The Atlas Materials Process for Nickel and Cobalt Recovery from Saprolite Ores – a Case Study in Disruptive Circularity

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How do we process saprolites currently?

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Saprolite Versus Limonite

There are 2 main types of laterite ore:

1. Limonite which is high in iron; treated by hydrometallurgy
2. **Saprolite** which is high in magnesia treated by reduction and smelting

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Idealized Nickel Laterite Ore-body

Depth in metres	Surface	Ni	Fe	Mg	Extractive Procedure
0-1	Overburden	<0.8			
1-5.5	Limonite	0.8 to 1.5	40 to 50	0.5 to 5	Hydrometallurgy **Limonitic ores**: High in FeO
5.5-7	Transition Zone	1.6 to 1.0	25 to 40	5 to 15	
7-10	Saprolite	1.8 to 3	10 to 25	15 to 35	Pyrometallurgy **Saprolite ores:** High MgO
>10	Unaltered Bedrock	0.5	5	35 to 45	

Approximate Analysis (wt%): Ni, Fe, Mg

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Fe-Ni Smelting

1. Ore Drying(from 30% down to 15-20%H_2O)
2. Reduction of NiO to Ni, Fe_2O_3 to FeO and some Fe(≈ 850 – 1000 ^oC)
3. Electric furnace smelting to form FeNi and slag
4. **FeNi is desulphurized and dephosphorized**

Requires 1500 to 1600 ^oC; **Energy Intensive**

All laterite processes involve huge amounts of material. For each tonne of nickel produced, 30 to 100 tonnes of slag will form at about 1600 ^oC

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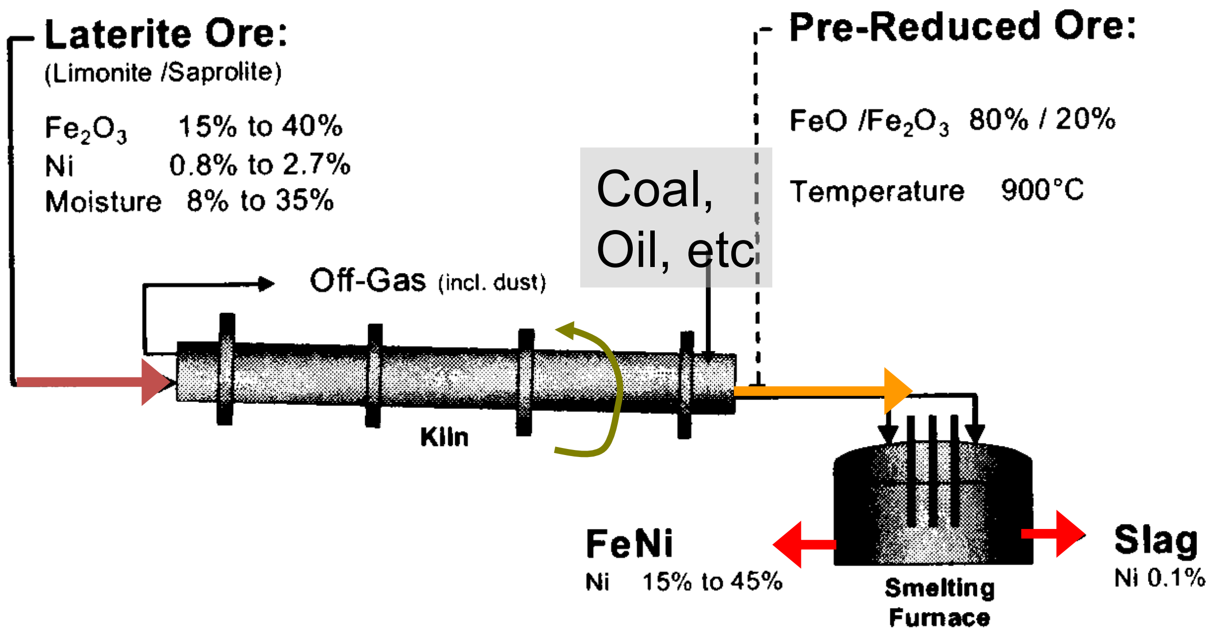
Typical Laterite Reduction Smelting Process



