DEVELOPMENTS IN THE PROCESSING OF REFRACTORY & COMPLEX GOLD ORES

Presented by

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INTRODUCTION

The increasing trend towards lower grade and more complex ores and the need for lower cost processes especially for small deposits have resulted in the introduction of a variety of new processes which are at various stages of development.

Additional incentives include increasing environmental pressure against the use of cyanide, concern over the release of toxic elements and the need to conserve water resources.

ORE CATEGORIES

- Ores containing gold locked in solid solution or as fine inclusions include:
  - iron/arsenic sulphide minerals such as arsenopyrite, arsenian pyrite, and pyrite
  - copper sulphides such as chalcopyrite, tetrahedrite
  - none sulphide gangue minerals such as silica minerals, iron oxides
- Ores with insoluble or slow leaching gold minerals including:
  - gold tellurides
  - aurostibnite – $AuSb_2$
  - Maldonite – Au_2Bi
  - Fischesserite - Ag_3AuSe_2
- Ores containing preg-robbing constituents such carbonaceous material or clays.

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ORE CATEGORIES (CONT.)

- Ores containing cyanide and/or oxygen consumers including:
  - oxide/hydroxide copper minerals, native copper, secondary copper sulphide minerals
  - reactive iron sulphide minerals, pyrrhotite, marcasite
  - reactive antimony and arsenic sulphide minerals, stibnite Sb_2S_3, orpiment As_2S_3, realgar As_4S_4

Note:

More than one category can apply to a particular ore deposit; e.g. double refractory ores in Nevada with gold locked in iron sulphides plus preg-robbing carbonaceous material.

SOLUBILITY OF COPPER MINERALS IN 0.099 PERCENT NaCN SOLUTIONS

Mineral		Percent Total Copper Dissolved At 23°C	At 45°C
Azurite	$2\ CuCO_3 \cdot Cu(OH)_2$	94.5	100.0
Malachite	$CuCO_3 \cdot Cu(OH)_2$	90.2	100.0
Cuprite	Cu_2O	85.5	100.0
Chrysocolla	$CuSiO_3$	11.8	15.7
Chalcocite	Cu_2S	90.2	100.0
Chalcopyrite	$CuFeS_2$	5.6	8.2
Bornite	$FeS \cdot 2\ Cu_2S \cdot CuS$	70.0	100.0
Enargite	$3\ CuS \cdot As_2S_5$	65.8	75.1
Tetrahedrite	$4\ Cu_2S \cdot Sb_2S_3$	21.9	43.7
Metallic Copper	Cu	90.0	100.0

Note: covellite solubility is similar to chalcocite.

(Ref: “Cyanamid wants you to know”, May 1955)

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TREATMENT PROCESSES

LOCKED GOLD

Iron/Arsenic Sulphides - pretreatment processes include:

- Roasting of whole ore or flotation concentrate.
- Low pressure intensive oxidation.
- Acid or alkaline pressure oxidation of whole ore or flotation concentrate.
- Bio-oxidation of flotation concentrate.
- Fine or ultrafine grinding of flotation concentrate followed by direct cyanidation or one of the above pretreatment processes.
- Heap bio-oxidation of whole ore or flotation concentrate.

Copper Sulphides – flotation followed by smelting, roasting or hydromet treatment of concentrate.

Non-Sulphide Gangue Minerals – fine grinding of whole ore followed by direct cyanidation.

INSOLUBLE OR SLOW LEACHING GOLD MINERALS

- Roasting of flotation concentrate followed by cyanidation.
- Alkaline chlorination leaching of flotation concentrate followed by cyanidation.
- Low pressure cyanidation of flotation concentrate.

PREG-ROBBING ORES

Oxidised or Low Sulphide Ores

- Maximization of gold recovery by gravity plus intensive cyanidation of concentrate.
- Application of CIL with high carbon concentration.
- Addition of kerosene or other substance to blanket the preg-robbing material followed by CIL or RIL (not subject to fouling).
- Chlorination to deactivate the carbonaceous material.
- Roasting to burn off the carbonaceous material.

Ores with Gold Locked in Sulphides

- Roasting of whole ore or flotation concentrate to burn off the carbonaceous material and oxidize the gold bearing sulphide .
- Pressure oxidation to deactivate the carbonaceous material and oxidize the gold bearing sulphide.
- Rejection of carbonaceous material in flotation circuit if included.

CYANIDE AND OXYGEN CONSUMING ORES

Cyanide Soluble Copper Minerals

- Provision of an optimum safe level of free cyanide to maximize gold recovery and minimize copper loading on carbon in CIP.
- Use of an ion exchange resin to selectively extract gold over copper.
- Oxygen sparging to maintain adequate oxygen in solution.
- Precipitation of copper from solution with H_2S or sodium hydrosulphide (e.g. SART Process) and recycle of cyanide.
- Removal of soluble copper by leaching with sulphuric acid for oxide/hydroxide copper minerals or bio-oxidation for sulphide copper minerals.
- Removal of native copper by gravity.

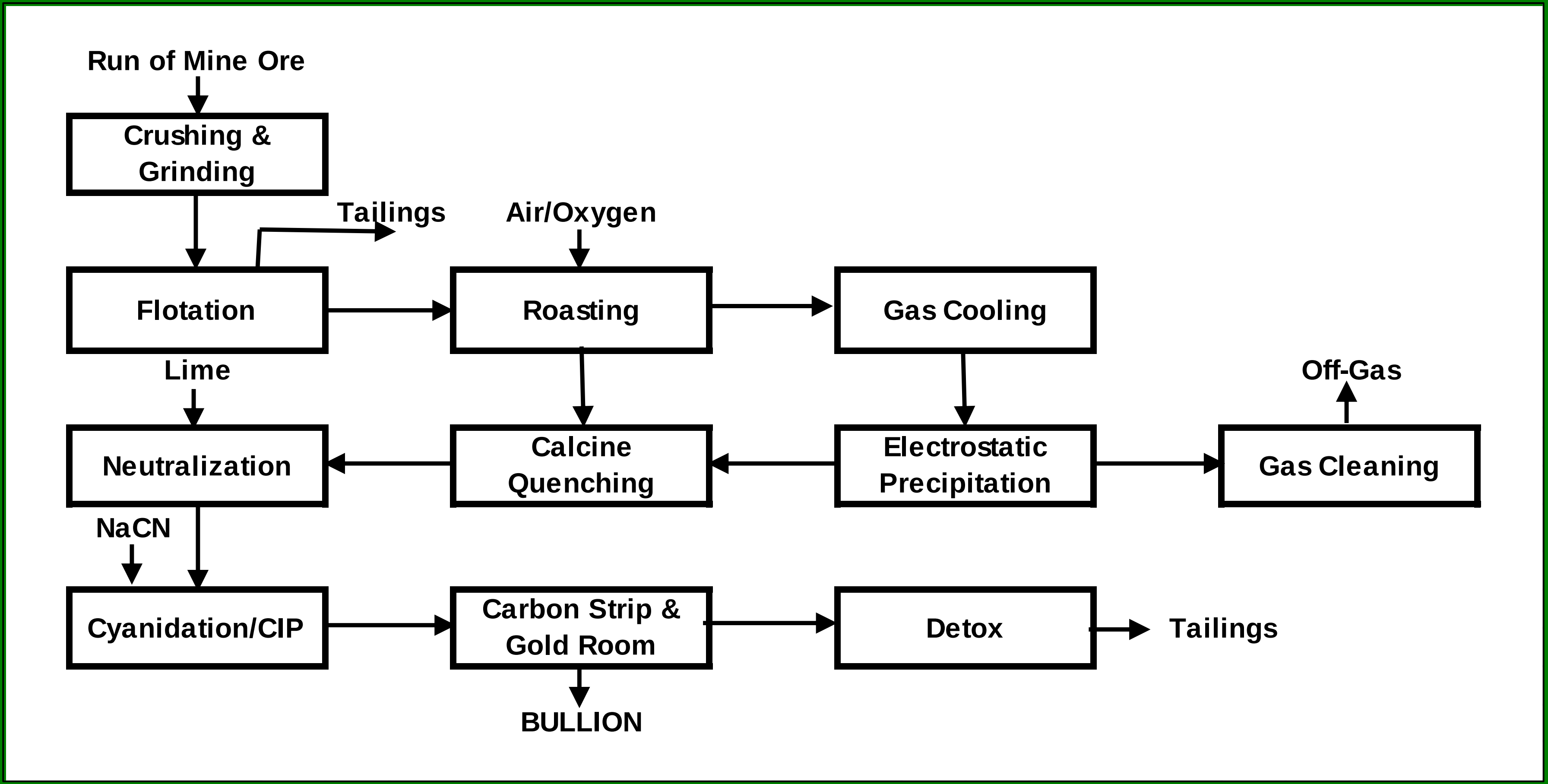
CYANIDE AND OXYGEN CONSUMING ORES

Reactive Iron, Antimony and Arsenic Sulphide Minerals

- Preaeration (air and/or oxygen) in alkaline solution which forms a protective oxidation film on the iron sulphide surface and oxidizes any soluble ferrous salts present in the ore
- Addition of a soluble lead salt such as nitrate which precipitates soluble sulphide and assists with the passivation of the iron sulphide surface.
- Flotation and roasting of concentrate for ores with high reactive sulphide levels.

