovery → Reduction → Acid plant → Metallic As

Waste acid → White ash

As used to be processed to obtain products (20%)

Increase of As superavit and regulations reduce the market and obliged safe storage

As for disposal (80%)

Valuable Metals recovery

Arsenic trioxide

Adapted from: http://www.jogmec.go.jp/content/300358439.pdf
Last accessed on October 17th, 2019
Worldwide Production of arsenic trioxide

Data retrieved from: https://www.usgs.gov/centers/nmic/arsenic-statistics-and-information
Last accessed on October 15th, 2019
Some copper concentrates can be harmful to marine environments and can represent a risk for crews. By the beginning of 2018, China set a ban on the import of scraps. The EU-28 established the Best Available Techniques (BAT) in 2016 for waste reduction of copper and other metal industries, including the reduction of the amounts of waste sent for disposal from copper production. In 2018, Chile set a minimum capture of As & SO2 at 95% for current operations.

Sources: ICSG, Cochilco.
Where do we remove impurities?
Capturing arsenic in early stage processing has cost advantages compared to processing high arsenic waste. Due to the relatively low capture rate of standard copper sulphide processing methods such as flotation, it cannot be applied to high arsenic waste in isolation. Several processing methods exist, as seen in the figure, to be applied in combination with conventional copper sulphide processes. These processes can be grouped into three categories: (1) those that improve the base copper sulphide flotation process, (2) those that improve the precipitation or removal of the arsenic before flotation, and (3) those that improve the capture and removal of the arsenic after flotation. This figure illustrates the complex process of arsenic capture and shows the potential for improving the process by combining different methods.

**Sources:** MineSpans by McKinsey; Copyright © McKinsey & Company, August 2019
JOGMEC initiatives for the separation of high As concentrates

Comminution
- Theme 1
  - Promotion of As liberation at the comminution stage

Conditioning
- Theme 2
  - Conditioning of the mineral prior flotation

Separation
- Theme 3
  - Development of new flotation agents

Processing As mineral
- Theme 4
  - Copper recovery & As fixation

Taken from: Kamiya, JOGMEC Project on arsenic reduction, International Seminar on Impurities in Copper Raw Materials, 2018, Tokyo, Japan
Other initiatives for high As concentrates treatment

- Hydroprocessing
- Alkaline leaching
- Chloride leaching
- Bioleaching
- Pressure leaching
- Roasting
As a result, copper production faces increased environmental scrutiny. Currently, the most environmentally friendly treatment is hydrometallurgy, and investment may flow into the technological development of these treatment facilities, as well as the management of waste from roasters and smelters.

**Sources:** MineSpans by McKinsey; Copyright © McKinsey & Company, August 2019
The project:

- is capable for processing 200 ktpa of High As CuCons
- has synergies with SX/EW available capacities nearby
- would produce 60 ktpa Cu cathodes
Reduced smelting capacity expected

Chile's Codelco says considering closure of coastal copper smelter

FILE PHOTO: The logo of Codelco, the world's largest copper producer, is seen at their headquarters in downtown Santiago, Chile March 29, 2018. REUTERS/Ivan Alvarado

SANTIAGO (Reuters) - Chile's Codelco, the world's largest copper producer, said on Monday that it is evaluating the closure of its Ventanas copper smelter in a polluted coastal region.

Media have reported that President Sebastian Pinera would announce the closure of the facility during the upcoming COP25 climate change conference, which will take place in capital Santiago in December.

The Ventanas smelter has been the target of criticism from social and environmental groups that accuse it of contributing to heavy pollution in the Quintero area on the central coast of the country.
# As abatement technologies

