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**Gold-PM
Conference**

Including

Fit-for-Purpose Leaching Systems Forum

Organised in partnership with Curtin Gold Technology Group

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Including
Fit-for-Purpose Leaching Systems Forum

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Gold-PM Keynote

FIT-FOR-PURPOSE PRECIOUS METALS LEACH SYSTEMS: MATCHING LEACH STRATEGIES TO SOURCE CHARACTERISTICS

By

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ABSTRACT

The gold industry has been supporting research into alternative lixiviants over a number of decades. However, it may sometimes appear to the casual observer that the industry is no closer now than it was 20 years ago to implementing a feasible solution at multiple sites. Although one industrial calcium thiosulfate plant has been commissioned, not many new processes have progressed beyond pilot scale. Often the problem lies in the fact that one-size-fits-all lixiviants are sought and it is clear that such a panacea does not exist. Ore mineralogy and chemistry, environmental conditions and water availability, mobilisation of toxic deleterious elements and creation of toxic by-products remain challenges, over and above the general required attributes such as sufficiently fast kinetics, low reagent consumption, low reagent price, reagent and gold complex stability, and the need to recycle reagent which mostly involve expensive solid-liquid separation equipment. Moreover, as leaching is only one part of the process, and metal recovery from solution, reagent recovery and recycle, waste bleed streams and downstream recovery, refining and waste treatment processes need to be technically and economically feasible while still offering lowered environmental and safety risks. Cyanide based processing has been particularly robust given a combination of the requirement of limited (if any) piloting required, biodegradability in tailing impoundments, and a process that is well understood by engineering companies (yet complexities remains often underestimated due to poor understanding of reagent-gangue mineral interactions).

This paper will explore a few of alternative lixiviants and contrast it to cyanide leaching. It will look at the attributes that modern lixiviant systems need to have to make them technically, environmentally and economically attractive from an overall processing perspective. It will be shown that an intelligent and engineered approach is required in modern gold extraction. In many cases cyanide may still suffice, but a fit-for purpose lixiviant evaluation is required to ensure that leaching processes are optimal for the ore, the site, the environment and the process economics. One of the key challenges in modern processing engineers is the lack of understanding of the overall process chemistry, mineralogy and by-product formation and a lack of risk appetite for process chemistries that are not well understood. Often process engineers are more comfortable with changes in mechanical process technology than changes in the chemistry that underpins the process. This risk aversion to changes in process chemistry is even more pronounced amongst mining engineers, geologists and mining company executives making the selection of alternative process chemistries a hard sell up the management chain and subsequently to company shareholders where analysts' views are even more conservative.

Keywords: Alternative Lixiviants, Gold, Silver, Deleterious Elements, Recovery Processes, Lixiviant Attributes

Why fit-for-purpose leach system and not alternative lixivants ?

- It is the leach system and the overall process that matters.
- It's all about context.
- Ore/concentrate chemistry, mineralogy, natural and geographical setting, engineering aspects requires engineered approaches.
- Elimination of cyanide (from a toxicity perspective) is seldom a major driver.
- Mobilisation of toxic elements in ores, even with benign reagents, still creates toxic process streams and effluents.
- Process economics is by far a greater driver for change.
- The major costs in gold mining operations is associated with mining and tailings impoundments (and their rehabilitation/closure) and real life-of-mine impacts addresses not only the processing, but the opportunities upstream (mining) and downstream (tailings).
- While revenue is in the 1 ppm fraction, the costs are based on the other 999,999 parts.
- Cyanide often is the most appropriate solution to the problem.

