Kullan talteenotto malmeista – uutta ja ikivanhaa

Jaakko Leppinen
## World gold production in 2012

<table>
<thead>
<tr>
<th>Rank</th>
<th>Country/Region</th>
<th>Gold production (kilograms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>China</td>
<td>355,000</td>
</tr>
<tr>
<td>2</td>
<td>Australia</td>
<td>270,000</td>
</tr>
<tr>
<td>3</td>
<td>United States</td>
<td>237,000</td>
</tr>
<tr>
<td>4</td>
<td>Russia</td>
<td>200,000</td>
</tr>
<tr>
<td>5</td>
<td>South Africa</td>
<td>190,000</td>
</tr>
<tr>
<td>6</td>
<td>Peru</td>
<td>150,000</td>
</tr>
<tr>
<td>7</td>
<td>Canada</td>
<td>110,000</td>
</tr>
<tr>
<td>8</td>
<td>Ghana</td>
<td>100,000</td>
</tr>
<tr>
<td>9</td>
<td>Indonesia</td>
<td>100,000</td>
</tr>
<tr>
<td>10</td>
<td>Uzbekistan</td>
<td>90,000</td>
</tr>
<tr>
<td>11</td>
<td>Papua New Guinea</td>
<td>70,000</td>
</tr>
<tr>
<td></td>
<td>Rest of the world</td>
<td>630,000</td>
</tr>
</tbody>
</table>

### Europe

- Finland: 10,800
- Sweden: 6,000
- Spain: 3,600
- Serbia: 0,900
- Greece: 0,800
- Romania: 0,600
- Poland: 0,500
- Slovakia: 0,300
- Denmark: 0,100

Courtesy: wikipedia.com
Hydrometallurgical processing of gold ores and concentrates is currently dominated by cyanide leaching and around 60% of all gold is produced using cyanide.
Artisanal gold mining

- 10 to 15 million artisanal miners producing around 380-450 tonnes Au/a in more than 70 countries

- About 100 million people – workers and their families - depend on artisanal mining compared to about 7 million people worldwide in industrial mining

- These gold mining operations are particularly dangerous, as they often use the mercury amalgamation process to extract gold from ores.
Gold production in the past

Gold washing

Wash table

Manual grinding

Smelting
Gold production today
Developments in gold ore processing

- Gold collected from stream beds (8000 BC)
- Washing of alluvial gold (before 3500 BC)
- Mining of gold (3500 BC)
- Smelting (3000 BC)
- Cupellation to separate other metals from gold-silver alloys (2000 BC)
- Parting to separate silver from gold (600 BC)
- Amalgamation (100 BC)
- Leaching with aqua regia (700 AC)
- Leaching with chloride (1850 AC)
- Cyanidation (1890)
- Flotation process 1905
- Refractory ore treatment with pressure oxidation (1985)
- Refractory ore treatment with bio-oxidation (1986)
- Use of alternative lixiviants for gold leaching (2000-)
- Sensor based ore sorting for gold ores (2000-)

**Gravity separation techniques**

**High-temperature techniques**

**Amalgamation**

**Leaching**

**Cyanidation**

**Flotation**

**Hydrometallurgical treatment of refractory ores**

**Alternative gold lixiviants**

**Sensor based ore sorting**
Mineralogical considerations for gold ore types

FREE-MILLING GOLD ORE

- Liberated gold
- Composite grain
- Locked particle in silicate

Leaching?
Flotation?
Fine grinding?
Gravity separation?

REFRACTORY GOLD ORE

- Invisible gold in sulfide
- Fine inclusions in sulfide

Leaching?
Flotation?
Fine grinding?
Gravity separation?
Decomposition of gold bearing minerals?
Process options for gold processing

Free Milling Au Ore
- Crushing
- Grinding
- Flotation
- Agitated Cyanide Leaching
- Gold
- Gold concentrate to smelter or leaching
- Gravity concentrate

Refractory Au Ore
- Crushing
- Grinding
- Flotation
- Pre-oxidation
- Agitated Cyanide Leaching
- Gold
Mineral Processing Plant

CRUSHING

GRINDING

FLOTATION

TAILINGS TREATMENT

THICKENING FILTRATION

ORE

Concentrate

Sorting

Thickening

Classification

Paste thickening

Concentrate Tailing
Size range applicability of gravity separation equipment

- Jigging
- Sluice box
- Reichert cone
- Shaking table
- Spiral
- Density separator
- Pneumatic jig
- Air table
- Centrifugal (MGS)

