Recent Developments in Copper Hydrometallurgy

John O. Marsden
Senior Vice President, Technology & Product Development
Outline

- Safety
- Historical context
- Solution extraction and electrowinning
- Atmospheric leaching
  - Secondary sulfides
  - Primary sulfides
- Pressure leaching
- Other developments affecting copper hydrometallurgy
Safety

- Phelps Dodge philosophy – “Zero & Beyond”
Hydrometallurgy in Copper Extraction

- Mine
- Primary Crushing
- Secondary/Tertiary Crushing
- Milling (Chalcocite) (Chalcopyrite)
- Flotation
- Heap Leaching (Bornite)
- Solution Extraction
- Electro-winning
- Customers
- Electro-Refining
- Smelting
- Concentrate Leaching
- Acid
- Stockpile Leaching (Chalcopyrite)
- Stockpile Leaching (Oxide) (Chalcocite)
Phelps Dodge – Long Track Record of Technology Deployment

- Large scale SX/EW
- Computerized haul truck dispatch
- GPS ore control
- Leach recovery optimization
- Concentrate grade enhancement

- “Expert” control systems
- Concentrator adaptive control
- Mine for leach
- Haul truck tire technology
- Concentrate leach (2003)

Copper Produced (millions of pounds)
Technology development efforts under way to reduce energy consumption in electrowinning by 15-35%.

Technology not yet proven, but showing promise.
Solution Extraction and Electrowinning at Bagdad, Arizona
<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
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</thead>
<tbody>
<tr>
<td>1968</td>
<td>Rancher’s Bluebird mine, Arizona</td>
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<tr>
<td>1971</td>
<td>Bagdad, Arizona</td>
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<tr>
<td>1974</td>
<td>ZCCM, Zambia</td>
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<td>1976</td>
<td>Miami, Arizona</td>
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<td>1979</td>
<td>Inspiration, Arizona</td>
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<td>1980</td>
<td>Cananea, Mexico</td>
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<td>1981</td>
<td>Pinto Valley, Arizona</td>
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<td>1984</td>
<td>Tyrone, New Mexico</td>
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<td>1985</td>
<td>Ray, Arizona</td>
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<tr>
<td>1987</td>
<td>Morenci, Arizona</td>
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<tr>
<td>1987</td>
<td>Sierrita, Arizona</td>
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<tr>
<td>1987</td>
<td>Chuquicamata, Chile</td>
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<tr>
<td>1988</td>
<td>Chino, New Mexico</td>
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</tbody>
</table>
Example of Technology Transforming Copper Production

(PDC share; millions of pounds)

1983 – 100% conventional
2004 – 66% SX/EW
Koch Solution Extraction In-Pipe Reactor
Enhanced Sulfide Heap and Stockpile Leaching

- Mine
- Primary Crushing
- Sec/Tert Crushing
  - Milling (Chalcocite) (Chalcopyrite)
- Heap Leaching (Oxide) (Chalcocite)
- Solution Extraction
  - Acid
  - Concentrate Leaching
  - Electro-Leaching
  - Smelting
  - Electro-Refining
- Customers
Biologically Enhanced Leaching

leach solution

air

air
Leaching Developments – Bacterial Augmentation

- Stream contains $3 \times 10^8$ cells/ml genetically selected bacteria
- Delivers two separate bacterial strains simultaneously
- Skid mounted
- Design based on Bagdad plant shown below
Advanced Modeling to Improve Heap Performance

Air and solution modeling in heap

Temperature profile in heap
Enhanced Chalcopyrite Leaching – Bagdad Crystal Mountain
Morenci Enhanced Stockpile Leaching

- Low-grade ore from Western Copper deposit
  - Below mill cut off grade material
  - Mixed sulfide minerals – chalcopyrite, chalcocite
  - 188 million ton stockpile to be constructed
  - Air injection
  - Bacteria augmentation
  - Controlled solution application

- Largest engineered chalcopyrite stockpile leach in the world
Concentrate Leaching – Alternative to Smelting & Refining
Copper Extraction in 1980s and 1990s

- **Primary sulfide ores**
  - Mine
  - Flotation
  - Smelting
  - Refining
  - Rod Mill or Customer

- **Secondary sulfide and oxide ores**
  - Mine
  - Leaching
  - SX
  - EW
  - Rod Mill or Customer
Concentrate Leach Technology Replaces Smelting/Refining

Primary sulfide ores

Flotation

Smelting

Refining

Mine

Concentrate Leaching

Secondary sulfide and oxide ores

Leaching

SX

EW

Rod Mill or Customer
Copper Concentrate Leaching History

- Process developments - 1970’s and 80’s
  - Ammonia - Arbiter
  - Chloride - CLEAR, SOX, Cuprex
  - Sulfate - Roast/Leach/Electrowin (Lakeshore)
  - Many others
Copper Concentrate Leaching History

- **Process developments - 1970’s and 80’s**
  - Ammonia - Arbiter
  - Chloride - CLEAR, SOX
  - Sulfate - Roast/Leach/Electrowin (Lakeshore)
  - Many others

