GOLD-PM KEYNOTE

CHLORIDE – A PRECIOUS METALS LEACHING MEDIUM YET TO REACH ITS POTENTIAL

By

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ABSTRACT

For centuries, oxidising chloride medium has been well known for its ability to dissolve precious metals including gold, silver, and platinum group metals (PGM) – platinum, palladium, rhodium, ruthenium, iridium. In modern times, gold and silver are mainly recovered by alkaline cyanidation and PGM by smelting – both of which process routes suffer environmental disadvantages.

Cyanidation has been the most widely used process for the extraction of gold from its ores for over 120 years. More recently, commercial application of cyanide in gold mining has been under increasing pressure around environmental concerns, particularly after high-profile cyanide spills at Baia Mare, Romania, and elsewhere.

Processing of PGM concentrates is typically by smelting at ~1550°C to a green matte, converting at ~1350°C to a white matte, removal of base metals by medium-temperature and pressure sulphuric acid leaching. The resultant precious metals refinery (PMR) feed contains 30-70% PGM and is suitable for chlorination leaching, typically using small-scale equipment operating on a batch basis. This process route is energy-intensive with a resulting high carbon footprint and PGM smelters are mostly located in regions with unstable electricity supply. Moreover, many smelters continue to allow sulphur dioxide to be emitted to the atmosphere with no sulphur abatement or off-gas scrubbing measures in place.

Chloride as a low-emissions and low-toxicity leaching system is receiving increasing interest but has yet to realise its full potential. Chlorination chemistry is well understood and the leaching rates are extremely fast – on the order of minutes as opposed to hours or days for cyanidation. This results in relatively small equipment and makes for low capital intensity and low precious metals inventory lockup in-process.

Current chloride-based leaching processes are reviewed, considering their development status and pending or current applications. Of particular note is the application of Lifezone's hydrometallurgy technology to several applications treating PGM concentrates in South Africa to produce refined metal products (Pt, Pd, Rh, Au, Ru, Ir, Ni, Co, Co) at the minesite in a footprint area considered to be about 10-15% of that for the equivalent pyrometallurgical plant. Lifezone hydromet flowsheet development and implementation status shall be presented. These initiatives are significant milestones, representing a potential game changer in the broader application of chloride-based hydrometallurgy to precious metals separation and recovery.

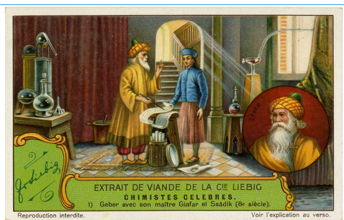
Keywords:

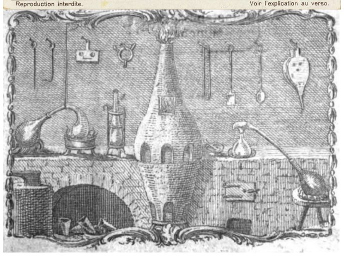
Chloride, precious metals, hydrometallurgy, gold, platinum, palladium, rhodium, PGM, Kell Plant

Background

Chloride leaching of precious metals

Discovery of Aqua Regia and Chlorine



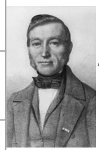
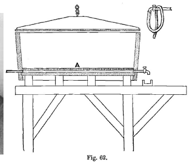
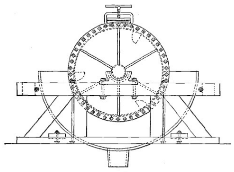
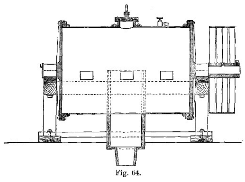


Aqua Regia was discovered by Persian alchemist Jabir Ibn Hayyan (720-813) by the mixture of hydrochloric and nitric acids

Chlorine was discovered by the Swedish chemist Carl Wilhelm Scheele (1742-1786) by the action of hydrochloric acid on manganese dioxide in 1774