Ore is dried to 15 to 20% moisture
(too dry means too much dust,
too wet and it gets too sticky)

Slag at 1600 ºC contains most of the energy input
Ni = 0.1 to 0.2 %

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Cerro-Matoso Rotary Reduction Kilns (Columbia)

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Barro Alto Ferro Nickel Project
(Brazil, Anglo American Owned)

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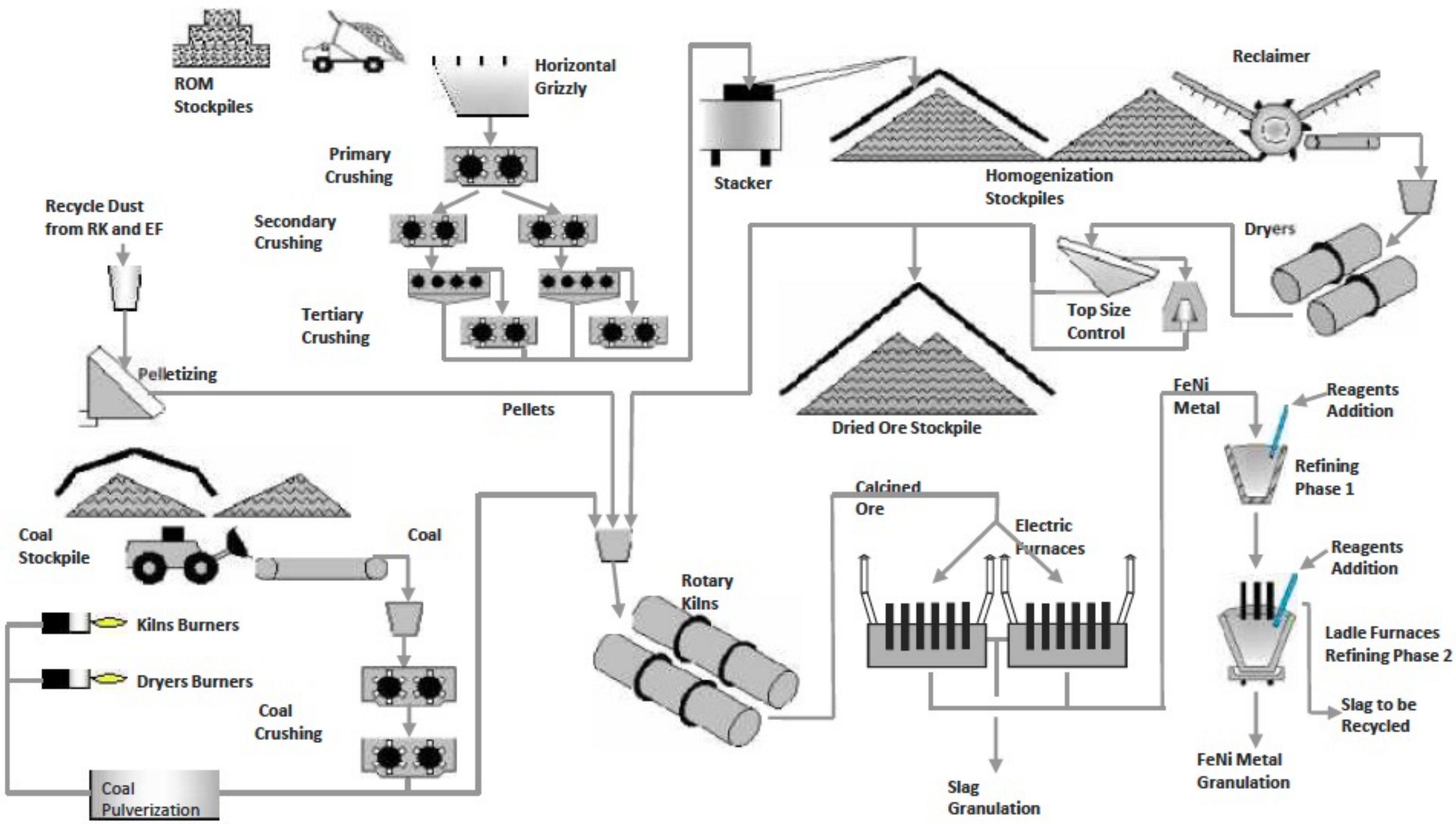
Barro Alto Process Flow Diagram