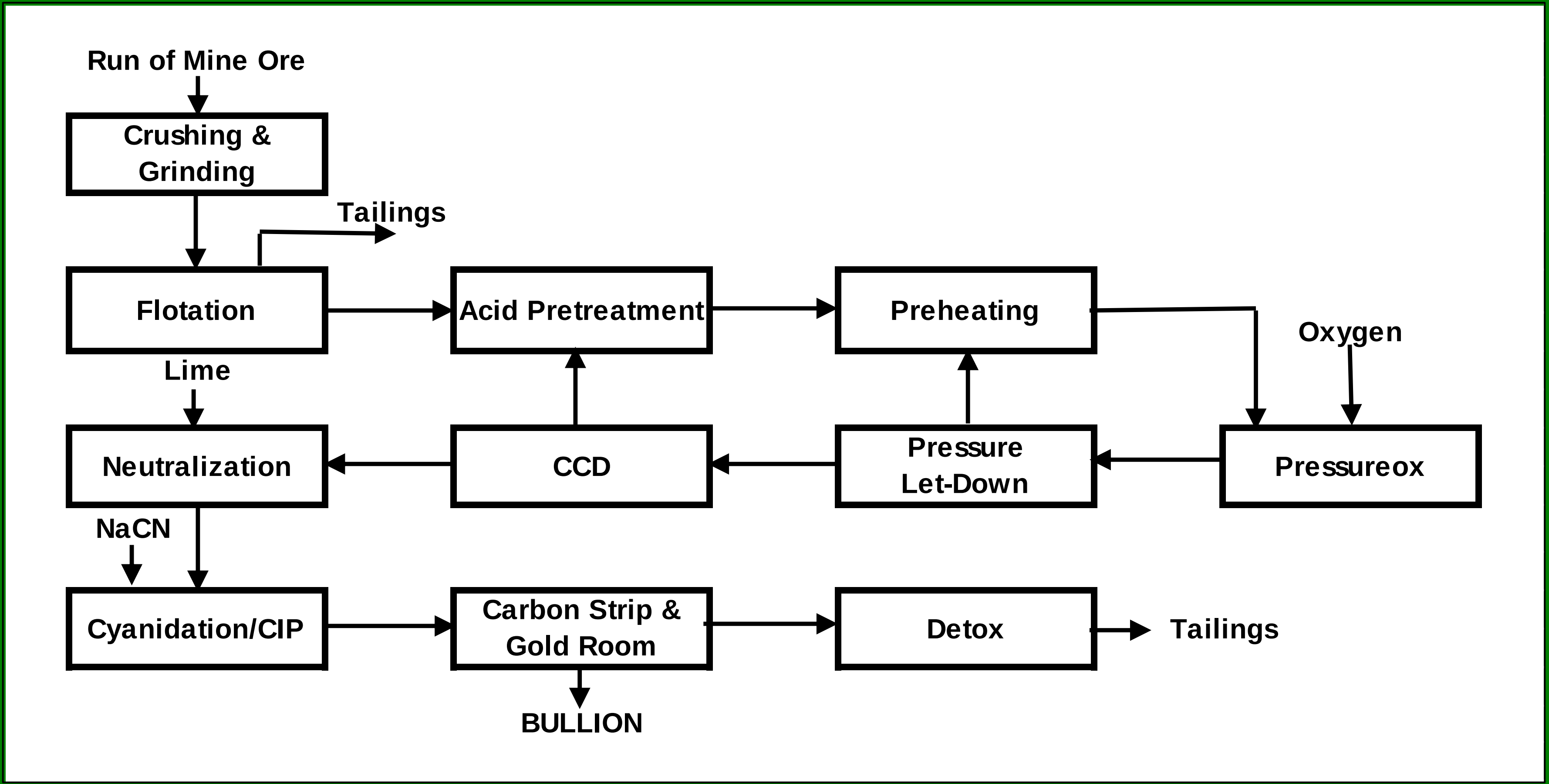
SELECTED PROCESS FLOWSHEETS

ROASTING OF FLOTATION CONCENTRATES
For Gold Locked In Iron/Arsenic Sulphides

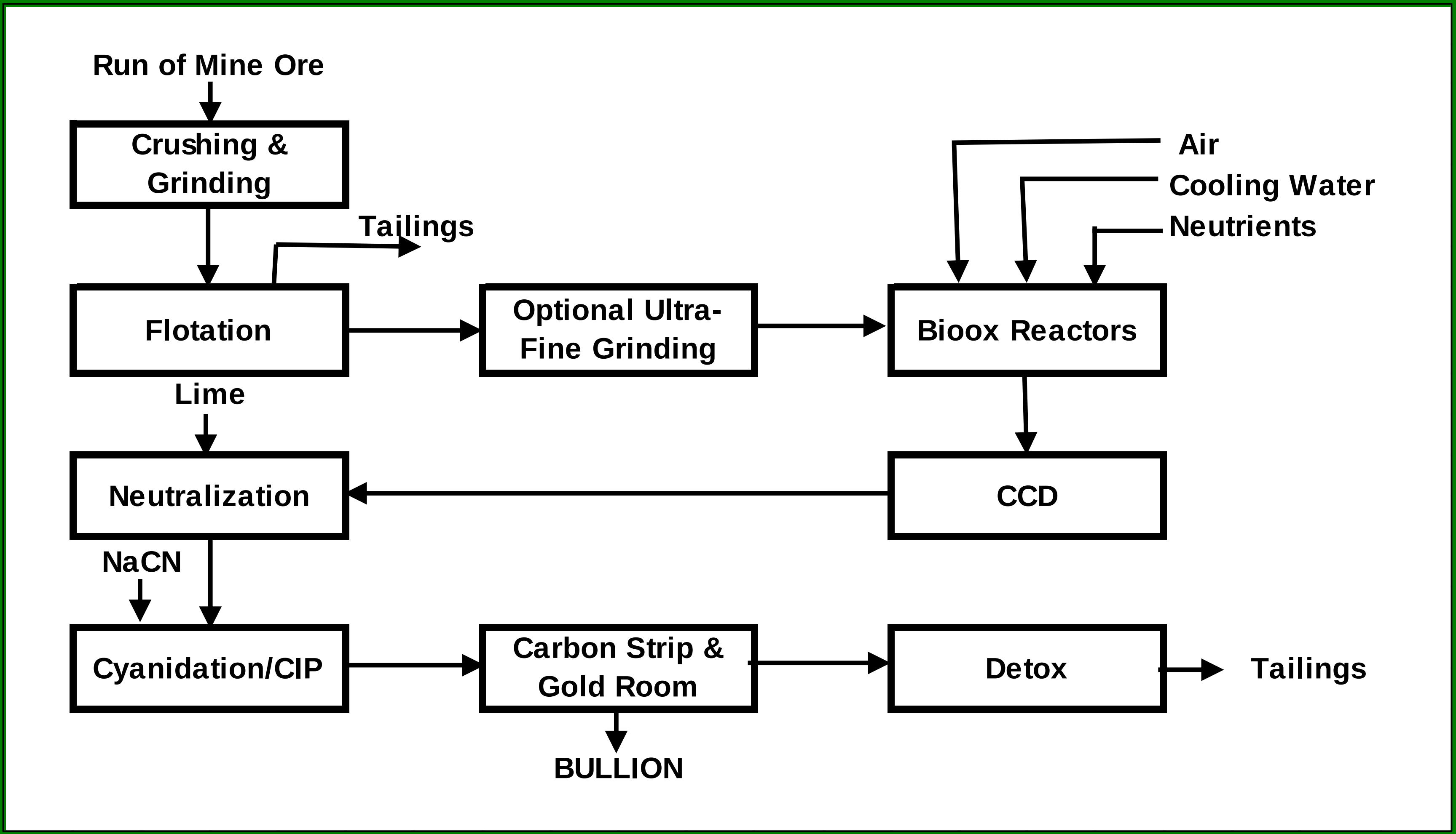


ACID PRESSURE-OX OF FLOTATION CONCENTRATE

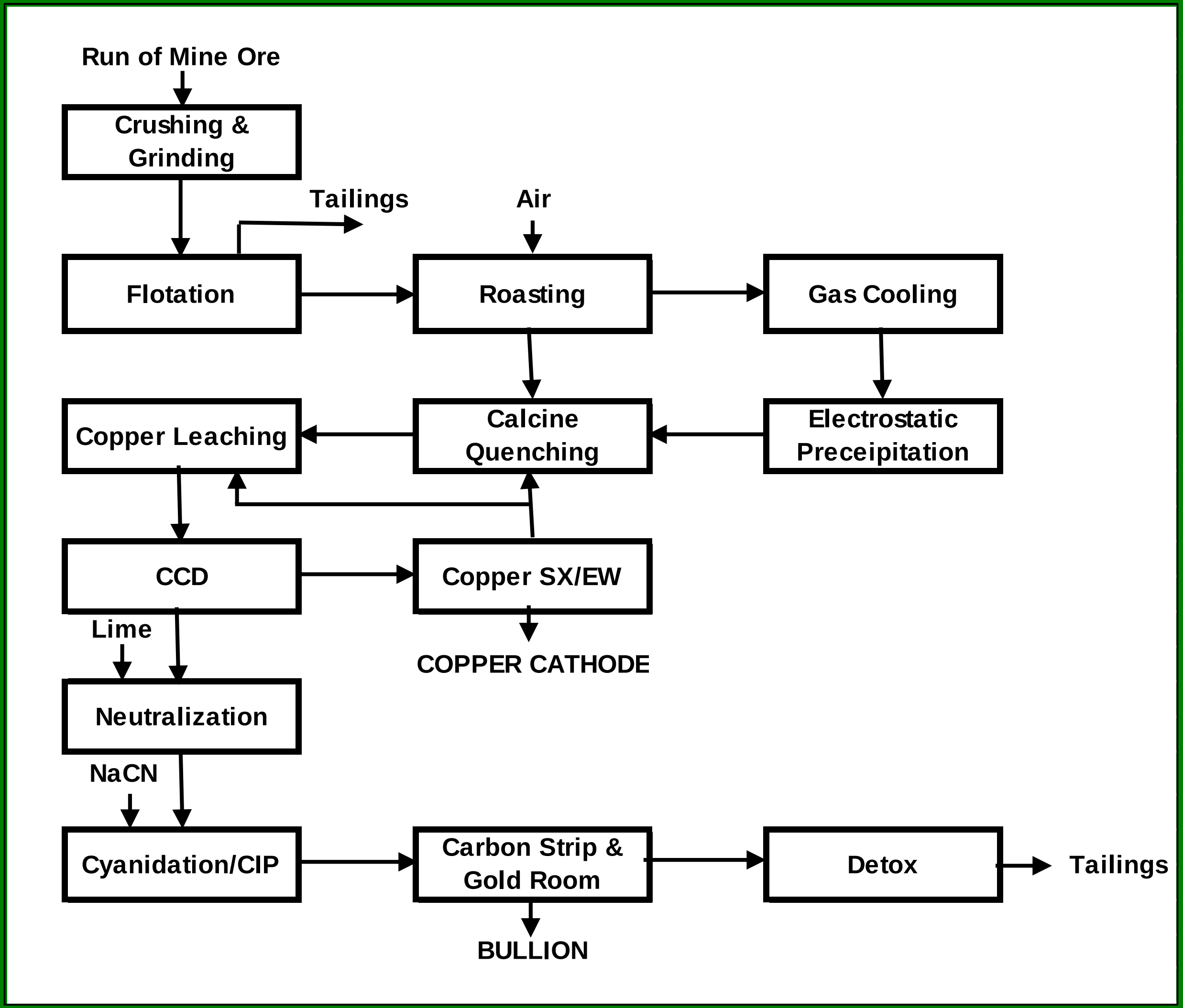
For Gold Locked In Iron/Arsenic Sulphides