Early Chlorination Processes for Gold Extraction

Process	Date	Pretreatment	Equipment	Treatment	Leach	Recovery
Plattner	1848	Dead roast	Damp fixed bed vat	Cl_2 permeation	Water percolation	$FeSO_4$ reduction
Duflos	1848	-	Damp fixed bed vat	In leach	Supersaturated Cl_2 percolation	Reduction
Mears	1877	-	Rotating barrel	Cl_2 300 kPa	Water leach	Reduction
Thies	1881	-	Rotating barrel	In leach	$CaOCl_2/H_2SO_4$ leach 30 kPa	Reduction
Lange	1885	-	Earthenware pots	Cl_2	Water leach	H_2S reduction
Munktell	1888	Dead roast	Damp fixed bed vat	Hot water then HCl or H_2SO_4 for Cu/Fe removal	$CaOCl_2/H_2SO_4$ leach	Lead acetate

Early Processes for Generation of Chlorine:

$2NaCl + MnO_2 + 2H_2SO_4 = Na_2SO_4 + MnSO_4 + 2H_2O + Cl_2$

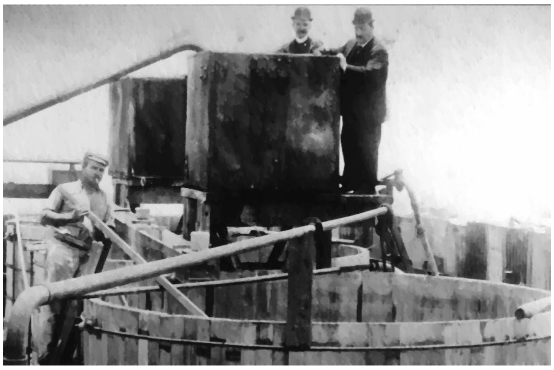
$CaCl_2 + Ca(OCl)_2 + 2H_2SO_4 = 2CaSO_4 + 2H_2O + 2Cl_2$

Factors in the Replacement of Gold Chlorination by Cyanidation

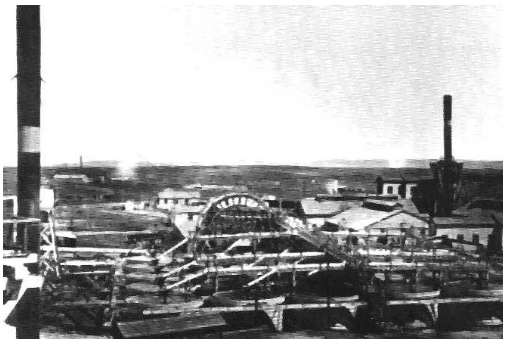
- Excess chlorine losses due to volatilisation from leaky vessels
- Excess chlorine consumption due to reaction with sulphides
- Excess chlorine consumption due to reaction with base metals

2. **Cyanide Extraction.** — Within the last few years it has been found that a weak solution (*e.g.*, 1 per cent. or under) of potassium cyanide can be profitably used for extracting gold, especially from the poor tailings of other processes. The reaction said to occur is—