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Saprolite Processing Summary

- The Fe-Ni process makes high quality Fe-Ni alloy for stainless steel manufacture
- High yield of Ni (+90-95%) and some Fe as product
- Generally no recovery of Mg, Si and other elements
- Co is part of the Fe-Ni alloy or is lost in slag
- ~50 tonnes of slag per tonne of recovered nickel
- Very high CO_2 footprint due to extensive use of carbon-based fuels for drying and reduction and often for electricity generation
- Does not normally provide Ni-Co for the EV battery supply chain
- But………some facilities converting to nickel matte as an alternate products followed by separate Ni/Co recovery for battery salt manufacture
- Overall high energy use

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How might we process saprolites differently using the principles of circular hydrometallurgy?

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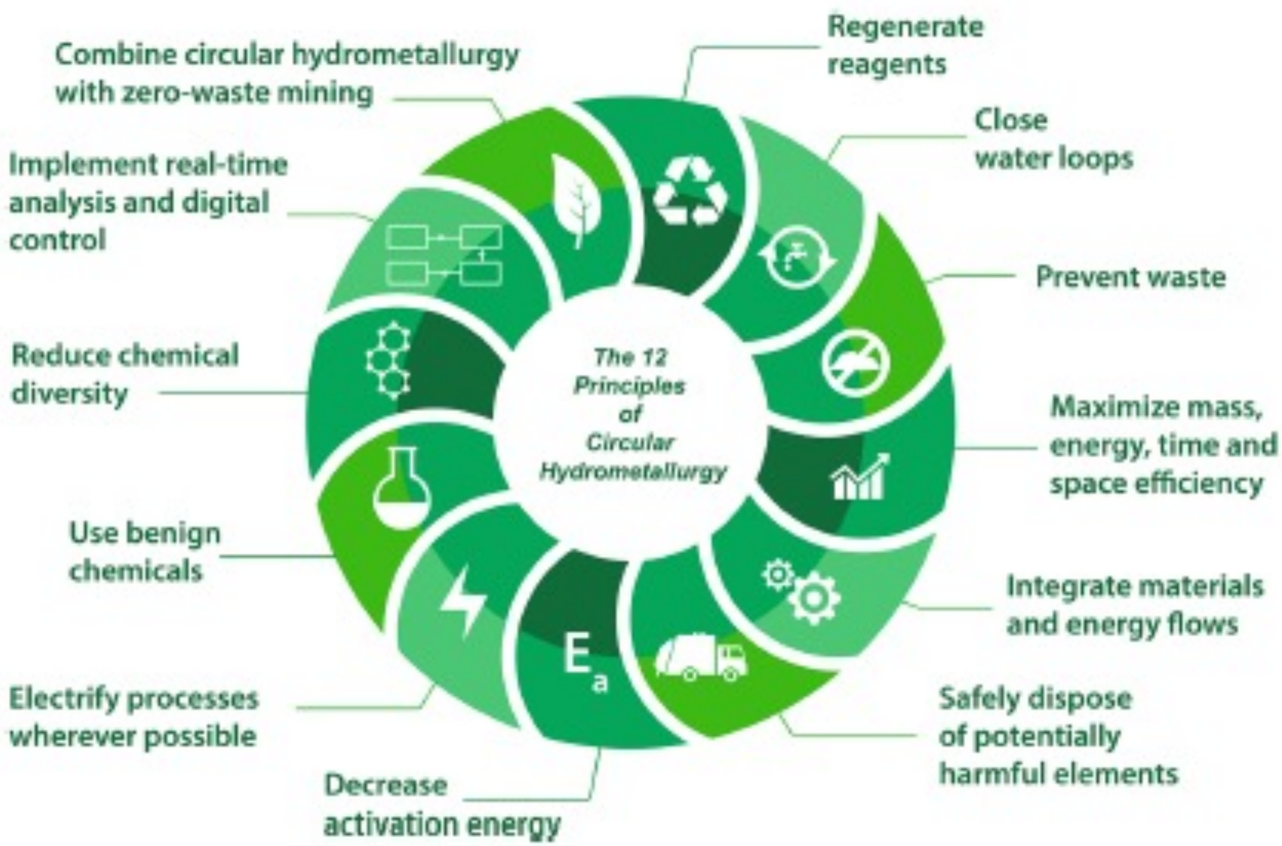
The 12 Principles of Circular Hydrometallurgy (Binnemans and Jones, J. Sust. Met. 2022)