BIO-OX OF FLOTATION CONCENTRATE
For Gold Locked In Iron/Arsenic Sulphides

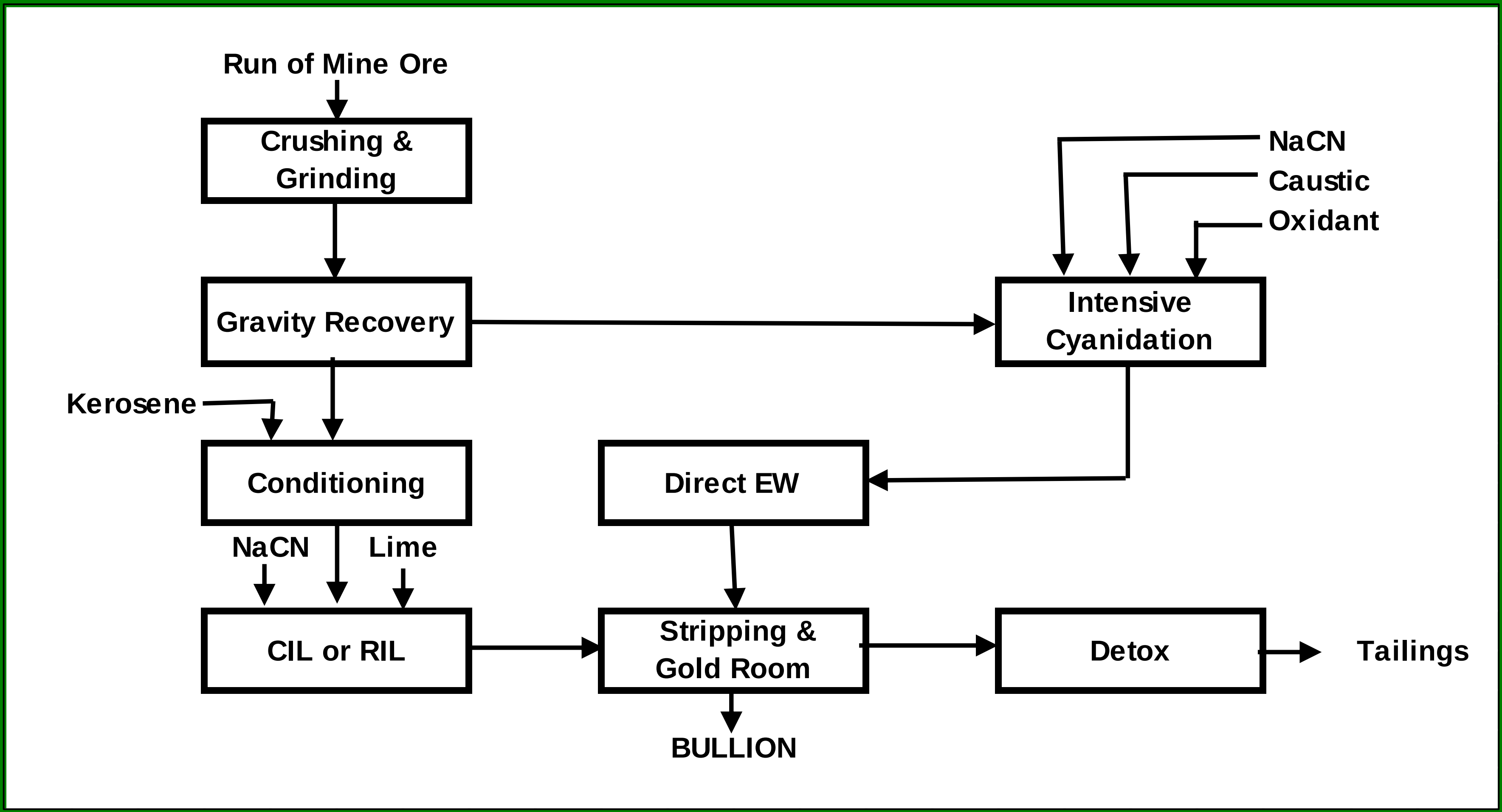


ROASTING OF FLOTATION CONCENTRATE
For Gold Locked In Copper Sulphides



GRAVITY RECOVERY MAXIMIZATION, KEROSENE BLANKETING & CIL/RIL

For Preg-robbing Ores



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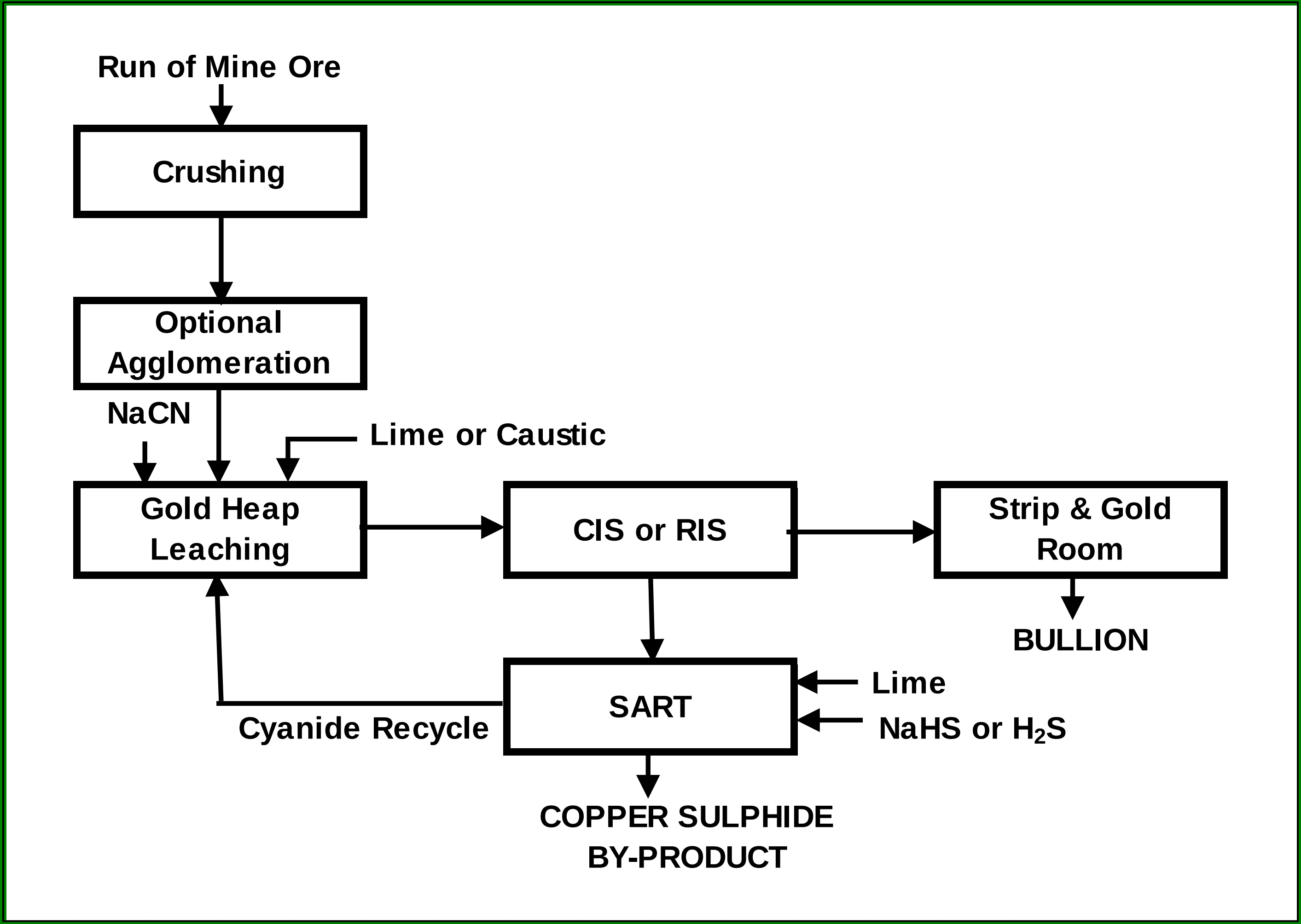
HEAP LEACHING INCLUDING SART