$$Au + 2KCy + O + H_2O = AuCy.KCy + 2KOH$$



Robinson GM, 1890



Simmer & Jack, 1893

Chemistry of Chlorination

Precious metals leaching reactions

Chloride Leaching Chemistry

Gold chlorination chemistry

$2Au(s) + 3\ Cl_2(g) + 2\ HCl(aq) = 2\ HAuCl_4(aq)$

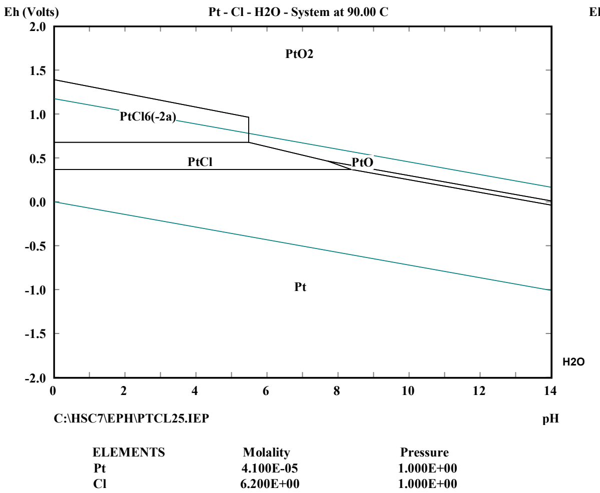
PGM chlorination chemistry

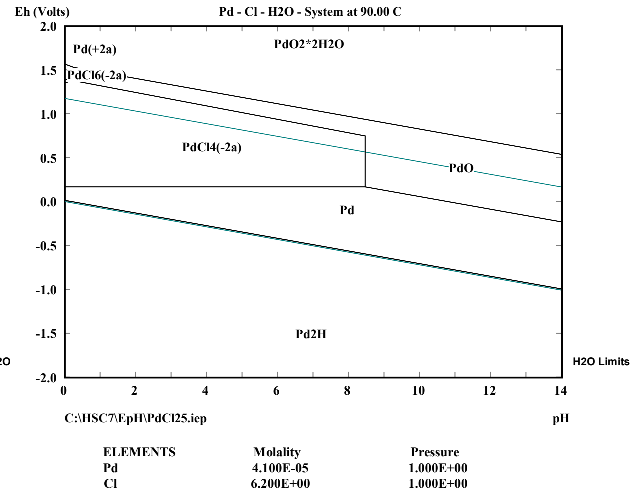
$Pt(s) + Cl_2(g) + 2\ HCl(aq) = H_2PtCl_4(aq)$