- **Reasons for lack of commercial success**
  - High cost (capital & operating)
  - Problems with materials of construction
  - Problems with operability/maintainability
  - Process complexity
  - Precious metals recovery problems
  - Problems with copper cathode quality
  - Primitive, early stage SX/EW technology
  - Not integrated with leaching operations
  - Significant advances in smelting technology
Copper Concentrate Leaching – More Recent Developments

- Ammonia - Escondida
- Sulfate
  - Phelps Dodge
  - Placer Dome
  - CESL/Teck Cominco (chloride-assisted)
  - UBC/Anglo American
  - Activox
  - Dynatec
- Biological
  - BHP-Billiton “BioCop”
  - Bactech-Mintek
  - Others
- Chloride/Bromide Process – Intec
- Chloride – Outokumpu “HydroCopper”
- Nitrate
- Other
## Phelps Dodge Concentrate Leaching Milestones

- **2Q 1998**  Sulfate-based concentrate leaching development started
- **1999-2000**  Batch testwork at Hazen Research, Dawson and Phelps Dodge Process Technology Center
- **2000-2001**  Continuous Pilot Plant Testing
- **3Q 2001**  Technology Development Agreement executed with Placer Dome
- **Nov 2001**  Bagdad HT Project approved
- **Mar 2003**  Start-up: First concentrate feed
- **July 2003**  All design parameters met, steady state operation

*Four years from first testing to commercial demonstration*
Solid-liquid Separation at Bagdad

August, 2003
Bagdad Concentrate Leach Plant Copper Production

Production (lbs)

- March 2003
- April 2003
- May 2003
- June 2003
- July 2003
- August 2003
- September 2003
- October 2003
- November 2003
- December 2003
- January 2004
- February 2004
- March 2004
- April 2004
- May 2004
- June 2004
- July 2004
- August 2004
- September 2004
- October 2004
- November 2004
- December 2004

Production (lbs) vs. Design Basis Production

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<table>
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<tr>
<th>Date</th>
<th>Milestone</th>
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<tbody>
<tr>
<td>May 2004</td>
<td>Conversion of Bagdad demonstration plant to medium temperature process started</td>
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<tr>
<td>May 2005</td>
<td>Start-up: medium temperature and direct electrowinning (MT-DEW) process</td>
</tr>
<tr>
<td>Dec 2005</td>
<td>Completion of MT-DEW process demonstration</td>
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<tr>
<td>2Q 2007</td>
<td>Scheduled completion of Morenci facility</td>
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</tbody>
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Bagdad MT-DEW Process Conversion – Super-fine Grinding
Morenci Concentrate Leaching Application

- Provides economically viable alternative to smelting and refining
  - Generates by-product acid for leaching
  - Eliminates freight cost for concentrate shipments and acid deliveries
  - Decouples Morenci from smelter balance dependency
  - Reduces Morenci’s mill conversion costs
- Morenci Western Copper concentrate mineralogy
  - Mixed chalcopyrite, covellite, chalcocite, pyrite
- Medium temperature and direct electrowinning (“MT-DEW”) process selected
  - Best fit with Morenci concentrate production and acid balance
  - Utilize existing EW and SX capacity at Morenci
- Copper production capacity = 75,000 tons per year
- Copper recovery slightly higher than smelting and refining
Production Decisions Impacted by Concentrate/Acid Balance

**North American Concentrate**
- Bagdad
- Sierrita
- Chino (partial capacity)
- Cobre
- Morenci (off line)

**North American Leach**
- Morenci
- Bagdad
- Sierrita
- Chino
- Tyrone (partial capacity)
- Miami (partial capacity)

**Chino Smelter**
- 650,000 tpy capacity
  - (off line)

**Miami Smelter**
- 750,000 tpy capacity
  - (operating)

**External concentrate source**
- Candelaria

**External acid source**
- External acid consumer

**Chino Smelter**
- 650,000 tpy capacity
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**Miami Smelter**
- 750,000 tpy capacity
  - (operating)
Morenci Concentrate Leaching Facility – 3D Model View
Other Developments Affecting Copper Hydrometallurgy

- Material Characterization
- Comminution
- Alternative Products
High-Pressure Grinding Rolls

- Cerro Verde milling circuit to include high pressure grinding rolls (HPGR) instead of SAG mills

**Pros**
- Higher throughput
- Greater energy efficiency
- Greater flexibility
- Lower unit cost

**Cons**
- Additional capital cost

**Financial Impact**
- Significantly reduces power consumption and unit production costs
Material Characterization – QemSCAN Technology
New Copper Products

- Copper powder technology
  - Potential replacement for cathode to rod
  - Specialty copper powders
- Copper powder process reduces or eliminates the following:
  - Manual harvesting of cathodes
  - Cell cleaning
  - Stainless blank repairs and replacement
  - Stripping machines
  - Slippery or brittle cathodes
- Focused on reducing costs and improving process safety and efficiency
- PDC proprietary technology
- Demonstration plant in operation at Morenci, AZ