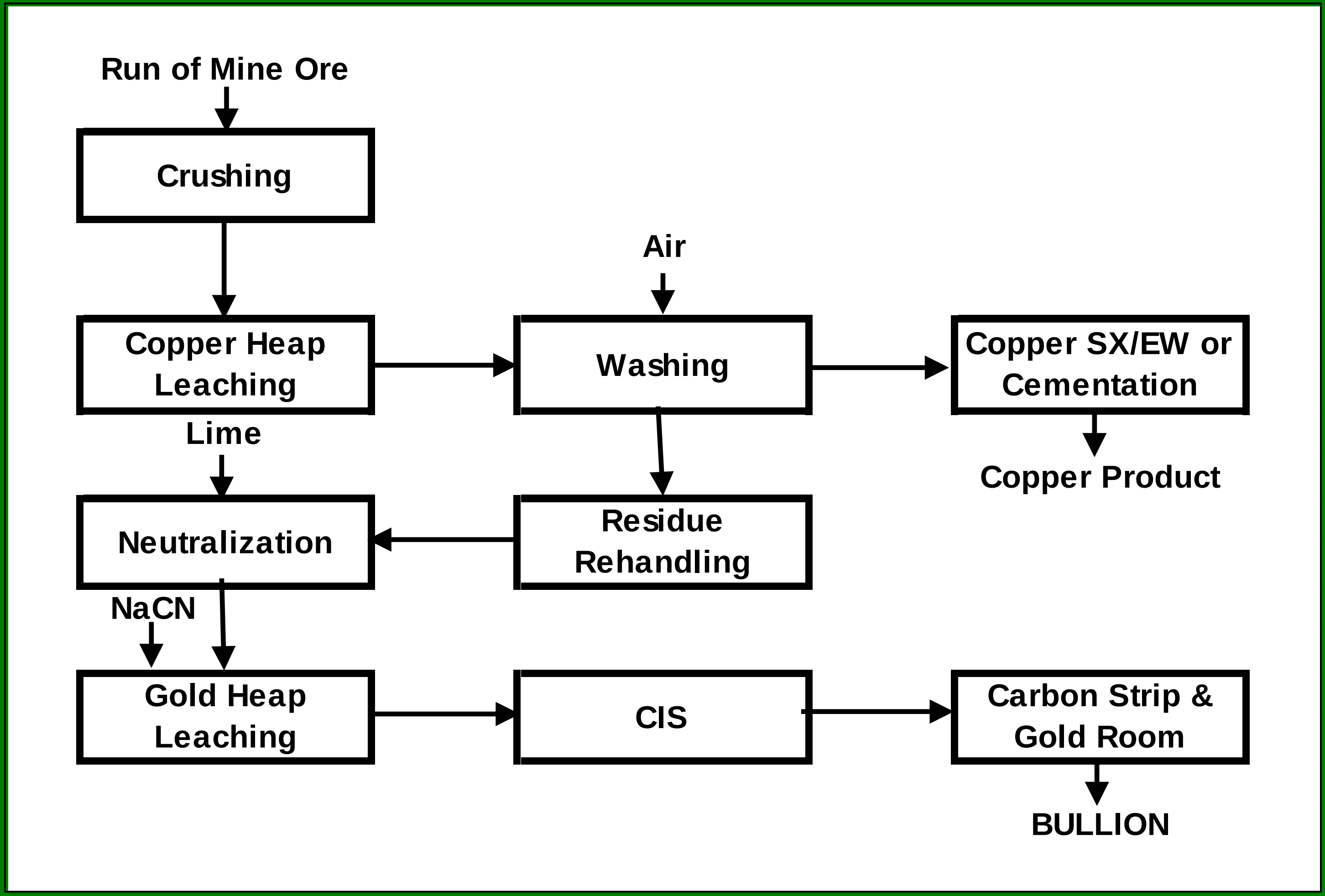
For Cyanide Soluble Copper Minerals



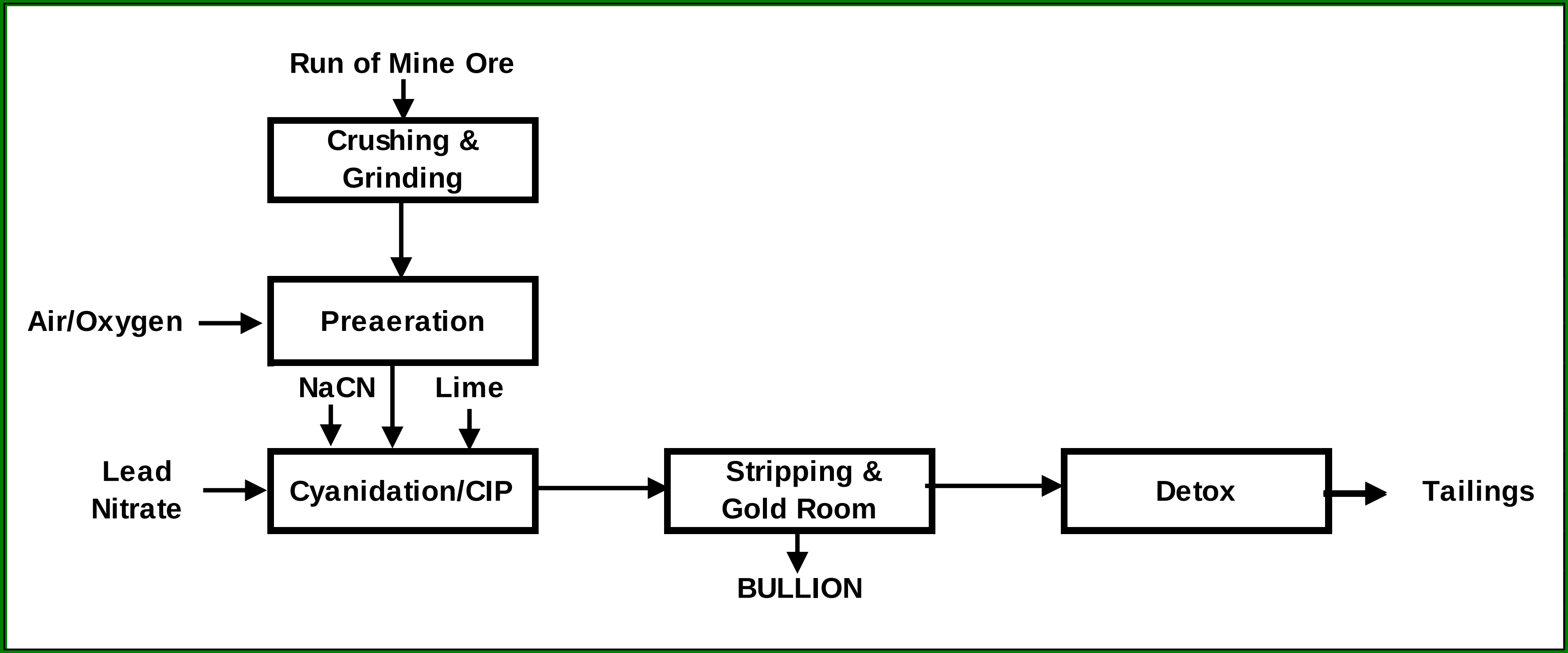
SEQUENTIAL HEAP LEACHING

For Cyanide Soluble Copper Minerals

Applied at Mt. Leyshon Mines, Qld, Australia in the 1990s



PREAERATION AND LEAD NITRATE ADDITION
For Reactive Sulphide Minerals



PROCESS DEVELOPMENT

ALBION PROCESS

- Developed by Xstrata, and marketed through Core Resources, Australia.
- Potentially lower cost option for gold locked in refractory iron/arsenic and base metal sulphide ores.
- Consists of flotation, ultrafine grinding of concentrate using Isamill technology, and agitated oxidative atmospheric leaching reactors with oxygen sparging operating autothermallly at 93-98C.
- Limestone dosing to maintain neutral pH of 5-7 used for pyrite, arsenopyrite, and tellurides.
- Followed by thickening, cooling and gold recovery by CIL.
- Two commercial zinc plants commissioned in Spain in 2010 and Germany in 2011.
- First commercial refractory gold plant in Dominican Republic in 2012. Second under construction in Armenia.

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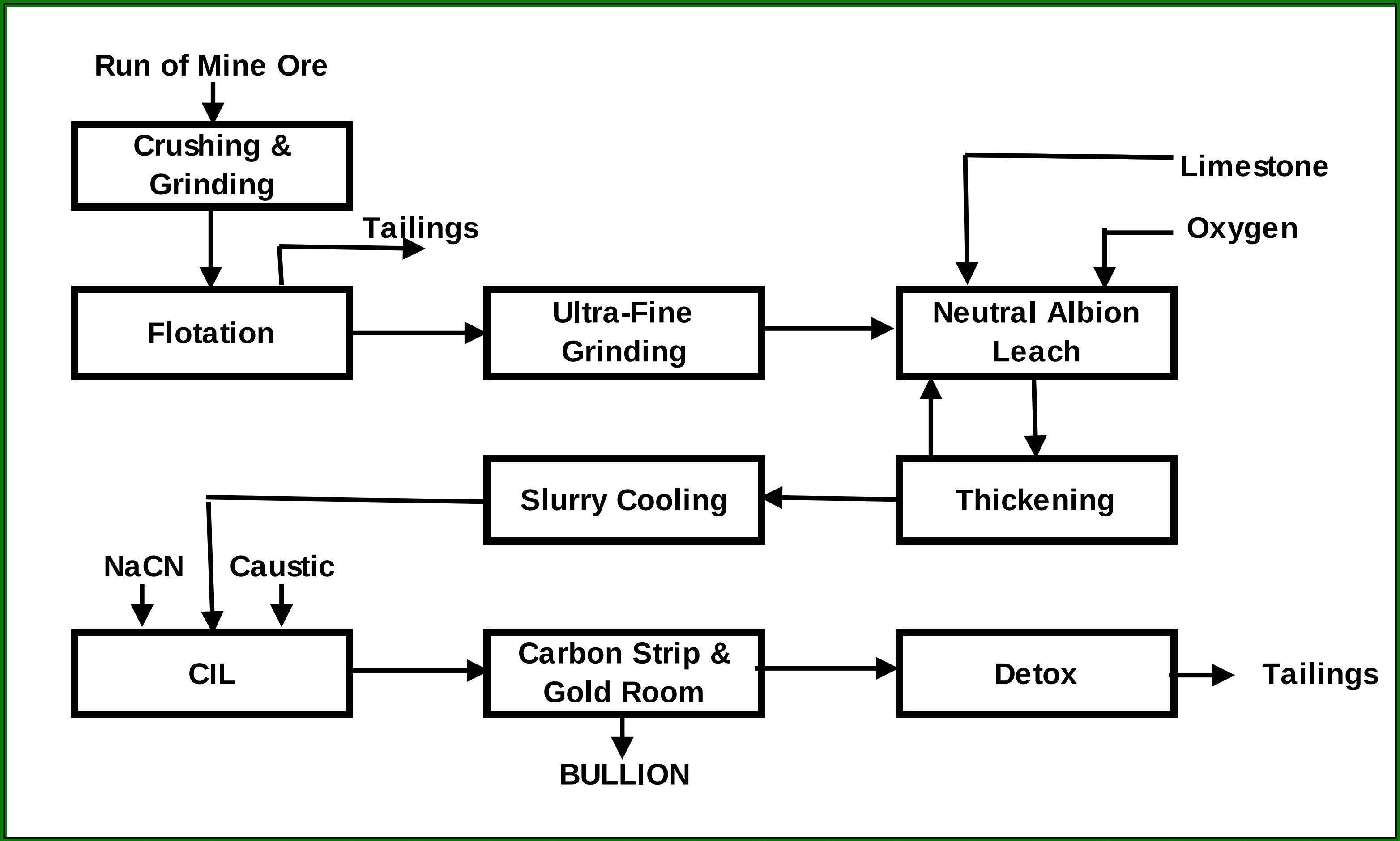
ALBION PROCESS FLOWSHEET