.... Our metallurgists knows all the right answers...
....to all the wrong questions...
(Technical EVP from a major gold company)

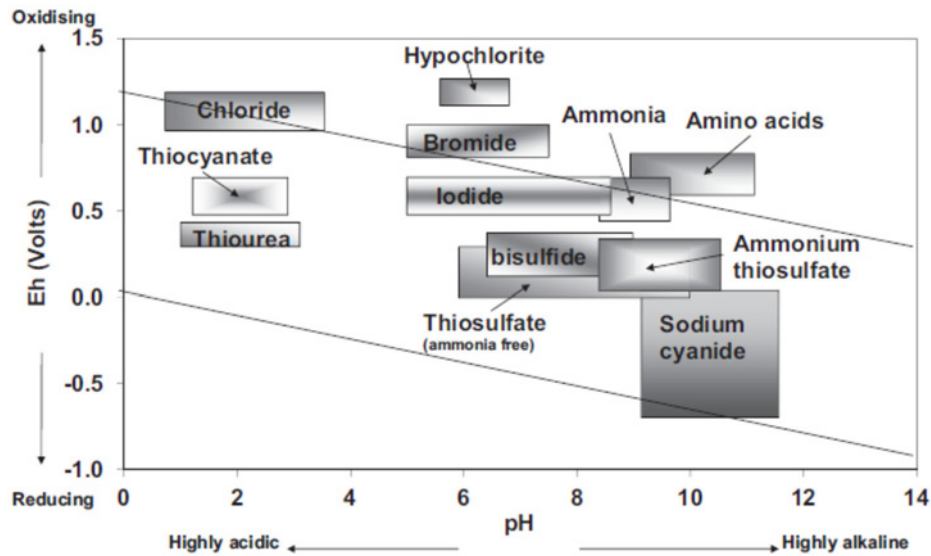
This presentation takes a stab at finding those questions.

We can't fight thermodynamics

Stabilities of some gold complexes at 25°C (Aylmore, 2016)

Ligand	Au(I) or Au(III) Complex	Log β_2 or β_4	E° Au(I or III)/Au (V vs. SHE ^a)	pH Range	Comment
CN ⁻	Au(CN) ₂ ⁻	38.3	-0.57	>9	Toxic, HCN volatile
S ₂ O ₃ ²⁻	Au(S ₂ O ₃) ₂ ³⁻	28.7	0.17	8–10	Unstable
CS(NH ₂) ₂	Au(NH ₂ CSNH ₂) ₂ ⁺	23.3	0.38	<3	Disproportionates
Cl ⁻	AuCl ₂ ⁻	9.1	1.11	<3	Acid, unselective
	AuCl ₄ ⁻	25.3	1.00		Acid, unselective
Br ⁻	AuBr ₂ ⁻	12.0	0.98	5–8	Volatile, toxic
	AuBr ₄ ⁻	32.8	0.97		Volatile, toxic
I ⁻	AuI ₂ ⁻	18.6	0.58	5–9	Expensive
	AuI ₄ ⁻	47.7	0.69		Expensive
HS ⁻	Au(HS) ₂ ⁻	29.9	-0.25	<9	Toxic, recovery
NH ₃	Au(NH ₃) ₂ ⁺	13	0.57	>9	Toxic, volatile
Glycinate	Au(NH ₂ CH ₂ COO) ₂ ⁻	18	0.632	9	Slow kinetics
SCN ⁻	Au(SCN) ₂ ⁻	17.1	0.66	<3	Selectivity, precipitn.
	Au(SCN) ₄ ⁻	43.9	0.66		Selectivity, precipitn.
SO ₃ ²⁻	Au(SO ₃) ₂ ³⁻	15.4	0.77	>4	Large reagent cons.

Areas of stable operation 25°C (Aylmore, 2016)



Cyanide: the tough competitor

- Very stable Au-complex with ease of low-cost recovery (CIL/CIP).
- Small anion with high diffusion rate making mass transfer rapid.
- Air and oxygen are low cost oxidising reagents.
- Mostly selective (except in the presence of high reactive S, Cu, Ni, Fe).
- Can be easily destroyed .
- High reaction kinetics at room and low temperatures.
- Human fatalities directly relatable to CN insignificant compared to most chemical industries.
- Chemistry (reasonably) well understood and processes widely accepted.