$Pt(s) + 2\ Cl_2(g) + 2\ HCl(aq) = H_2PtCl_6(aq)$

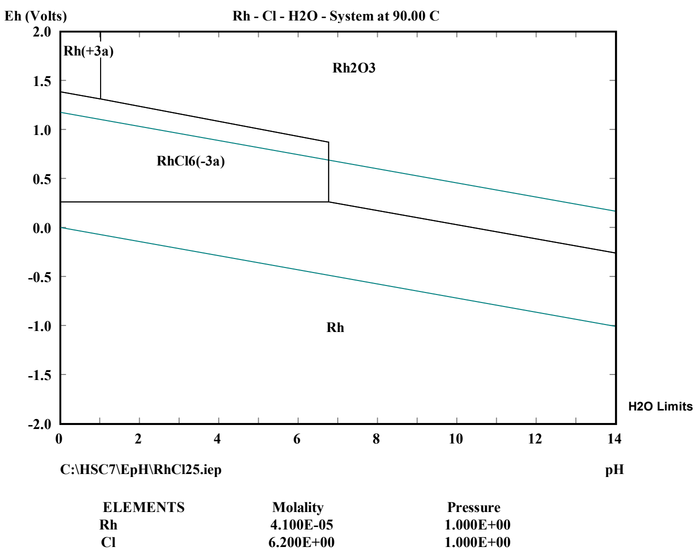
$Rh(s) + Cl_2(g) = RhCl_2(aq)$

Potential-pH Diagram for Pt-Cl-H_2O and Pd-Cl-H_2O Systems

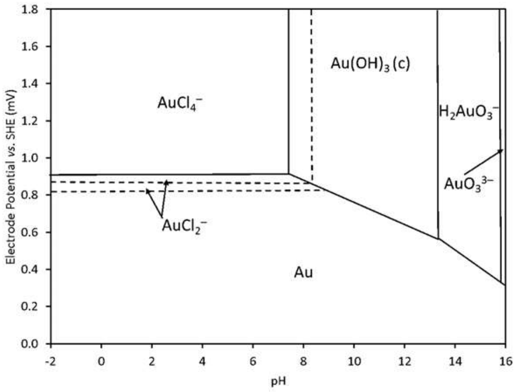




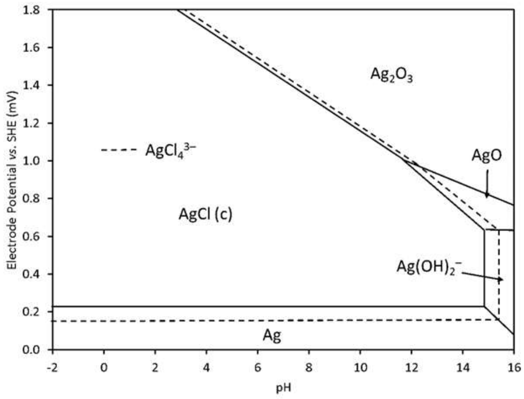
Potential-pH Diagram for Rh-Cl-H_2O System



Potential-pH Diagram for Au-Cl-H_2O and Ag-Cl-H_2O Systems



$a_{Au} = 10^{-3}$ and $a_{Cl} = 1$ (solid) and = 5 (dashed); 25°C
Kelsall et al., 1993



$a_{Au} = 10^{-4}$ and $a_{Cl} = 1$ (solid) and = 2 (dashed); 25°C
Welham et al., 1993

Chloride-Based Leaching Processes

Gold and PGM recovery

Chloride-Based Leaching Processes for Gold

Process	Ligand	Oxidant	Tested	Application Level	References
Hydrocopper	Cl^-	Cu^{2+}, O_2	D		Hyvärinen and Hämäläinen (2005), Canadian Mining Journal (2006), and Infomine (2008); Lundström et al (2009, 2011, 2012)
Intec	Cl^-/Br^-	Cu^{2+}, Fe^{3+}	P		Moyles (1999), Severs (1999), and Monument Mining Ltd (2016)
Lifezone Metals	**Cl^-**	**Cl_2**	**P**	**FS (2x sites, South Africa)**	**Liddell (2009), Liddell et al. (2011), Liddell and Adams (2012a,b), Adams et al. (2015, 2019, 2020)**
N-Chlo	Cl^-/Br^-	Cu^{2+}, Fe^{3+}	D		Nippon Mining and Metals (2008)
Neomet	Cl^-	Cu^{2+}, Fe^{3+} HNO_3 O_2 H2O2	P		Harris and White (2011a,b, 2013)
Nichromet	Cl^-/Br^-	Cl_2/Br_2	P		Lalancette (2009), and Lemieux et al. (2014)
Outotec	Cl^-/Br^-	Cu^{2+}, Fe^{3+}	P		Miettinen et al. (2013)
Platsol	Cl^-	O_2	P	FS (Northmet, USA)	Ferron et al. (2000, 2003), Wardell-Johnson et al. (2009), Dreisinger et al (2016)

Chlorination in Platinum Refineries

A heated agitated 2.2 m^3 titanium vessel for batch dissolution of a PGM concentrate via intermittent chlorine sparging

Photograph courtesy of Impala Platinum
(after Crundwell et al 2012)

Platinum-Group Metals Refineries

Parameter	Unit	Lonmin	Kratsvetmet	Vale Acton	JM/Anglo	Impala
Main feed material		Leached matte	Anode slime	Concentrate/ Catalyst/ E-Waste	Leached mag concentrate	Leached matte
HCl	g/L	219	175			109
Temperature	C	65	70	90-98	120	65-70
Pressure	bar	1	3	1	4	0.7
Residence time	h	6	2			8
Material		Glass-lined	Ti			Ti Gr2; jacketed
Volume	m3	2.2	1			2.5
Impeller		Pitched-blade turbine	Hollow shaft inductor			Pitched-blade turbine
Free Cl_2 removal		Air sparging				"Dechlorinated"
Gold recovery method		N2H4 reduction/HCl	Precipitate with concentrate	SX	SX	IX
Gold product		Crude gold	99.99% Au	99.99	99.95	99.95
Typical gold recovery	%	99	98	99	99.5	94
First-pass yield	%	92		98	84	98