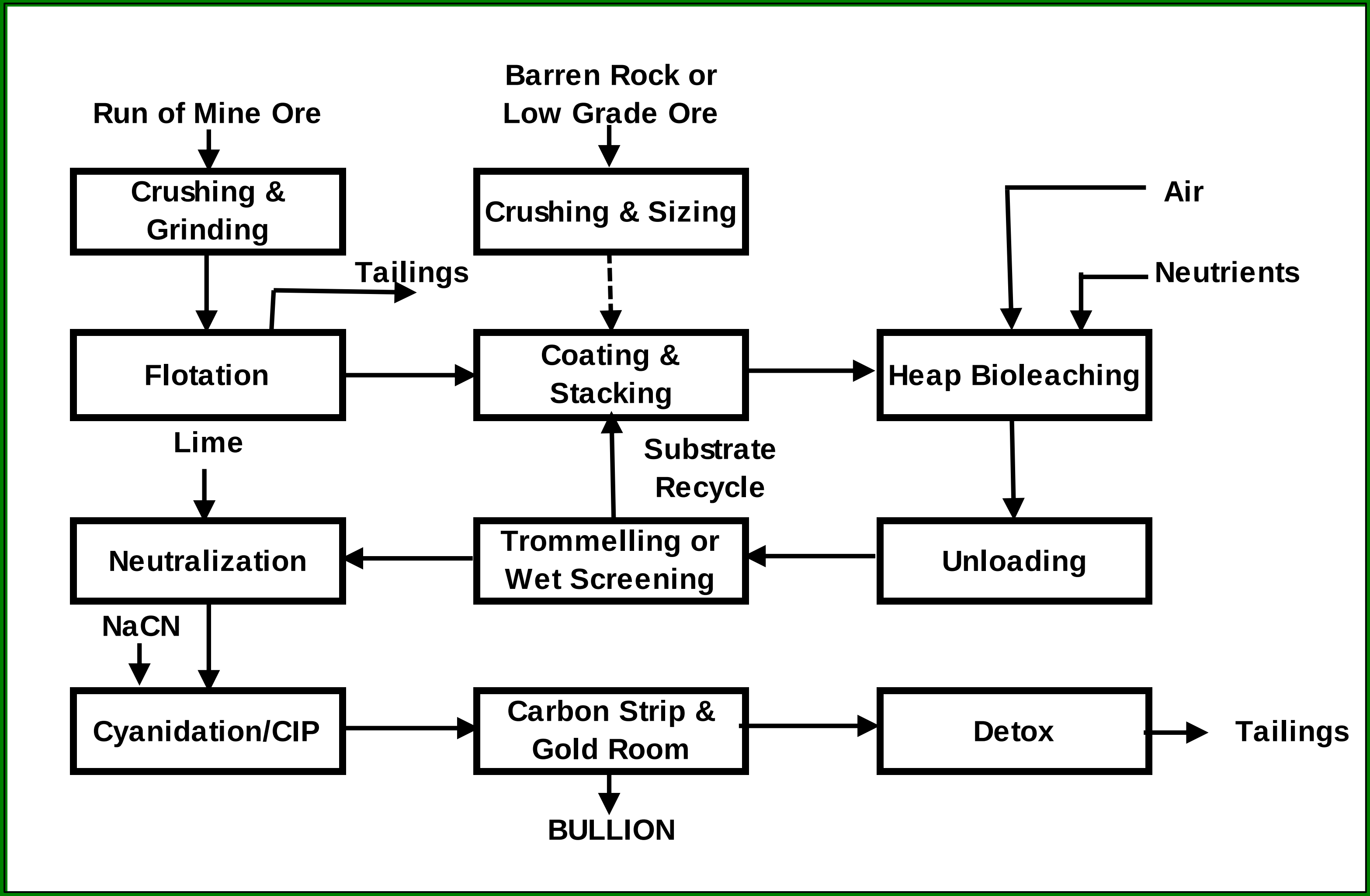
LAS LAGUNAS ALBION LEACHING PLANT DOMINICAN REPUBLIC

Ref: Xstrata/Core Paper, ALTA 2012

GEOCOAT PROCESS

- Developed by GeoBiotics, USA.
- Potentially lower cost option for gold locked in refractory iron/arsenic and base metal sulphide ores.
- Involves coating of flotation concentrate onto a suitable substrate, e.g. crushed barren rock or low grade ore, then heap bioleaching with inoculation of naturally occurring bacteria.
- Nutrients added to the circulating solution and low pressure air for bioleaching and cooling injected into the base of the heap.
- The residue is unloaded and the oxidized concentrate removed by trommelling or wet screening. The concentrate residue is neutralized then subjected to conventional cyanidation.
- The supporting substrate can be recycled or, in the case of low grade ore, replaced with fresh ore as needed.
- Operated commercially in South Africa 2003-2006.

GEOCOAT PROCESS FLOWSHEET



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GEOCOAT FACILITY, AGNES GOLD, SOUTH AFRICA

Ref: GeoCoat Presentation, ALTA 2005

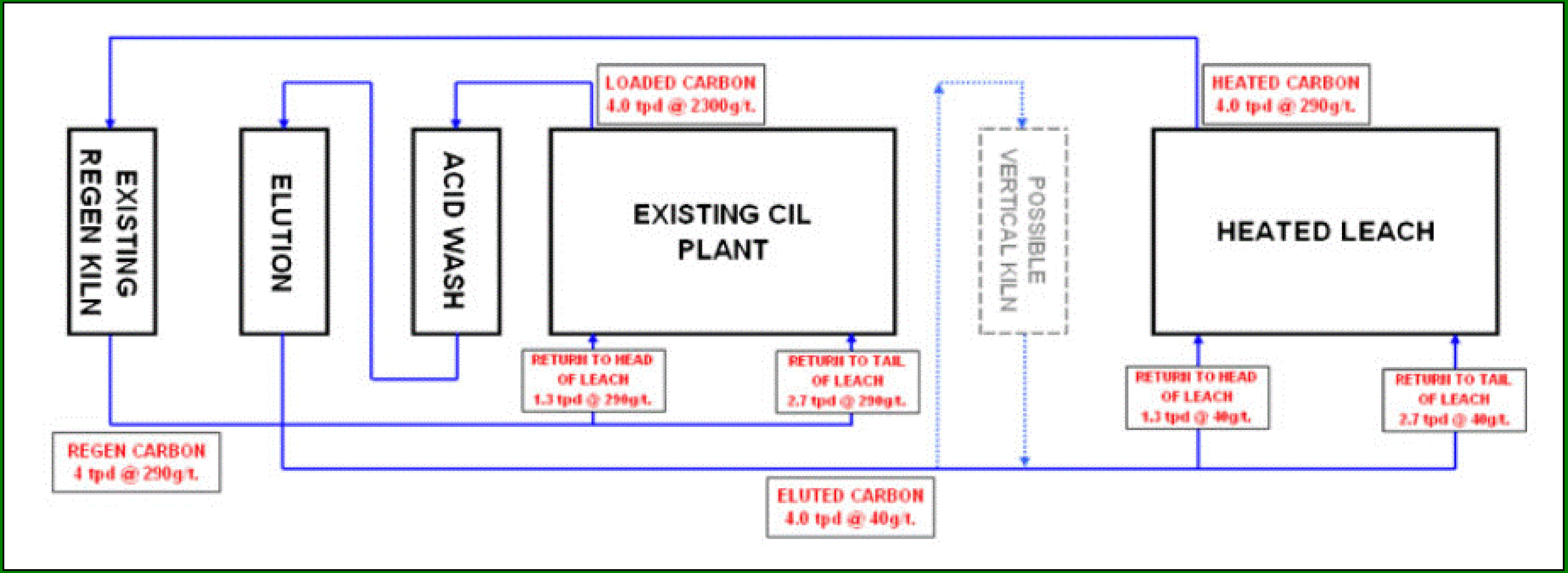