<table>
<thead>
<tr>
<th>Final residue</th>
<th>TCLP</th>
<th>Industrial application</th>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium arsenite</td>
<td>Liquid effluents and low copper containing solutions</td>
<td>Known technology</td>
<td>High volumen residue. Does not allow for the recovery of metals. Low As content</td>
<td></td>
</tr>
<tr>
<td>Arsenical ferryhydrate</td>
<td>Unstable, harmful to the environment. Handling as hazardous waste</td>
<td>Technology applied in El Teniente and Japan</td>
<td>Unstable residue, requires high Fe/As ratios to ensure As immovilization</td>
<td></td>
</tr>
<tr>
<td>Arsenic trioxide &amp; Metallic arsenic</td>
<td>Cu concentrates with high As content</td>
<td>Commercial use for arsenic</td>
<td>Highly hazardous chemical</td>
<td></td>
</tr>
<tr>
<td>Scorodite (atmosferic pressure)</td>
<td>Sulfuric acid plant and refinery effluents, leaching solution of high copper content flue dust</td>
<td>Highly stable residue Allows for Cu recovery</td>
<td>Requires Fe and oxidants as inputs. 12-17% As residue.</td>
<td></td>
</tr>
<tr>
<td>Scorodite (autoclave)</td>
<td>Cu &amp; Au Ore and concentrates with high As content</td>
<td>One step process. Does not requires iron as input</td>
<td>High pressure and requires Oxygen plant. 5% As residue when processing Cu concentrates</td>
<td></td>
</tr>
</tbody>
</table>
R&D new developments for As abatement

1. Toowong Process
2. Vitrification
3. Encapsulation with cement and geopolymers
4. Stabilization in presence of biological agents
5. Encapsulation with Aluminum gels
6. Stabilization in presence of Iron nanoparticles
The scorodite process has advantages over other stabilization technologies

The process uses similar equipment sizing of the two flowsheets, Hatch estimates the atmospheric scorodite process can offer about 15% capital cost savings and about 25% operating cost savings over the ferrihydrite process. These potential savings can be significant in determining the economic viability of processing a complex copper concentrate with high arsenic.

A COMPARISON OF ROASTING TECHNOLOGIES FOR ARSENIC REMOVAL FROM COPPER CONCENTRATES

*K. Adham, C. Lee, S. Francey, and A.M.S. Hussein
Hatch Ltd. - Mississauga, Ontario, Canada L5K 2R7
D. Lemieux and J.P. Mai
Dundee Sustainable Technologies - Montreal, Quebec H3A 3L6
(*Corresponding author: kadham@hatch.ca – 905-403-3877)

ABSTRACT

Copper concentrates contain an increasing amount of arsenic, as the older sources of cleaner ores are depleted. At the same time, the market-determined price penalties on arsenic rich concentrates are rising due to limited arsenic treatment capacity at smelters and increasingly stringent environmental emissions limits, necessitating arsenic removal from the copper concentrates. Heating the concentrate to about 700°C can remove significant amounts of arsenic (as elemental and/or sulfide); however, it is important to achieve that removal economically and with due consideration to post-roasting arsenic (toxic waste) treatment. A comparison is made among different roasting options (kilns, multi-hearth and fluid beds) to qualify their potential application to arsenic roasting of copper concentrates. Both direct and indirect methods of heating as well as inert, air and oxygen atmosphere options are considered. Technology comparisons are made with respect to the roaster’s operation, its off-gas treatment and arsenic stabilization.
Final remarks
Arsenic is known to be a toxic element that can be harmful to humans and the environment. As a consequence of arsenic oxide processing, miners, and smelters are dealing with arsenic that tends to accumulate in the environment and can pose a serious health risk. The regulation and environmental considerations are making it more difficult to dispose of and treat arsenic. To remain competitive, high arsenic miners and processors need to invest in treatment and storage facilities now to avoid future penalties or operational issues.

**Potential future TCI/RIC ranges for copper concentrate**

TCI/RICs are likely to become a function of cost for each tonne of concentrate produced. Higher TCI/RICs are expected for higher-quality copper concentrate. As a matter of fact, high-quality copper concentrate is produced for a premium price on the market. This is due to the increasing environmental regulations and the need for higher-quality copper to meet the demand for clean and sustainable energy technologies.

**Number of new facilities required in 2028**

To meet the increasing demand for copper, new facilities will need to be built. This will increase the cost of production and the need for efficient waste management and treatment. The environmental regulations will continue to evolve, and the industry must be prepared to adapt to these changes.

**SOURCES**: MineSpans by McKinsey; Copyright © McKinsey & Company, August 2019
We are a strategic partner for the mining industry
Contact us for further information

072 Nueva de Lyon St., Floor 17th Providencia, Santiago, Chile
Phone (56 2) 23784100
Fax. (56 2) 23784111

www.ecometales.cl

Road to Radomiro Tomic Km. 16 ½ Calama, Antofagasta, Chile
Phone (56 55) 2320 950