Technology Development in the Copper Industry

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Presentation Outline

- Background and Introduction
- Material Characterization
- Open Pit Mining
- Size Reduction
- Leaching
- Concentrate Leaching
- Summary
"As for a Research Department, the Board feels you should try to find whatever you’re looking for the first time you search for it."
Drivers for Technology Development

- Declining grade of deposits (currently mined and new)
- Increasingly large tonnages must be mined to produce equivalent metal volumes
- Capital cost escalation
- Increasing complexity of deposits
- Deposits must be mined in increasingly remote locations
- Migration to underground mining
- Internal cost pressures (through life of mine)
  - Mine depths, haulage distances, etc.
- External cost pressures
  - Inflation, environmental regulations/requirements, etc.
- Depletion of technical and skilled workforce
Opportunities for Technology Development

- Optimization of existing technologies and methods
- Development and implementation of new “transformational” step change technologies
- Potential value-creating benefits
  - Improve safety attributes
  - Improve energy efficiency
  - Decrease capital and operating cost
  - Increase metal extraction and/or recovery
  - Decrease time to market for product
  - Improve environmental performance/enable compliance
- Results in improved opportunity for exploration success
  - Both “greenfield” and “brownfield” sites
Emerging Technologies Impact All Aspects of Copper Production

Mining
- Advanced GPS navigation
- Autonomous and “smart” equipment
- High-displacement engines
- Material characterization
- Slope optimization
- Alternative mass transport
- Blast fragmentation
- High-pressure grinding rolls
- Stirred fine grinding mills

Size Reduction
- Material characterization
- Narrower particle size distribution

Leaching
- Material characterization
- Enhanced biological heap leaching
- Chalcopyrite heap leaching
- Environmental remediation
- Novel electrowinning technology
- Concentrate pressure leaching
- Direct electrowinning

Flotation

SX/EW

Smelting/Refining

Cathode Product
- New copper products
Material Characterization – QemSCAN
Material Characterization – Techniques

Definitions:
- XRD: X-Ray Diffraction
- NIR: Near Infra-Red
- XRF: X-Ray Fluorescence

XRD NIR
- Rapid, inexpensive
- Mineral composition (quantitative)

Analytical Chemistry

XRF
- Rapid, inexpensive
- Multi-element chemistry and mineral composition by calculation

QEMSCAN
- Expensive, not rapid
- Mineral composition (quantitative), mineral textures, associations, locking, grain size, alteration and gangue mineral details
Using Mineralogy to Improve Decisions

Morenci Alteration Codes – Visual Logging Data

QemSCAN Alteration Codes – QemSCAN Data

QemSCAN Alteration Codes – XRD Data

Precision and accuracy of data greatly improved

Improves:
- Ore control & ore type routing
- Process control
- Mine design & sequencing
- Plant design
Open Pit Mining

- Advanced GPS navigation
- Autonomous and “smart” equipment
- High-displacement engines

Mining

- Material characterization
- Pit slope optimization
- Alternative mass transport

Size Reduction

Leaching

Flotation

SX/EW

Smelting/Refining

Cathode Product
Open Pit Mining of the Future

- Efficient unit operations
  - Customized fragmentation (drilling & blasting) to produce material sizes that optimize extraction in downstream process
  - Partially-automated loading with payload optimization
  - Centralized operations control

- Smart mining equipment
  - Real-time monitoring of operator performance and machine health
  - Automated drilling, truck haulage and dozing/ripping of leach stockpiles
  - Vehicle off-path detection and collision avoidance systems
  - Remote equipment control for hazardous situations
1) High-speed, large-bandwidth wireless communications

- Hard link to intranet
- Peer-to-peer wireless connection

Phelps Dodge Network

 ✓ Enables:
   ✓ Equipment control
   ✓ Video feeds
   ✓ Machine health monitoring

 ✓ Already developed and implemented at several of our mines
Open Pit Mining – Enabling Technology

1) High-speed, large-bandwidth wireless communications

2) High-precision GPS for equipment tracking and navigation

- Provides coverage when satellites aren’t visible from deep pits or steep terrain
- Can be supplemented by wireless communications system
- Already developed and implemented at Morenci
1) High-speed, large-bandwidth wireless communications
2) High-precision GPS for equipment tracking and navigation
3) Digital controls and health monitoring systems for each piece of equipment
Advanced material transport systems
- Replace truck haulage in deep pit applications
Size Reduction Technology

- **Mining**
  - Size Reduction
    - Blast fragmentation
    - High-pressure grinding rolls
    - Stirred fine grinding mills
- **Leaching**
- **Flotation**
- **SX/EW**
- **Smelting/Refining**
- **Cathode Product**
Cerro Verde milling circuit incorporates high pressure grinding rolls (HPGR) instead of SAG mills
- 108,000 mtpd
- Four 2.4 x 1.6 m HPGR’s

Advantages vs. SAG mills
- Greater total energy efficiency
  - 2.4 kWh/t vs. 12.0 kWh/t
- ~10% reduction in Bond Work Index of product
- Greater flexibility
- Lower unit cost

Disadvantages vs. SAG mills
- Additional capital cost

Significant financial impact
Cerro Verde - Scope of Facilities
Cerro Verde Concentrator
Cerro Verde Tailing Dam
HPGR Installation at Cerro Verde
HPGR Roll – 2.4 m diameter
Freeport-McMoRan Copper & Gold Inc.