FOSTERVILLE HEATED LEACH PROCESS

Ref: Trans. Inst. Min. Metall. C 2012 Vol 121 No 4

- Developed by Fosterville Gold Mine, Victoria, Australia (now owned by Crocodile Gold Company, Canada).
- To solve preg-robbing problem in CIL circuit caused by carbonaceous material (bituminous coal).
- After flotation, bio-oxidation, CCD washing, and conventional CIL, the slurry is passed countercurrently to activated carbon through a 6 stage heated leach circuit.
- Gold is desorbed from the carbonaceous material in the first 3 stages at up to 70C, then is adsorbed by the activated carbon in the final 3 stages after cooling in a heat exchanger and by cooling water addition.
- Based on lab and pilot scale studies, a commercial circuit was installed and commissioned in 2009 - gains in gold recovery of 4-14% are reported.

FOSTERVILLE CARBON MOVEMENT FLOWSHEET

Ref: Trans. Inst. Min. Metall. C 2012 Vol 121 No 4



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FOSTERVILLE HEATED LEACH CIRCUIT

Ref: Trans. Inst. Min. Metall. C 2012 Vol 121 No 4

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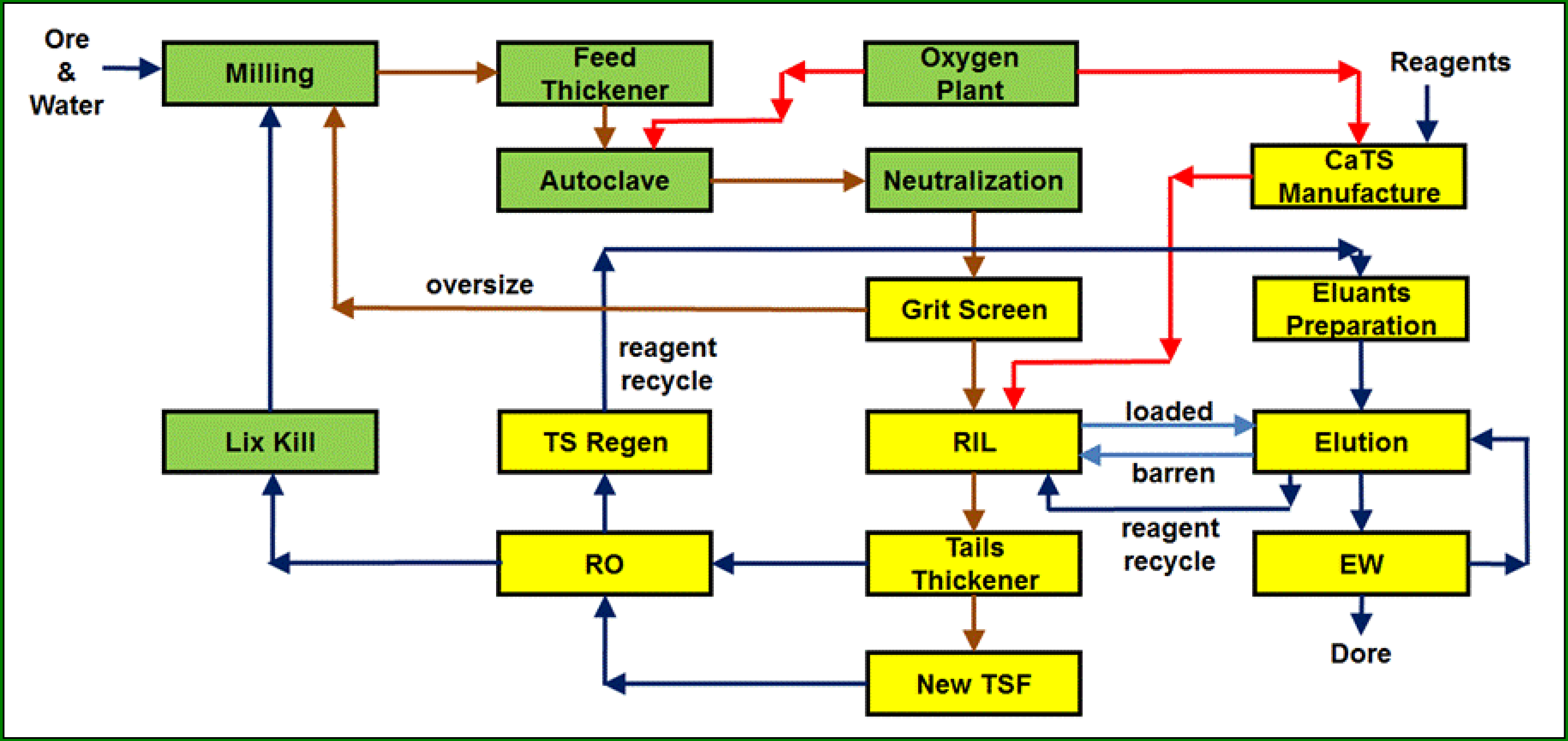
BARRICK THIOSULPHATE LEACHING PROCESS