Particle size μm

10μm  100μm  1,000μm  10,000μm
Shaking table
Main Applications of Flotation in Gold Processing

1. Flotation of free gold and gold-bearing sulfide minerals to produce a gold-rich concentrate. The concentrate can be treated by:
   - Cyanidation
   - Regrinding and cyanidation
   - Intensive cyanidation,
   - Oxidative pretreatment and cyanidation
   - Direct smelting

2. Flotation of carbonaceous material, carbonates, or other material that would otherwise interfere with processing
Cyanidation process for gold

Comminution

Crushing

Grinding

Leaching

Cyanide leaching

Sorption in activated carbon

Recovery

Elution from activated carbon

Electrowinning

Smelting

Gold

Gold ore

\[ 4Au + 8CN^- + O_2 + 2H_2O = 4Au(CN)_2^- + 4OH^- \]

Zinc cementation

Merrill-Crowe

Outotec
Carbon-in-pulp (CIP) process

ORE FROM GRINDING → CYANIDE LEACHING → CARBON ADSORPTION

ORE FROM GRINDING

CYANIDE LEACHING

CARBON ADSORPTION

LOADED CARBON

ELECTROWINNING

ELUTION

ACTIVATED CARBON

TAILING

REGENERATION

BARREN CARBON
Cyanidation process routes for gold

Gold ore

Crushing

Grinding

Cyanide leaching

Solid-liquid separation

Heap leaching

Zinc cementation (Merrill-Crowe)

Gold is precipitated from cyanide solution using zinc powder

Carbon in Column CIC

Gold adsorbed on activated carbon from cyanide solution (CIC)

Carbon in Pulp CIP

Gold adsorbed on activated carbon from cyanide solution with solids. Adsorption takes place in a separate stage (CIP)

Carbon in Leach CIL

Gold adsorbed on activated carbon in slurry cyanide solution with solids. Adsorption takes place simultaneously with leaching (CIL)

Comminution

Heap leaching

Leaching

Recovery
Cyanidation process for gold

1. Gold ore
   - Cyanide leaching
     - Solution
   - Sorption in activated carbon
     - Carbon
     - Elution from activated carbon
   - Electrowinning
   - Smelting
   - Refining
     - Gold
   - Tailings

2. Concentrations:
   - Au in ore: 1-10 g/t
   - Au in solution: 1-5 mg/l
   - Au in carbon: 5-10 kg/t
   - Dore bars: 100-1000 mg/l
   - Gold bullion: 99.99%
   - Au in carbon: 70-80%
Cyanidation process

Some milestones:

1867  First patent on cyanide leaching
1889  First cyanidation plant : Crown Mine in New Zealand
1890  First cyanidation plant in South Africa: Robinson Deep
1891  First cyanidation plant in USA: Mercur, Utah
1894  Johnson patents charcoal adsorption from cyanide solutions
1904  Merrill introduces zinc dust for gold precipitation
1906  Crowe applies vacuum deareation to zinc precipitation
1949  First CIP plant at San Andreas in Honduras
1951  CIP process patented by McQuiston and Chapman
1952  USBM develops carbon elution process (Zadra)
1970  First cyanide heap leach operation in Carlin, Nevada
1973  AARL elution process
1985  First pressure oxidation plant at Homestake McLaughlin (USA)
1986  Start-up of concentrate biological oxidation plant in Fairview, South Africa
Treatment of gold concentrates in copper smelters

- **Flash Furnace**: ore concentrate and hot blast
- **Converter**: blister copper
- **Anode Furnace**: fire-refined copper
- **Anode Casting Machine**: anode to electrolysis
- **Electro refining**: Copper cathodes
- **Anode slime treatment**: Gold, Palladium, Platinum
Treatment of gold concentrates in copper smelters

- Flash Furnace
- Converter
- Anode Furnace
- Anode Castir Machine
- Electro refining
- Copper cathodes
- Anode slime
- Anode slime treatment
- Gold
- Palladium
- Platinum
SENSOR BASED ORE SORTING
Hand sorting in 1556
Sorting of vein-type gold ore

Laser image  Sorting image  Photo
Preconcentration of material – Sensor Based Ore sorting

- Suitable particle size 10-250 mm
- Depending on ore characteristics 10 to 70 % of material can be rejected
- Capacities capable of meeting the needs of many concentrators (upto 500 tph per unit)
- Today - mature technology
- Good understanding of mineralogy and ore geology is required
- The most common sensors: optical and X-ray transmission (XRT)

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Processing of refractory gold ores
Refractory gold ore