Heap & Stockpile Leaching Technology

- Material characterization
- Enhanced biological heap leaching
- Chalcopyrite heap leaching
- Environmental remediation

Flowchart:
1. Mining
2. Size Reduction
3. Leaching
   - SX/EW
4. Flotation
   - Smelting/Refining
5. Cathode Product
Morenci Biological Heap Leaching
Biologically Enhanced Leaching

leach solution

air

air
Phenomenological Modeling to Improve Heap Design & Performance

Air and solution modeling in heap

Temperature profile in heap
Downstream Conversion-to-Metal

- Mining
- Size Reduction
- Leaching
- Flotation
- SX/EW
- Smelting/Refining
- Cathode Product

- Concentrate pressure leaching
- Direct electrowinning
Traditional Copper Extraction Routes

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

Secondary sulfide and oxide ores:
- Mine
- Leaching
- SX
- EW
Concentrate Leaching Technology

Primary sulfide ores

Mine

Secondary sulfide and oxide ores

Flotation

Concentrate Leaching

Leaching

SX

EW

Smelting

Refining

Rod Mill or Customer
High-temperature Pressure Leaching

- **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
  - 225ºC
  - 16,000 metric tons per year copper
  - Over 98% copper recovery
- **Mar 2003**  Start-up: First concentrate feed
- **July 2003**  All design parameters met, steady state operation

_Four years from first testing to commercial demonstration_
Medium-temperature Pressure Leaching Development

- Super-fine grinding
  - 98% minus 15 µm
  - 80% minus 7 µm
- Medium-temperature pressure leaching
  - 160°C
  - 200 psig oxygen over-pressure
  - 90 minutes
- Single-stage flash let down
- Solid-liquid separation
- Silica removal
- Direct electrowinning
- SX/EW treatment of low grade solution
- Residue disposal
Sulfide Conversion to Elemental Sulfur - Batch Test Results

Proportion of sulfide sulfur in feed converted to elemental sulfur (%)
Medium-temperature Pressure Leaching Residue

- Particle size fraction: <25 µm >10 µm
Medium-temperature Pressure Leaching Residue

- Particle size fraction: <10 µm
Morenci Concentrate Leaching Application

- Morenci Western Copper concentrate mineralogy
  - Mixed chalcopyrite, covellite, chalcocite, pyrite

- Medium temperature and direct electrowinning process selected
  - Best fit with Morenci concentrate production and acid balance
  - Utilize existing EW and SX capacity at Morenci

- Key production statistics (approximate)
  - 215,000 tons per year concentrate
  - 34% copper in concentrate
  - 147 million lbs copper per year produced
  - 97.5% copper recovery

- Capital cost - $107 million

- Start up - mid 2007
Morenci Concentrate Leaching Plant - 3-D Model View
Morenci Concentrate Leaching Plant – Site Progress August 2007
Phelps Dodge Concentrate Leaching Developments – Summary

- Suite of sulfate-based processes developed, including:
  - High temperature (225°C) pressure leaching
  - Medium temperature (150-165°C) pressure leaching with direct electrowinning
- Low cash cost alternative to smelting and refining
- Safe, environmentally-sound
- Acid balance is a critical cost driver
- Concentrate, cathode and acid freight considerations
- Ability to utilize existing SX and EW capacity
- Utilize existing infrastructure
- Intellectual property – a complex environment
Production Components

- People
- Feed material
- Energy
- Water
- Knowledge
Energy in Copper Extraction (kWh/lb)

- ROM stockpile leaching, SX, EW  3.9
- Crushing, heap leaching, SX, EW  4.0
- HPG, heap Leaching, SX, EW  3.8
- HPG, heap Leaching SX, EW  3.6
  (with alternative anode technology)

ROM Leach = 0.25% Cu, Other processes = 0.50% Cu
**Energy in Copper Extraction (kWh/lb)**

- SAG & ball milling, flotation, smelting, refining 8.3
- HPGR, ball milling, flotation, smelting, refining 7.3
- SAG & ball milling, flotation, high-temperature pressure leaching, SX, EW 7.1
- SAG & ball milling, flotation, medium temperature pressure leaching, SX, EW 6.7
- HPGR, ball milling, flotation, medium-temperature pressure leaching, DEW 5.7

35% Energy Reduction Possible
Key Enablers for Effective Technology Development

- **Technology Champions**
  - Vision, capability, experience, dedication

- **Infrastructure/Environment**
  - Research & development facilities
  - Operational excellence platform
  - Effective technology implementation capability

- **Resources**
  - People, money, time

- **Ability to manage expectations**
  - Effective communication to key stakeholders

- **Economic conditions**
  - Maintain initiatives through industry downturns & fluctuations

- **Long term perspective**

- **Senior management, Board, & shareholder commitment**