- Developed by Barrick Gold, Canada.
- More environmentally favourable alternative to roasting/cyanidation for highly preg-robbing double refractory sulphide ores with high content of carbonaceous material.
- Consists of pressure oxidation of whole ore followed by resin-in-leach using calcium thiosulphate, then elution of the resin.
- Includes an innovative approach to reduce reagent consumption comprising RO and thiosulfate regeneration, with CaTS manufacturing on site
- Demonstration plant operated at Goldstrike, USA, 2010-2011.
- Commercial plant under construction, due on stream 2014.

BARRICK THIOSULPHATE PROCESS FLOWSHEET

Ref: Barrick Presentation, ALTA 2013



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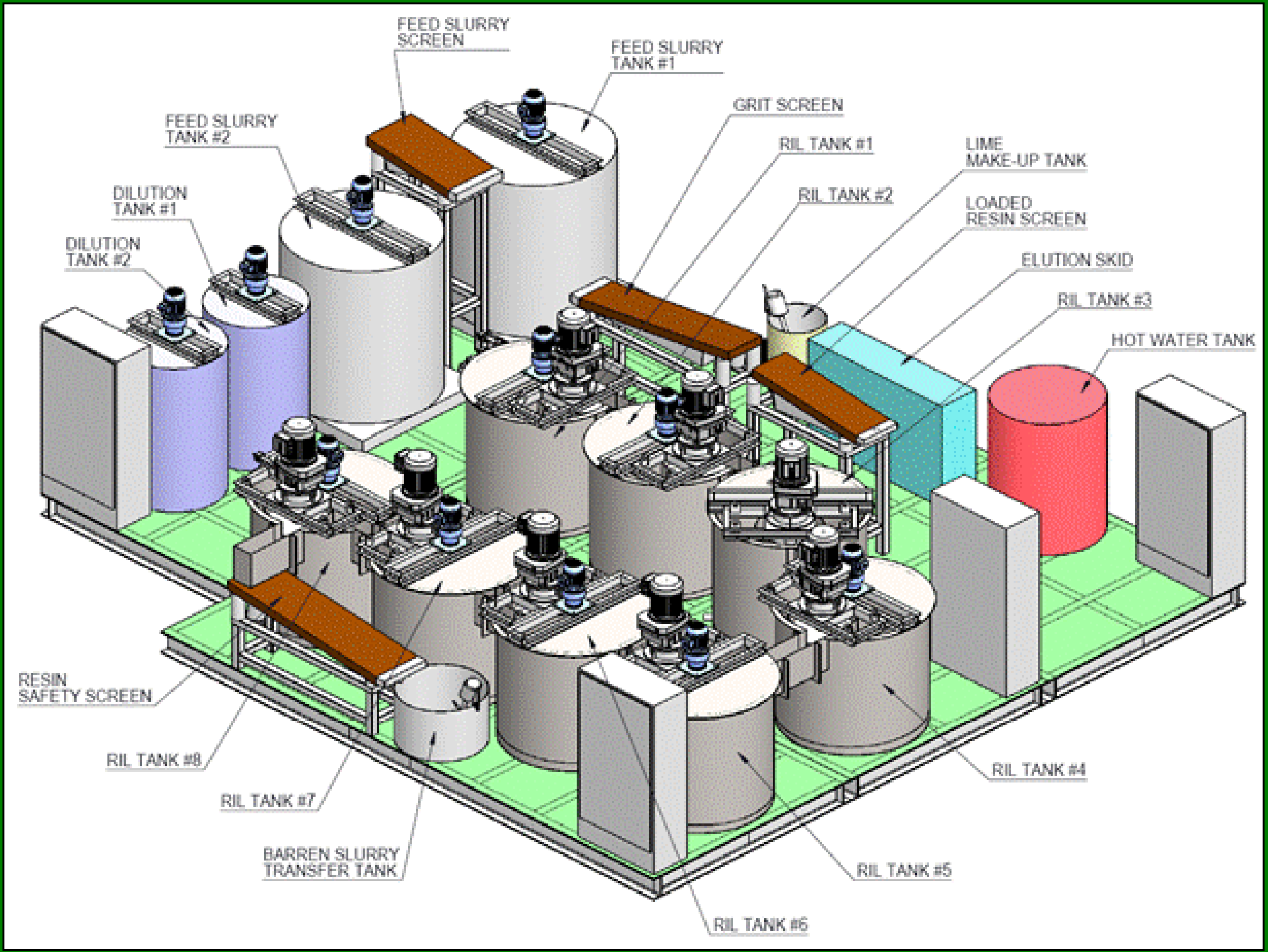
THIOSULPHATE DEMONSTRATION PLANT LAYOUT

Ref: Barrick Presentation, ALTA 2013



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NEOMET PROCESS

- Being developed by Neomet, Canada.
- Potentially lower cost none-cyanide option for both refractory and carbonaceous ores, concentrates or tailings.
- Allows for the recovery of other value metals such as copper, nickel, cobalt, rare earths, minor rare metals such scandium, gallium and indium, and the platinum group metals.
- Comprises agitated atmospheric leaching with hydrochloric acid at 105-110°C.
- For feeds with significant pyrrhotite or other reactive sulphide component, the leach is divided into two stages - a primary (reducing) leach to destroy all reactive sulphide, followed by a secondary (oxidising) leach to dissolve the gold with addition of an oxidant such as peroxide or chlorine.

NEOMET PROCESS (CONT.)

- Gold is recovered by IX followed by elution with very dilute hydrochloric acid from which pure gold is can be recovered by various methods.
- Silver can be extracted with activated carbon.
- The residual solution is injected into an inert matrix bath at 180-190°C (“atmospheric autoclave”) in which iron hydrolyzes to hematite, releasing concentrated HCl gas to be condensed or recycled directly to the leaching stage.
- The process has been tested at a mini-plant level.

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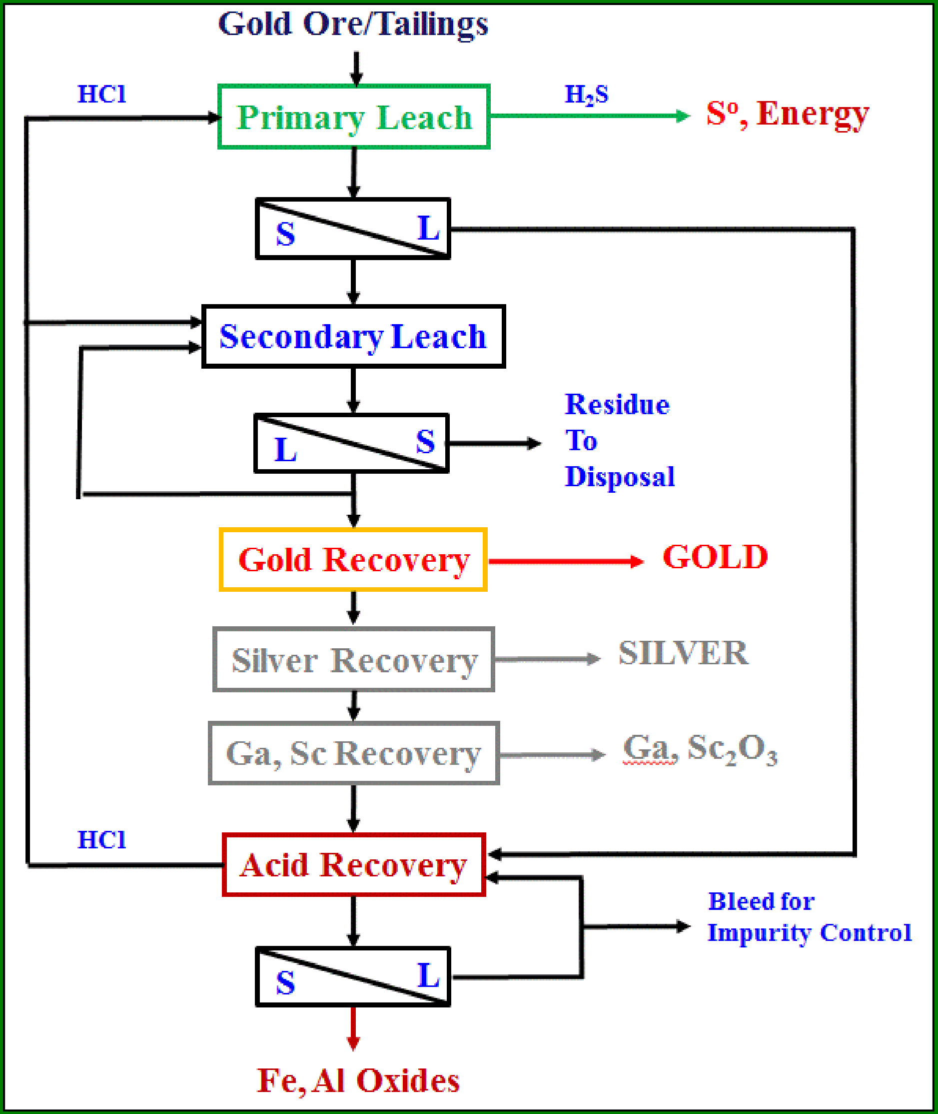
NEOMET PROCESS FLOWSHEET