INVISIBLE GOLD IN SULFIDE

FINE INCLUSIONS IN SULFIDE
Process options for refractory gold ores

GOLD ORE

CONCENTRATION

FINE GRINDING
PRESSURE OXIDATION
BIO OXIDATION
ROASTING
CHEMICAL OXIDATION

CYANIDATION

GOLD
Occurrence of gold in refractory ores, examples

Mineral composition in concentrates

<table>
<thead>
<tr>
<th></th>
<th>Ccp</th>
<th>Sp</th>
<th>Gn</th>
<th>Bou</th>
<th>Apy</th>
<th>Py</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conc A</td>
<td>0.17</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>0.02</td>
<td>9.05</td>
<td>65.28</td>
<td>74.53</td>
</tr>
<tr>
<td>Conc B</td>
<td>2.47</td>
<td>1.58</td>
<td>0.54</td>
<td>0.31</td>
<td>15.60</td>
<td>63.48</td>
<td>83.98</td>
</tr>
</tbody>
</table>

Ccp = chalcopyrite (CuFeS₂)
Sp = sphalerite (ZnS)
Gn = galena (PbS)
Bou = bournonite (PbCuSbS₃)
Apy = arsenopyrite (FeAsS)
Py = pyrite (FeS₂)

Distribution of gold between minerals

<table>
<thead>
<tr>
<th></th>
<th>Au g/t (Pyr)</th>
<th>Au g/t (AsPyr)</th>
<th>Au g/t free</th>
<th>total g/t</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONC A</td>
<td>20.9</td>
<td>16.8</td>
<td>1.6</td>
<td>39.4</td>
</tr>
<tr>
<td>CONC B</td>
<td>16.2</td>
<td>17.3</td>
<td>0.9</td>
<td>34.4</td>
</tr>
</tbody>
</table>
Chemical reactions in pressure oxidation

Autoclave

\[ 2\text{FeS}_2 + \text{O}_2 + 2\text{H}_2\text{O} \rightleftharpoons 2\text{FeSO}_4 + 2\text{H}_2\text{SO}_4 \]

\[ 4\text{FeSO}_4 + \text{O}_2 + 2\text{H}_2\text{SO}_4 \rightleftharpoons \text{Fe}_2(\text{SO}_4)_3 + 2\text{H}_2\text{O} \]

\[ 2\text{FeAsS} + 7\text{O}_2 + 2\text{H}_2\text{O} + \text{H}_2\text{SO}_4 \rightleftharpoons 2\text{H}_3\text{AsO}_4 + \text{Fe}_2(\text{SO}_4)_3 \]

\[ 4\text{CuFeS}_2 + 17\text{O}_2 + 2\text{H}_2\text{SO}_4 \rightleftharpoons 4\text{CuSO}_4 + \text{Fe}_2(\text{SO}_4)_3 + 2\text{H}_2\text{O} \]

Decomposition of sulfide minerals through oxidation
Five-compartment autoclave
Alternative lixivants for gold

Thiosulfate

Barrick Gold introduced thiosulfate leaching circuit that achieved commercial production in Q3 2015 and is expected to complete its ramp up by Q3 2016. Barrick Gold’s Goldstrike mine will be the largest scale use of the alternative lixiviant the world has ever seen.

Thiourea

Has been used to treat antimony –rich concentrate in Australia. No large scale operations so far.

Thiocyanate

Acidic thiocyanate has been investigated by Newmont Gold

Chloride

Outotec is developing it own non-cyanide technology basing on chloride leaching and solvent extraction. No full-scale operations so far.
Barrick Gold Goldstrike operation with thiosulfate leaching
General diagram for Outotec chloride leaching process

Oxygen

Au-concentrate

Leaching → S/L → Au extraction → Au stripping → Au reducing

Leach residue

Effluent treatment

Evaporation → S/L

Steam

Cu-Zn precipitate

S/L → Ag extraction → Ag stripping → Ag cementation

Cu-powder

S/L → Ag -product

Effluent treatment

S/L → S/L → Effluent treatment

Reductant

Au -product

Solution bleed

Hydroxide precipitate

Steam
Conclusions

• History of gold processing is long, extending back thousands of years
• Minerals processing, hydrometallurgical and pyrometallurgical techniques are commonly used for gold recovery
• Hydrometallurgical methods play the predominant role in gold processing
• Currently main new developments are ore sorting and alternative lixiviants for cyanide
• In addition to conventional mineral processing engineering students should acquire basic knowledge of gold hydrometallurgy