So when do we consider alternatives?

- When it is not allowed in the jurisdiction.
- When *in-situ* or *in-mine* leaching is considered.
- When the ore contains highly active preg-robbing carbon.
- When there are significant cyanicides present (elemental sulfur, copper, reactive sulfides, reactive iron minerals, nickel, zinc, etc.).
- When detox costs and or cyanide recovery costs are large.
- When dry tailings disposal implies barren leachate recycling (with accumulation of CNS^- , CNO^- and $\text{Fe}(\text{CN})_6^{4-}$).
- When it's difficult to economically achieve operating pH's greater than 9.

What are the purposes our lixiviant system has to fit?

The contexts of:
Geology and Mineralogy
Natural and Geographic Setting
Engineering and Economics
Materials, reagents and products

Fitting Geological, Hydrogeological and Mineralogical Contexts and Purposes (1st slide)

We have to design our system for the other 999,999 parts; we have to understand our gangue minerals and how they interact with our lixiviant system. The following aspects are key (continued on next slide):

- Grade → Impact Leach Mode → Lixiviant choice
- Acid consumers → Important when acidic lixiviants are considered (SCN⁻, Cl⁻, thiourea)
- Alkali consumers (active silicate, reactive sulfides)
- Cyanide consumers (Cu, Ni, Zn, Fe (as reactive sulfide))
- Carbon and Pregrobbbers
- Reductants and oxygen demanding minerals (sulfides)
- Bacteria and degradation (native bacteria that can attack lixiviants)

Fitting Geological, Hydrogeological and Mineralogical Contexts and Purposes (2nd slide)

- Groundwater (hypersaline, high magnesium, pH)
- Clays and preg-borrowers (illite, montmorillonite, nontronite, kaolin)
- Arsenic (different mobilisation in acidic an alkaline systems)
- Mercury (extent of mobilisation)
- Silver (passivation of gold surfaces)
- High sulfur ores and concentrates (elemental S passivation, high SCN⁻ generation ability).
- Refractory ores (requiring matrix dissolution for gold exposure)
- Polymetallic ore (see cyanide consumers)

Fitting Lixivants to Geographic and Natural Settings

- Local legislation (roasting not allowed, cyanide not allowed)
- Rainfall and snow melt (impacts on heap leach, tailings impoundments)
- Elevation above sea level (impacts on O₂ partial pressure)
- Temperatures (Canada versus northern parts of Australia /Africa)
- Prevailing wind (Roaster gases, NH₃, H₂S, SO₂)
- Earthquakes, tsunamis and volcanoes (impact on heap leach and valley fill)
- Topography and land availability: Flat versus hilly or mountainous
- Water availability and quality (chloride changing acid leach chemistry)
- Politics and sovereign risk (extent to which processing have to happen on site, e.g. in Indonesia)

Engineering and Economics (1st slide)

- Tailings dam impoundment or river/ocean disposal and lixiviant impacts.
- Geotechnics (for ins-situ, in-mine, heap and dump leaching).
- Nature of the ore deposit and mining methods (spatial variation in mineralogy) and robustness of the lixiviant to variability.
- Financing, cash flow, cash availability for capital (how much working capital is tied up in process, upfront cash requirement).
- Filtered tailings and solution recovery (good for more expensive reagents, as long as reagents are not “sterilised” through conversion to unrecoverable forms (e.g. CNO⁻, SCN⁻ and Fe(CN)₆⁴⁻ or polythionates, or degradation products) may make more “exotic” lixiviant systems more economic.
- Detox and neutralisation requirements may be reduced or eliminated using hybrid/synergistic systems.