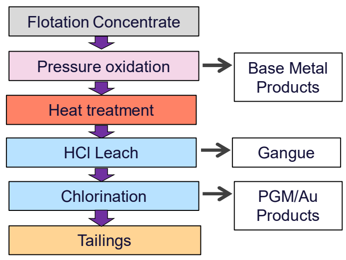
Lifezone Metals

Gold and PGM Hydromet Processing

Lifezone Metals Hydromet – Overcoming the Chlorination Limitations

The globally patented hydrometallurgical Lifezone Metals Process:

- ***Chlorine losses*** due to volatilisation
  - minimised via properly engineered vessels
- ***Chlorine consumption*** due to reaction with sulphides and base metals
  - eliminated via prior removal of these reagent consumers by pressure oxidation
- ***Gas-liquid-solid contact*** constraints in static and rolling reactors
  - eliminated by use of modern CSTR reactors
- ***Refractory, complex*** and deleterious PGM-Au-gangue mineral phases
  - eliminated by heat treatment conditioning and preleach prior to chlorination



Lifezone Metals Hydromet Process Background

The globally patented hydrometallurgical Lifezone Metals Process:

- Developed for the extraction of platinum group metals (PGM), gold, silver and base metals from PGM sulphide flotation concentrates without smelting or cyanidation
- Successfully demonstrated on various PGM and polymetallic concentrates, including UG2, Merensky, Platreef and Great Dyke from southern Africa and polymetallic concentrates from North America, Australia and Africa.
- High recoveries (94 % - 99 %) for selective extraction of a range of value metals, including precious metals (Pt, Pd, Rh, Au, Ag) and base metals (Ni, Co, Cu, Zn, Sn, Pb, Mo) with stabilization of impurities such as As and S without gaseous emissions.
- KellGold process variation for refractory gold, Cu/Au and preg-robbing gold concentrates, enabling production of refined metals at the mine site without the use of cyanide
- Licensed as Kell Process in SADC region via KellTech Ltd, along with shareholders Sedibelo Platinum and IDC (Industrial Development Corporation of South Africa)

Lifezone Metals Hydromet – Technical Features

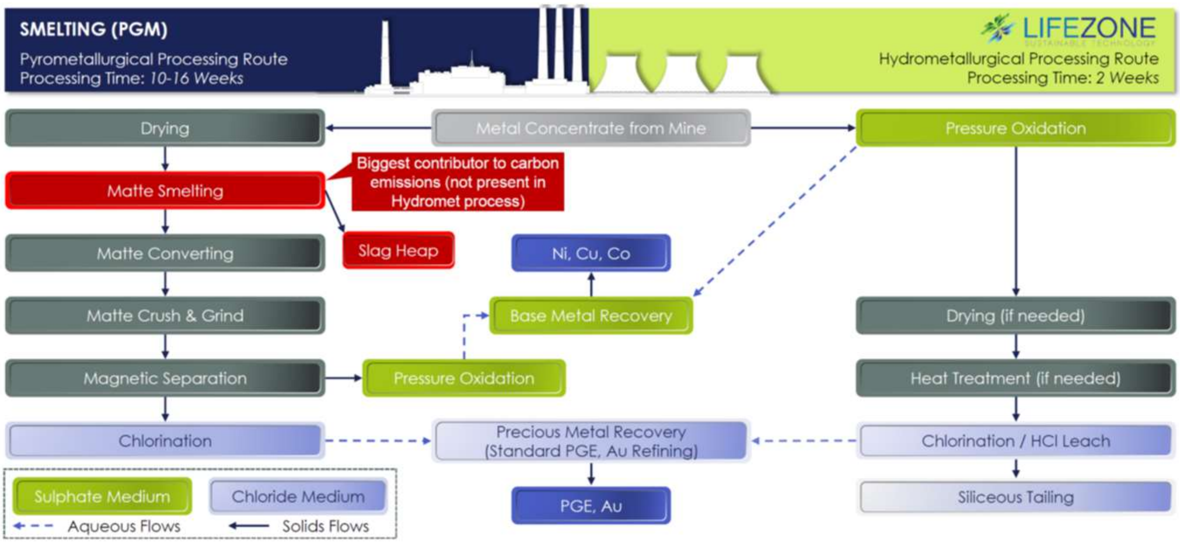
Patented process comprising four basic sequential steps, all of which are well proven and commonly used in the metallurgical industry and provide high recoveries of base and precious metals:

1. **Aqueous pressure oxidation** in an acidic sulphate medium to dissolve the sulphides and remove the base metals while minimising dissolution of the precious metals, producing copper, nickel and cobalt products;
2. **Heat treatment** of the pressure oxidation residue as required, to condition the mineral phases, rendering the material amenable for subsequent leaching;
3. **Atmospheric leaching** of the iron and other gangue components in chloride media;
4. **Atmospheric leaching of the PGM and gold** in chloride medium in a similar manner as typically used in PGM refineries, with PGM and gold recovery to high-purity products

Separate leaching stages for the precious metals and base metals:

- keeps sulphate and chloride chemistries separate
- small autoclave and tanks – fast leach kinetics
- optimizes selection of materials of construction
- fast production of metals and low lock-up of value

Lifezone Metals Hydromet – Comparison with Smelting



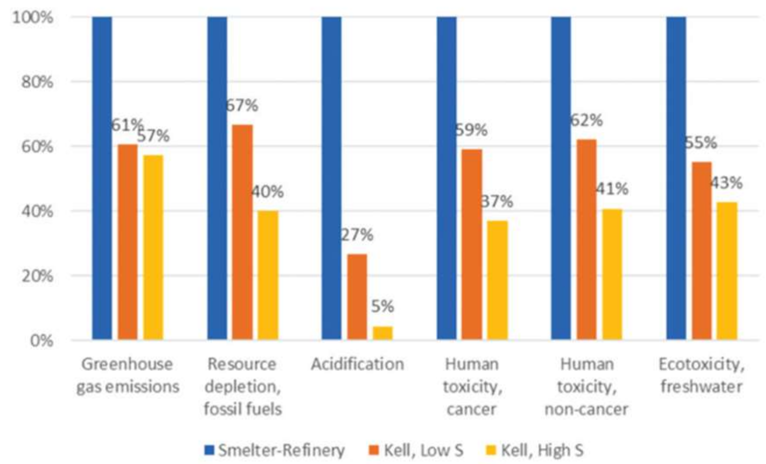
Lifezone Hydromet Testwork – Metals Extraction Results

PGM-Au-Ni-Cu-Co Concentrate		Overall Recoveries into Solution (%)						
Sample ID	Type	Pt	Pd	Rh	Au	Ni	Cu	Co
	Kabanga Nickel Scoping Test Results - Test 1	-	-	-	-	98.5	96.9	97.5
	Kabanga Nickel Scoping Test Results - Test 2	-	-	-	-	99.7	99.6	99.8
A	UG2	99	97	93	99	97	93	99
B	UG2	99	98	96	97	95	96	83
C	Merensky	99	98	97	99	99	99	98
D	UG2-Merensky	99	98	96	99	98	99	93
E	Platreef	99	98	96	99	99	99	99
F	Platreef	98	99	97	96	99	99	99
G	Polymetallic Great Lakes	97	99	95	96	99	99	99
H	Polymetallic Great Lakes	99	99	-	99	99	99	99
I	UG2-Merensky	99	98	90	99	97	96	95
J	Polymetallic North America	95	99	-	99	99	99	98
K	Great Dyke	99	98	95	98	98	98	96
L	Great Dyke	99	98	89	99	99	99	96
M	Polymetallic Australia	99	99	-	92	99	99	93
N	Platreef	98	99	-	97	99	99	99
O	Platreef	97	93	93	94	99	99	98
P	Platreef	99	98	94	97	99	99	98
Q	Ni-Cu-Co Sulphide	-	-	-	-	98	99	99
	Mean	**98**	**98**	**94**	**97**	**98**	**98**	**96**