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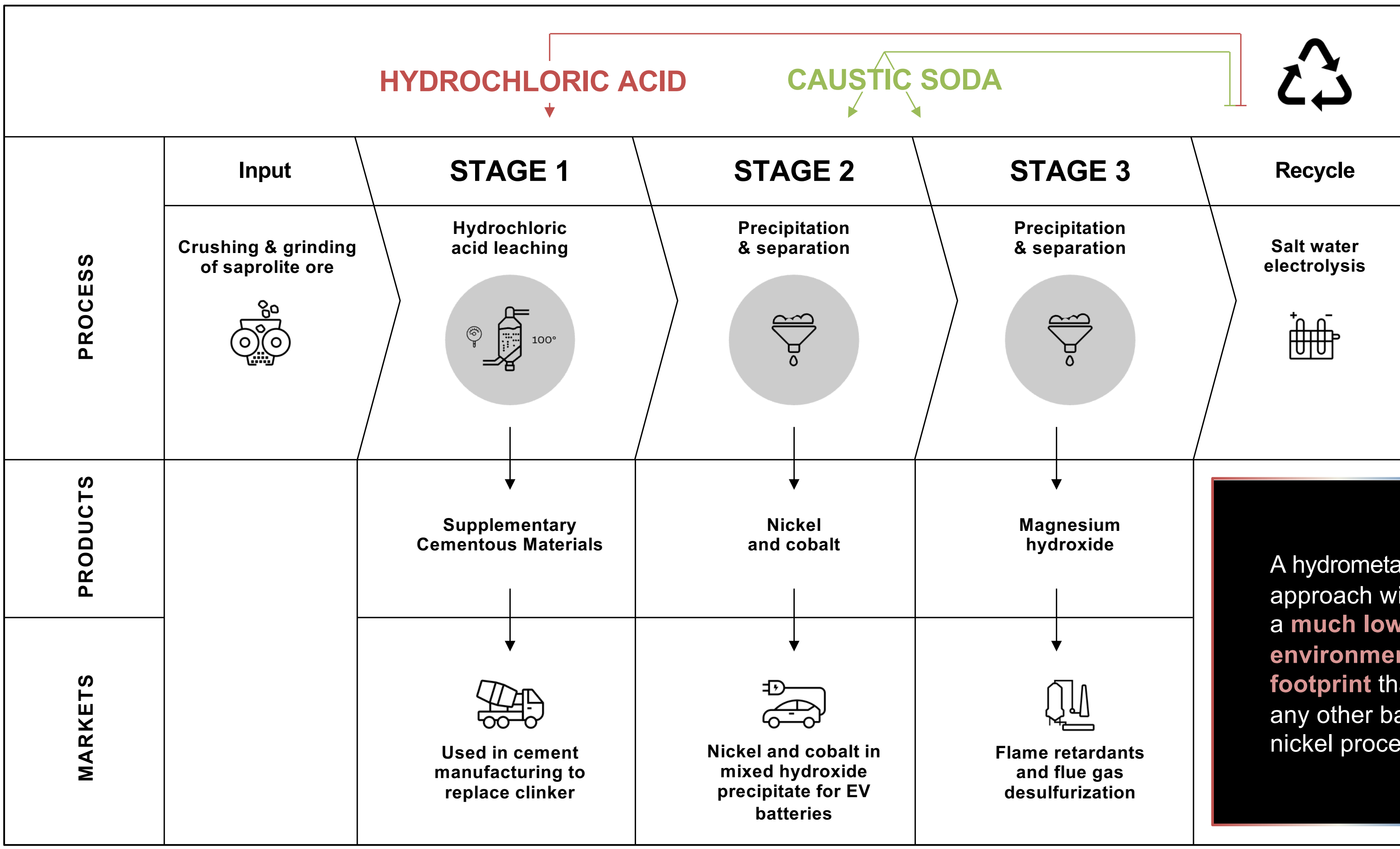