Engineering and Economics (2nd slide)

- Mineralogical change in process intermediates: calcines, versus acidic POX residue, versus alkaline POX residue, versus BIOX residue
 - Lock up in jarosites, elemental sulfur coatings, gypsum and calcite coatings
- Downstream impacts when ultra fine grinding is required
 - UFG mechanically activates pyrites to become more reactive
 - Significant amounts of cyanide converts to SCN⁻
- Corrosion, erosion and materials of construction
 - Halide and nitrate leaching systems, acid leach systems, SH⁻ attack
- Ores, versus tailings, anode slimes, waste rock and concentrates (gravity and flotation), versus urban mining (e-scrap).
 - Some lixivants are better suited to concentrates and high grade materials

Engineering and Economics (3rd slide)

- Energy: availability, reliability at site and cost.
 - Heap leach and ISL options with PV in remote areas poorly served by power networks, using a irrigate-soak cycle (irrigate during day, soak and drain during night).
- Labour turnover and link to level of training of staff and process complexity
 - Complex chemistry and high process sensitivity (small operating window) requires well trained operators that remain on site.
- Safety, health and environment (lixiviant toxicity, odour, process safety, impacts on bird and marine life, health impacts due to long term exposure).
- Logistics, distance from port, road, rail infrastructure and social unrest and criminality impacting reagent and product transport.
 - Road accidents, transport of dangerous goods, highjacks.

Engineering and Economics (4th slide)

- Metallurgical understanding of upper management
 - Often poor understanding and anxiety about any chemical change.
- Risk apatite and the need for cut & paste solutions
 - Stick to standard designs (often promoted by the EPC companies themselves).
- Ease of site remediation, closure and legacy.
 - Dealing with residual reagents, products and mobilised deleterious elements.

Reagents, intermediates and products (1st slide)

- Complexing strength of ligand in lixiviant mix
 - Weaker complexes require higher reagent concentrations.
- Reagent-metal chemical thermodynamics
 - What are the Eh-pH-T-concentration stability areas of reagents and metal complexes?
- Leach kinetics of metal in lixiviant and gangue in lixiviant
 - How much gangue co-dissolves and how does it impact reagent requirement?
- Cost of provision of oxidation
 - Will air suffice, or is O₂, O₃, H₂O₂, KMnO₄, Fe³⁺ Oxalate, Cu²⁺ to be used as oxidant?
- Stability of lixiviant and products to oxidation, reduction, temperature, pH change, biological degradation, UV degradation

Reagents, intermediates and products (2nd slide)

- Reagent and product adsorption on gangue, graphitic components and clays (very much lixiviant dependent).
- Reagent cost and bulk availability, and supplier diversity.
 - Expensive reagents require recovery: normally by expensive S/L separation.
 - Some reagents only produced by small number of suppliers and monopolies and cartels may control availability.
 - Not large amounts available.
 - Environmental permitting of new reagents (even benign) can cause long delays.
- Reagent and product transport restrictions
 - Overland transport can be particularly risky in some developing countries.

Reagents, intermediates and products (3rd slide)

- Reagent and product volatility and possible vapour losses depending on pH.
 - NH_3 , H_2S , HCN , HCl , NO_x , I_2 , Cl_2 , Br_2 .
- Reagent and product solubility (silver halides, CuSCN etc).
- Reagent and product disproportionation / degradation.
 - Thiourea breaking down to formamidine disulphide, cyanamide, sulfur and possibly H_2S
- Selective recoverability from solution through adsorption, SX, IX precipitation, cementation.
 - Can one selectively recover the metal complex of interest without excessive co-recovery of other lixivated metals?
 - Does the metal complex transfer to the new phase (e.g. during adsorption of SX), or only the metal cation?

Reagents, intermediates and products (4th slide)

- Selectivity of leach
 - Acidic leaches can cause significant gangue co-dissolution and acid consumption
- Thermal and energy requirements
 - Does the lixiviant system require heating?
 - Is the leach environment naturally hot (e.g. ex-POX, or high rock T in ISL) ?
- Molecule size, diffusion and mass transfer
 - What is the size and diffusion coefficient of the reagents and products?
 - This becomes a significant issue for ISL and where diffusion through micro-cracks can be rate determining.

