Energy Efficiency & Copper Hydrometallurgy

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Presentation Outline

- Purpose & background
- Methodology & assumptions
- Operations & process routes considered
- Energy consumption by unit operation
- Energy consumption by process route
- Energy consumption by source
- Opportunities for energy reduction
Purpose

- To provide a high level overview of specific energy consumption for copper extraction processes from ore in the ground to final salable cathode product (i.e. mining through electrorefining or electrowinning) to:
  - compare process routes,
  - identify and prioritize opportunities for energy reduction, and
  - support the Global Mining Initiative, ICMM and sustainable development initiatives
Prior Energy Studies for Industry

- Kellogg & Henderson (1976)
  - Best overall study historically
  - Efficiency of electricity generation considered
- BCS Inc. for US DOE (2002)
Copper Hydrometallurgy

- Heap/stockpile leaching, Early 1900s
- Iron cementation, Early 1900s
- Direct electrowinning, Early 1900s
- Roasting, leaching, electrowinning, 1960-70s
- SX/EW, 1970-80s
- Enhanced sulfide heap/stockpile leaching, 1990-2000s
- Concentrate pressure leaching, 2000s
Methodology

- Generic energy consumption model developed using averaged data from Freeport-McMoRan copper operations in North & South America
- All major sources of energy consumption considered
  - Electric power
  - Natural gas
  - Diesel and oil
  - Wear steel energy equivalent
- Energy consumption estimated for each unit operation from ore in the ground through final saleable cathode product
Major Mine Operations & Development Projects
All major assets majority-controlled and operated

North America¹

<table>
<thead>
<tr>
<th></th>
<th>Copper</th>
<th>Copper/Gold/Silver</th>
<th>Molybdenum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reserves</td>
<td>25.8 billion lbs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>25.8 billion lbs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mo</td>
<td>1.8 billion lbs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production</td>
<td>1.7 billion lbs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>1.7 billion lbs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mo</td>
<td>77 million lbs</td>
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</table>

Grasberg (90.64%)

<table>
<thead>
<tr>
<th></th>
<th>Copper</th>
<th>Gold/</th>
<th>Molybdenum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reserves</td>
<td>37.1 billion lbs</td>
<td>41.0 million ozs</td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>37.1 billion lbs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Au</td>
<td>41.0 million ozs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production</td>
<td>1.25 billion lbs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>1.25 billion lbs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Au</td>
<td>1.8 million ozs</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tenke (57.75%)

<table>
<thead>
<tr>
<th></th>
<th>Copper</th>
<th>Gold/</th>
<th>Molybdenum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reserves</td>
<td>4.3 billion lbs</td>
<td>0.6 billion lbs</td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>4.3 billion lbs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Co</td>
<td>0.6 billion lbs</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note: FCX consolidated reserves and annual production; Reserves as of December 31, 2007. Production figures are based on average annual estimates for 2008-2010.*

¹ Cu operations: Morenci (85%), Sierrita (100%), Bagdad (100%), Chino/Cobre (100%), Tyrone (100%), Miami (100%) and Safford (100%), Primary Mo: Henderson (100%) and Climax (100%)

² Copper operations Candelaria/Ojos del Salado (80%), Cerro Verde (53.6%) and El Abra (51%)
Freeport-McMoRan
Revenue/Production Mix

Mining Revenue by Commodity

2007 Pro Forma

- Copper: 78%
- Molybdenum: 12%
- Gold: 10%

Copper Production by Method

2007 Pro Forma

- SX/EW: 35%
- Concentrate: 65%
Operations Considered in This Study

- Bagdad (Arizona)
- Morenci (Arizona)
- Sierrita (Arizona)
- Chino (New Mexico)
- Tyrone (New Mexico)
- Candelaria (Chile)
- El Abra (Chile)
- Cerro Verde (Peru)
- Miami Smelter (Arizona)
- El Paso Refinery (Texas)
Morenci Crushed Ore Heap Leaching
Morenci Crushed Ore Agglomeration
Cerro Verde Crushed Ore Heap Leaching
Chino Concentrator
Candelaria SAG Milling
Cerro Verde HPGR Installation
Cerro Verde HPGR Rolls – 2.4 m Diameter
Miami Smelter
Bagdad Concentrate Leaching
Morenci Concentrate Leaching
Electrowinning & Electrorefining
Data modifications

- Normalized the data to standard mining rates and waste:ore strip ratio
- Normalized the data for standard ore hardness
- Adjusted product transfer size between unit operations (e.g. primary and secondary grinding) to a standard size
- Set freight requirements to standard distances and rates
Methodology (continued)

- Energy consumption for material streams with low copper content expressed as kJ/ton ore
  - Upstream operations including; mining, crushing, grinding, flotation, heap leaching, etc.

- Energy consumption for material streams with high copper content expressed as kJ/lb contained copper
  - Downstream operations including; smelting, refining, concentrate leaching, SX, EW, etc.
Methodology – Exclusions

- Efficiency of electricity generation
  - Direct conversion of kWh to kJ applied
- Energy for sulfuric acid delivery to heap and stockpile leaching operations
  - Highly site specific
  - Energy for sulfur dioxide capture and acid production included in smelter energy data
- Energy for delivery of supplies and reagents
Methodology – Disclaimer

- This generic analysis only considers energy consumption and does not take into account process capital and operating costs, nor other factors that may be important for process development and process selection for a particular mine site or application.