Ref: Neomet Paper, ALTA 2011



NEOMET MINPLANT

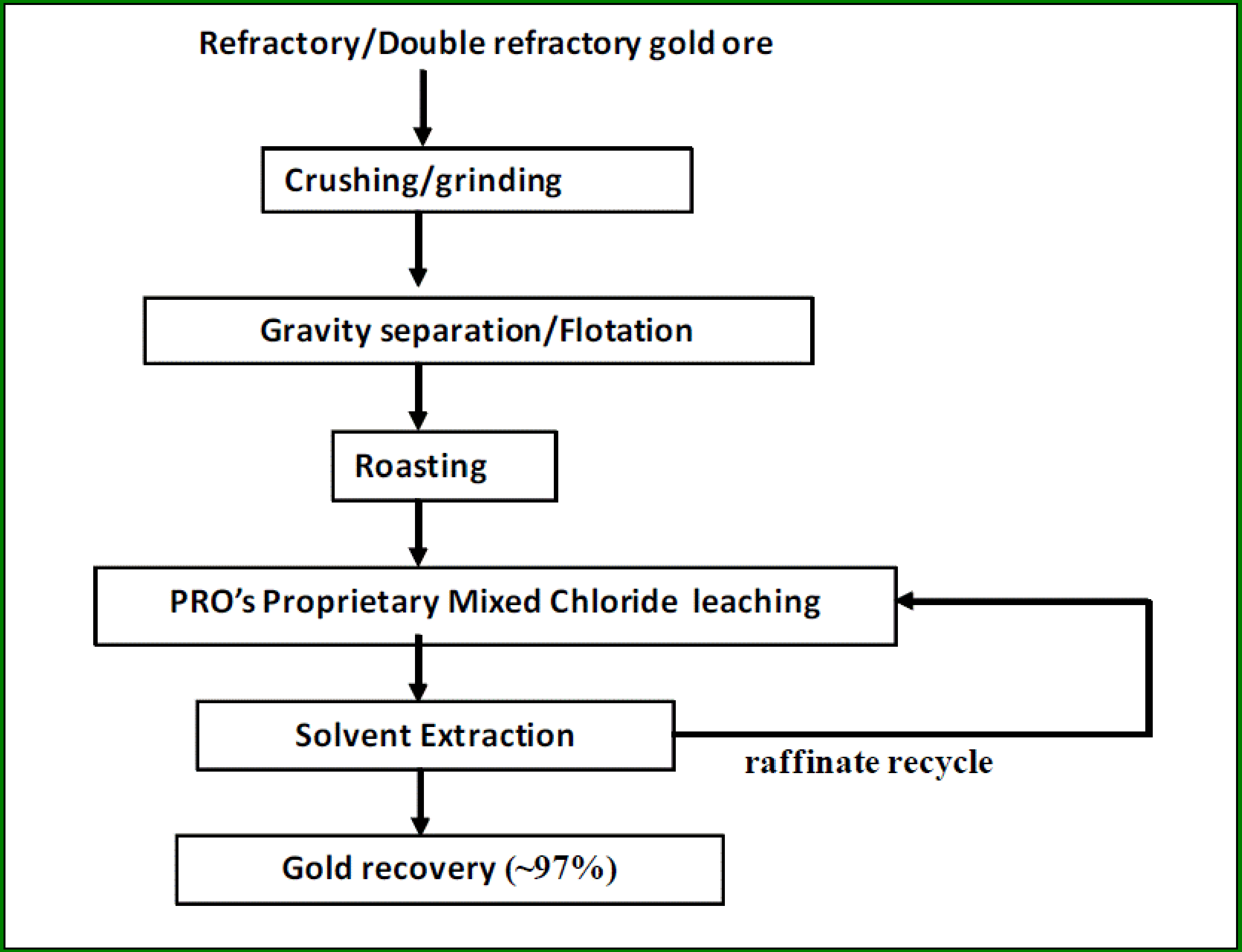
Ref: Neomet Paper, ALTA 2011

PRO PROCESS

- Being developed by Process Research Ortech, Canada.
- Potentially lower cost none-cyanide option for refractory/double refractory gold ores.
- Consists of crushing, grinding, gravity separation, flotation, roasting of concentrate, leaching of calcine in PRO's proprietary mixed chloride lixiviant ($HCl+MgCl_2$), solvent extraction for gold recovery and recycle of reagents.

PRO FLOWSHEET

Ref: Process Research Oretech Paper, ALTA 2013



OTHER PROCESS DEVELOPMENTS

- Heap bioleaching of low grade refractory sulphide ores at elevated pH which reduces cost of neutralization ahead of cyanidation (BioHeap/Western Areas, Australia, paper at ALTA 2013 Gold).
- Use for selective gold IX resins for gold-copper ores – e.g. Gedabek Heap Leaching Operation, Azerbaijan.
- Hydrometallurgical processes for copper/gold sulphide ores – e.g. pressure oxidation, bio-oxidation, ferric leaching, and chloride leaching.

GEDABEK RESIN-IN-SOLUTION PLANT

Ref: Mintek Presentation, ALTA 2010

INCENTIVES FOR NEW PROCESS DEVELOPMENT

- Trend towards lower grade, more complex, ores.
- Need for low capex and/or opex processes, especially for small deposits and low grade ores.
- Treatment of high carbonate refractory ores.
- Increasing environmental opposition to cyanide.
- Increasing environmental concerns over long term disposal of potentially toxic elements, including As, Hg, Se, Sb, and Te.
- Increasing concern over process water consumption.

REFERENCES

- Dunn, R., “Challenges and Opportunities In the Treatment of Refractory Gold Ores”, Gold Proceedings ALTA 2012 Perth, 1-15, 2012.
- Zhou, J., Jago, B., & Martin, C., “Establishing the Process Mineralogy of Gold Ores”, SGS Minerals Technical Bulletin 2004-03, 2004.
- Vaughan, J.P. “The Process Mineralogy of Gold: The Classification of Ore Types”, Journal of Metals July 2004, 46-48, 2004.
- Taylor, A., “Heap Leaching and its Application to Copper, Gold, Uranium and Nickel Ores’ Short Course Manual, 2013.

Upcoming Short Courses

Copper Hydromet *November 2013, Melbourne, Australia*

Practically-oriented full-day courses – a valuable introduction for newcomers and a useful refresher for old hands.

A-Z of Copper Ore Leaching	20 November
Copper SX-EW Basic Principles and Detailed Plant Design	21 November
Copper Oxide Ore Heap Leaching Testwork and Scale-up	22 November

Upcoming Conference

ALTA 2014 Nickel-Cobalt-Copper, Uranium-REE and Gold-Precious Metals Conference & Exhibition *May 2014, Perth Australia*

Now in its 18th year, this major event has become an annual gathering of the global Nickel-Cobalt-Copper, Uranium and Gold industries. Uniquely incorporating three international conferences in one week, the event is organised around highly focused technical programs, forums and discussion panels with key international presenters. ALTA 2014 will provide an excellent opportunity for technical interchange and networking with senior industry professionals from around the globe.

Conference Sessions
Nickel-Cobalt-Copper 26-28 May including Hydroprocessing of Sulphides Forum
Uranium-REE 29-30 May including Uranium SX Forum *Parallel with Gold-PM sessions*
Gold-Precious Metals 29-30 May including Refractory Gold Ores Forum *Parallel with Uranium-REE sessions*
Short Courses
SX and its Application to Copper, Uranium and Nickel-Cobalt **24 May**
Uranium Ore Processing 31 May
Exhibition 26-30 May

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