Reagents, intermediates and products (5th slide)

- Ability to destruct or convert into more benign forms.
 - Can be done easily for CN, (acidic) glycine, but more difficult for SCN⁻, impossible for Br⁻.
- Mobilisation of arsenic and mercury
 - Some does not dissolve, other mobilise, others mobilise and re-precipitate
- Electrochemistry, passivation and semiconductors
 - Some sulfide minerals behave like semiconductors (e.g. chalcopyrite) which has the biggest effect on the rate determining step during leaching.
- Porosity, micro-fractures and enhancing fluid convection and diffusion
 - If diffusion in pores is problematic hybrid/synergistic system may need to be considered for heap leach and ISL.

Beware of the snake oil salesmen

Risks in unknown / partially unknown reagents

- Be careful of “magical” and secret additives.
 - Understand the chemistry.
 - Understand the impacts of each reagent in the process during leaching and downstream up to tailings and recycle impacts.
 - Make sure that there is a sizeable corpus of publications and scientific knowledge to back up the claims and sales talk.
 - Secret ingredients in premixed lixiviant systems can have unwanted and unpredictable impacts on corrosion and materials of construction, the environment, safety, process operability, particularly when allowed to accumulate in recycle systems, and mobilisation of deleterious elements.
 - There may be unknown interactions with other minerals, process water and other reagents can occur and it is very difficult to perform an acceptable process hazard and risk analysis.

There is no holy grail, no panacea...

We have to do our homework

- We have to apply the same rigour to our metallurgical evaluation of lixiviant systems as geologists apply to the orebody and mining engineers to mine design. Metallurgy cannot be an afterthought.
- Cut & paste approaches are not wise, particularly as the more complex ores and lower grade ores require bespoke studies of interactions with gangue.
- Choose the lixiviant system that is fit for purpose for the context within which it need to function.
 - Ask the right questions before you proceed.
 - Understand the risks, but don't feel overwhelmed by them.
 - Understand the chemistry, not only of the leach, but the overall process
- Identify how upstream mineral processing and preconcentration may impact your decision of a lixiviant system. More lixiviant expensive options may be considered on higher grade materials.

But our real challenges are human related...

... but the real questions are...

- Do metallurgists and chemical engineers understand sufficient chemistry and mineralogy to evaluate the process chemistry and process mineralogy?....
Ouch... a reflection on the quality of chemistry knowledge and training.
- Are real metallurgists with in-depth metallurgy insight beyond comminution and concentration still around at operations?
- Do companies have the risk apatite to implement new process chemistries, even if those chemistries pose much lower safety, health and environmental risks and operate under mild conditions (ambient pressure and mild temperatures)?
- Would engineering companies support new processes of which they don't have the expertise to judge the chemistry and interactions with mineralogy and electrochemistry?
- Given the poor understanding of conventional cyanide systems (or acid leach systems for base metals) that are known for more than a century, it is no surprise that the uptake for any remotely different processing chemistries is so low.

We stand on the shoulders of giants....

- The answers are out there... ask, investigate and read.
- Special acknowledgement to the superstars of gold hydrometallurgy such AJ Parker, Ian Ritchie, David Muir, Stephen La Brooy, Mark Aylmore, Jim Avraamides, John Rumball, Jannie van Deventer, Mike Nicol, Tam Tran, Jan Miller, Chris Fleming, Mike Adams, Paul Breuer, Matthew Jeffrey, Gus van Weert, John Marsden, Iain House, David Dreisinger, John Monhemius, Guy Deschenes, Jurgen Loroesch, Dave Lunt, , Joe Ferron, Yeonuk Choi, Peter Kondos, Dan Kappes, Gamini Senanayake, Brent Hiskey, Bill Staunton, Bruno Sceresini, Martie Kotze...
and others who have, in turn built on the legacy of
McArthur, the Forrest brothers, Zadra, Merrill and Crowe.
- May we have the insight and imagination to address the challenges of gold metallurgy in future environments.