- Process selection decisions should not be made solely on the basis of energy consumption.
Process Selection Drivers

- Ore type/mineralogy
  - Copper minerals
  - Gangue minerals
  - Presence of bad actors/deleterious species
- Ore grade (Cu and by-products)
- Metal recovery (Cu and by-products)
- Metal prices
- Capital cost
- Operating cost
- Other (throughput rate; environmental, geographic factors, etc.)
## Major Assumptions

<table>
<thead>
<tr>
<th></th>
<th>Flotation</th>
<th>Heap Leach</th>
<th>ROM Leach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore Head grade (% Cu)</td>
<td>0.50</td>
<td>0.50</td>
<td>0.25</td>
</tr>
<tr>
<td>Strip ratio (Waste:Ore)</td>
<td>3.0</td>
<td>3.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Recovery (%)</td>
<td>90</td>
<td>75</td>
<td>50</td>
</tr>
<tr>
<td>Concentrate grade (% Cu)</td>
<td>30</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Milling
- SAG Power Index (SPI) 150 minutes
- Bond Work Index (BWI) 13.5 kWh/st (14.9 kWh/mt)

Smelting & refining
- Smelter recovery 97%
- Concentrate truck freight 200 miles, 0.009 gal-diesel/ton-mile
- Concentrate ocean freight 6,000 miles, 0.002 gal-oil/ton-mile
- Cathode truck freight 400 miles, 0.009 gal-diesel/ton mile

Concentrate Leaching
- High temperature recovery 98.5%
- Medium temp. recovery 97.5%

Wear Steel Energy-Equivalent 5.23 MWh/st (5.75 MWh/mt)
Energy in Copper Extraction (mixed units)

Ore in Ground

Mining (49,700 kJ/ton)

Primary Crushing & Conveying (7,200 kJ/ton)

Mining (31,100 kJ/ton)

Secondary Crushing (3,600 kJ/ton)

Tertiary Crushing (3,600 kJ/ton)

High Pressure Roll Grinding (8,700 kJ/ton)

SAG Milling (50,300 kJ/ton)

SAG Milling & Pebble Crush (43,100 kJ/ton)

AG Milling & Pebble Crush (26,200 kJ/ton)

Run-Of-Mine Leaching (3,600 kJ/ton)

Heap Leaching (7,200 kJ/ton)

Solution Extraction (1,880 kJ/lb)

Incremental SX Throughput (200 kJ/lb)

Electrowinning With AART (2,220 kJ/lb)

Electrowinning With AA (3,360 kJ/lb)

Transportation to Market (120 kJ/lb)

Oxygen Production

Ball Milling (38,600 kJ/ton)

Ball Milling (53,900 kJ/ton)

Ball Milling (38,900 kJ/ton)

Ball Milling (38,900 kJ/ton)

Ball Milling (53,900 kJ/ton)

Flotation & Regrinding (16,300 kJ/ton)

Gravity Concentration (~1,080 kJ/ton)

Flotation & Regrinding (3,250 kJ/lb)

Transportation (3,250 kJ/lb)

Smelting (5,150 kJ/lb)

Refining (2,700 kJ/lb)

Transportation to Market (120 kJ/lb)

Cathode to Market

Residue Disposal

Legend

- Ore/Slurry
- Solution
- Concentrate
- Solid/Slurry
- Gas
- Metal

Energy in Copper Extraction (mixed units)
**Process Routes Considered**

- ROM stockpile leaching, SX, EW
- Crushing, heap leaching, SX, EW
  - with and without alternative anode
  - with and without ferrous/ferric reaction
- SAG-Ball milling, flotation, smelting, refining
- HPGGR-Ball milling, flotation, smelting, refining
- SAG-Ball milling, flotation, HT concentrate leaching, SX, EW
- SAG-Ball milling, flotation, MT concentrate leaching, DEW, SX, EW
- HPGGR-Ball milling, flotation, MT concentrate leaching, DEW, SX, EW
Electrowinning Advances

- **Alternative anode**
  - Precious metal-coated titanium mesh
  - Replaces conventional Pb-Sn-Ca anode
  - 15% power reduction possible
  - Proprietary Freeport-McMoRan technology

- **Ferrous/ferric anode reaction**
  - 20-50 g/L Fe concentration in electrolyte
  - Anode reaction is oxidation of ferrous to ferric
  - Cell voltage reduced by approximately 50%
  - Carbon-catalyzed reduction of ferric to ferrous by SO$_2$
  - Resin bed acid retarddation system to remove acid generated from SO$_2$ reduction step
Energy Consumption vs. Head Grade

Total energy consumption as a function of ore head grade for various process routes.
Energy Consumption Sources by Process Route