A hydrometallurgical approach with a **much lower environmental footprint** than any other battery nickel processes.

Process chart

Evolution of the Atlas Materials Process

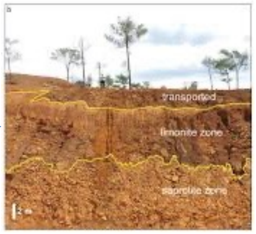
2021 – Batch Testing to Develop Base Process

2022 – Proof of Principle Pilot Plant

2023/24 – Further Batch Testing for Improvement + Demonstration Pilot Plant(s)

Silica for cement

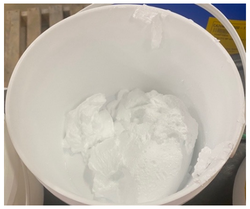
Electricity



Nickel Saprolite

MHP for EV Battery Supply

Mg hydroxide



How Atlas compares

	HYDROMETALLURGICAL ROUTES		PYROMETALLURGICAL ROUTES	
	Atlas Process	**High Pressure Acid Leach (HPAL)**	**Laterite Matte**	**Flash Smelting**
CO_2 Emissions (scope 1 and 2) t CO_2 per t Ni equivalent	0.1t[1,2]	19t	44t[3]	13t[4]
Gaseous Emissions	None	CO_2	CO_2	CO_2 and fugitive SO_2
Solid Emissions per t contained Ni	None	39t residue (dry basis)	50t slag	50 – 200t flotation tails 5.5 smelter slag

1. Determined by a third party engineering company as a part of a study commissioned by Atlas. Reference: Perrenin, A, & Benotmane, A. (2023). Atlas Saprolite Process Comparison: Final Report (No. H370678-0000-100-066-0001), Hatch.
2. Production in USA using renewable energy. The stated value is for the primary production step within Atlas. Operational control, from mined ore to MHP.
3. Production in SE Asia. The stated value is for the primary production step, from mined ore to MHP or matte.
4. Production I Australia. The stated value is the average of BHP's Australian operations, and includes all emissions within BHP's operational control. Reference: BHP ESG Standards and Databook 2022. (2022). BHP.