Au-Ag-Cu-Co-Zn-Pb-Sb Concentrate		Overall Recoveries into Solution (%)						
Sample ID	Type	Au	Ag	Zn	Pb	Cu	Co	Sb
1	High-grade carbonaceous polymetallic ore	91	95	99	95	98	-	-
2	Refractory gold concentrate	96	-	-	-	98	97	-
3	Refractory gold polymetallic concentrate	98	97	99	97	99	-	95
4	Double refractory Cu-Au concentrate	98	98	-	-	99	-	-
5	Refractory gold concentrate	98	98	-	-	-	-	-
	Mean	**96**	**97**	**100**	**96**	**99**	**97**	**95**

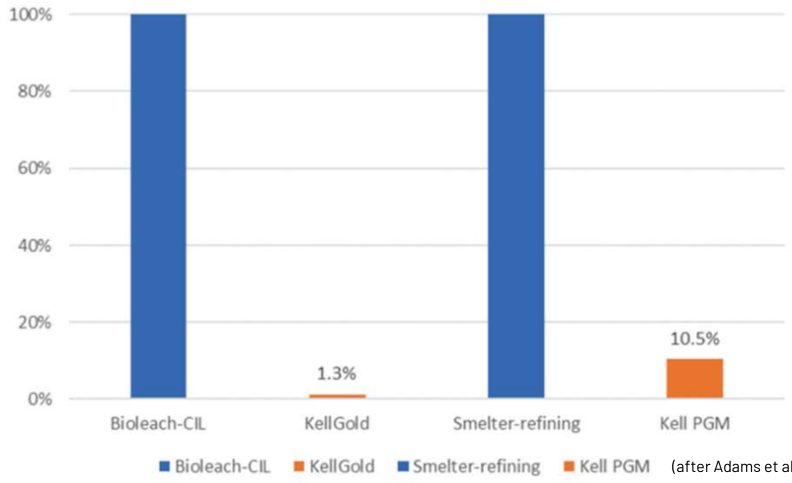
Liddell, K.S., Adams, M.D., Smith, L.A., and Muller, B 2019. Kell hydrometallurgical extraction of precious and base metals from flotation concentrates – Piloting, engineering, and implementation advances. Journal of the Southern African Institute of Mining and Metallurgy.

Comparison of Environmental Profiles



(after Smith, Adams, and Liddell, 2019)

Comparison of Working Capital Value Lockup (In-process Metal Inventory)



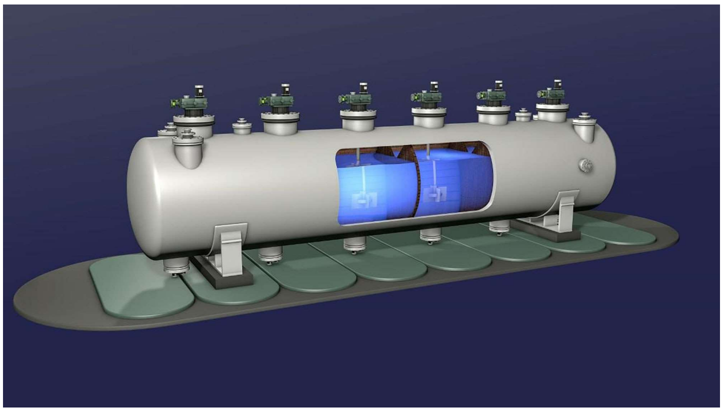
(after Adams et al 2019)

Outlook

Chloride-Based Leaching Systems

Outlook for Chloride-Based Leaching Systems

- Several chloride-based leaching systems have been tested in recent years at batch or pilot scale
- Lifezone Metals technology is at DFS or Detail Design stage for several commercial-scale applications
- Implementation of bulk chloride-based leaching systems at commercial scale is likely to take place in the next few years



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