- ROM Leach, SX, EW
- Crush, heap leach, SX, EW
- Crush, heap leach, SW, EW (Alternative Andoe)
- Crush, heap leach, SW, EW (Ferrous/Ferric)
- SAG mill, ball mill, float, smelt, refine
- HPGR, ball mill, float, smelt, refine
- SAG mill, ball mill, float, HT conc. Leach
- SAG mill, ball mill, float, MT conc. Leach
- HPGR, ball mill, float, MT conc. Leach

Energy Consumption (kJ/lb)
Summary of Energy Consumption Sources by Process

Crush, Heap Leach, SX, EW

SAG, Ball Mill, Float, Smelt

HPGR, Ball Mill, Float, Smelt

SAG, Ball Mill, Float, MT Conc. Leach

Legend:
- Electric Power
- Natural Gas
- Diesel & Oil
- Wear Steel Energy Equivalent
## Energy Consumption For Copper Extraction

### Total energy consumption for copper extraction by various process routes

<table>
<thead>
<tr>
<th>Process Route</th>
<th>Total Energy Consumption $^2$ (kJ/lb)</th>
<th>% Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crush, heap leach, SX, EW (Base case)</td>
<td>15,449</td>
<td>-</td>
</tr>
<tr>
<td>- with alternative anodes</td>
<td>14,966</td>
<td>3.2%</td>
</tr>
<tr>
<td>- with ferrous/ferric reaction</td>
<td>13,835</td>
<td>10.5%</td>
</tr>
<tr>
<td>SAG mill, ball mill, float, smelt, refine (Base case)</td>
<td>29,171</td>
<td>-</td>
</tr>
<tr>
<td>HPGR, ball mill, float, smelt, refine</td>
<td>25,429</td>
<td>12.8%</td>
</tr>
<tr>
<td>SAG mill, ball mill, float, HT Concentrate Leach</td>
<td>24,144</td>
<td>17.2%</td>
</tr>
<tr>
<td>SAG mill, ball mill, float, MT Concentrate Leach</td>
<td>23,556</td>
<td>19.3%</td>
</tr>
<tr>
<td>HPGR, ball mill, float, MT Concentrate Leach</td>
<td>19,833</td>
<td>32.0%</td>
</tr>
</tbody>
</table>

1. Includes energy for mining through final cathode product
2. Considers direct conversion of electric power to kJ (100% efficiency factor)
# Energy Consumption For Copper Extraction

## Total energy consumption for copper extraction by various process routes

<table>
<thead>
<tr>
<th>Process Route</th>
<th>Total Energy Consumption(^2) (kJ/lb)</th>
<th>% Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crush, heap leach, SX, EW (Base case)</td>
<td>28,511</td>
<td>-</td>
</tr>
<tr>
<td>- with alternative anodes</td>
<td>27,304</td>
<td>4.2%</td>
</tr>
<tr>
<td>- with ferrous/ferric reaction</td>
<td>25,298</td>
<td>11.3%</td>
</tr>
<tr>
<td>SAG mill, ball mill, float, smelt, refine (Base case)</td>
<td>47,468</td>
<td>-</td>
</tr>
<tr>
<td>HPGGR, ball mill, float, smelt, refine</td>
<td>41,169</td>
<td>13.3%</td>
</tr>
<tr>
<td>SAG mill, ball mill, float, HT Concentrate Leach</td>
<td>47,055</td>
<td>0.9%</td>
</tr>
<tr>
<td>SAG mill, ball mill, float, MT Concentrate Leach</td>
<td>45,453</td>
<td>4.2%</td>
</tr>
<tr>
<td>HPGGR, ball mill, float, MT Concentrate Leach</td>
<td>39,186</td>
<td>17.5%</td>
</tr>
</tbody>
</table>

\(^1\) Includes energy for mining through final cathode product

\(^2\) Assumes 40% efficiency factor to generate electric power (kJ to kWh)
Conclusions

- Crushed ore heap leaching (of secondary sulfides) consumes approximately half the energy of milling-flotation-smelting process
  - Overall resource utilization is less efficient
  - 75% vs. 87% copper extracted

- ROM stockpile leaching
  - Similar energy efficiency to crushed ore heap leaching, based on ore grade assumption
  - Low overall resource utilization (~50%)
Conclusions (continued)

- **HPGR vs. SAG milling**
  - 13% energy reduction possible

- **Concentrate leaching vs. smelting**
  - 17-19% energy reduction possible, depending on configuration
  - 1-4% if efficiency of power generation is considered (concentrate leaching consumes more electricity than smelting)
Conclusions (continued)

- Electrowinning with alternative anodes
  - 3% energy reduction possible
- Electrowinning with ferrous/ferric anode reaction
  - 10-11% energy reduction possible
Other Opportunities

- Alternative haulage/ore transportation systems
- Enhanced/engineered biological leaching of primary sulfide ores
- Alternative solution concentration and purification technologies
- Pressure leaching of lower grade concentrates
- Hybrid processes incorporating heap/stockpile leaching and grinding-flotation-concentrate pressure leaching
- Solar energy to supply electrowinning
Acknowledgements

Thanks to Charles H. Maxwell for preparation of the generic energy model and other Freeport-McMoRan staff for their work on the development and implementation of energy efficient technology for copper extraction.