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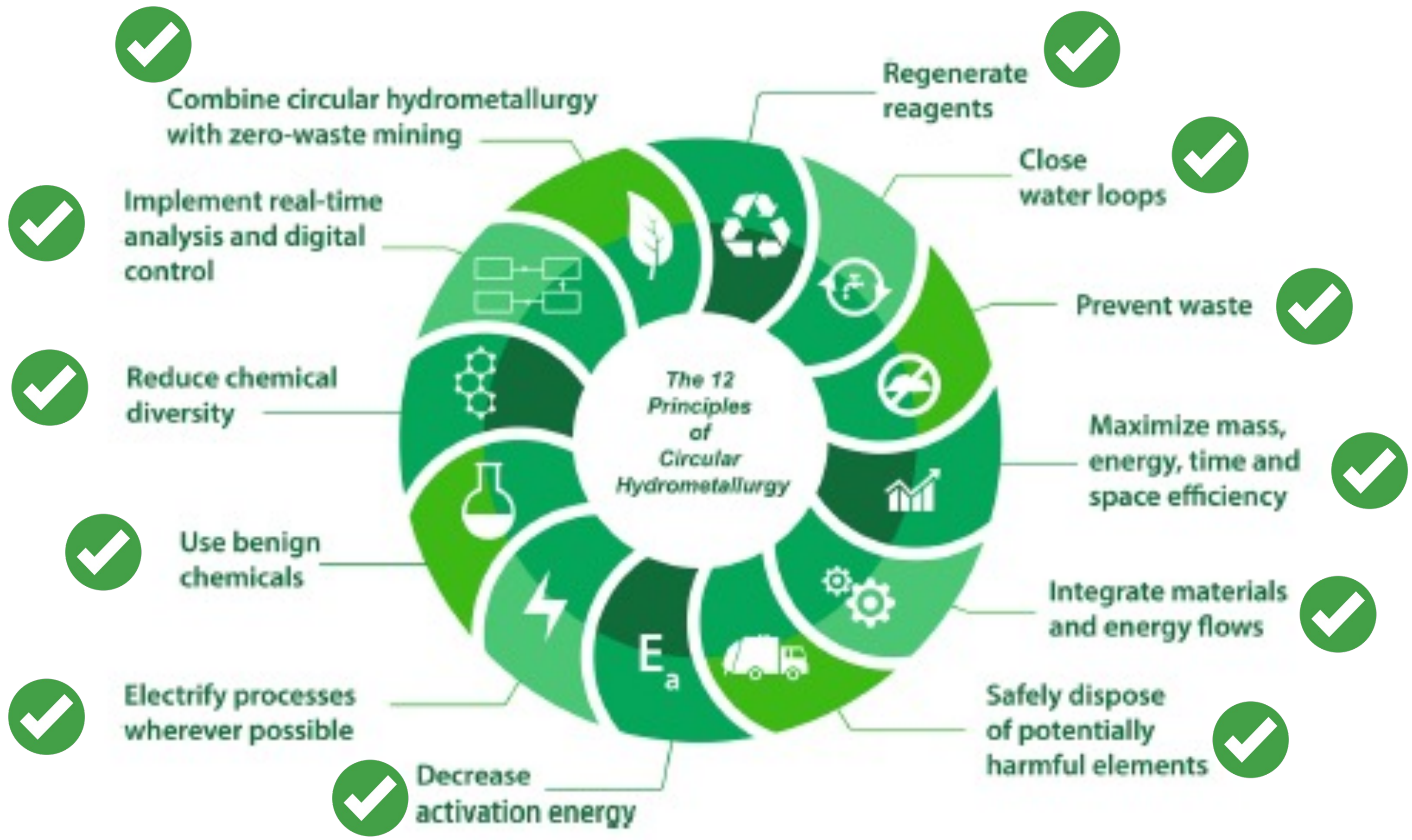
The 12 Principles of Circular Hydrometallurgy (Binnemans and Jones, J. Sust. Met. 2022)



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The Atlas Process in Detail

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Original Concept (Simplified)

- Hydrochloric Acid Extraction of Magnesium from Magnesium Silicate Materials
- Precipitation of Magnesium Hydroxide Using Caustic
- Regeneration of Hydrochloric Acid and Caustic Using Renewable Electricity
  - $Mg_2SiO_4 + 4HCl(a) = 2MgCl_2 + SiO_2 + 2H_2O$ (1)
  - $2MgCl_2 + 4NaOH = 2Mg(OH)_2 + 4NaCl$ (2)
  - $4NaCl + 4H_2O = 4NaOH + 2Cl_2(g) + 2H_2(g)$ (3)
  - $2Cl_2(g) + 2H_2(g) = 4HCl(g)$ (4)
  - $4HCl(g) = 4HCl(aq)$ (5)

What about other elements?

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Other Elements

- Fe, Al, Cr, Ni, Co, Zn, Mn etc are extracted by the strong HCl leach

- Original approach
  - Caustic to remove Fe/Al/Cr as hydroxide
  - Caustic to precipitate Ni/Co + (Zn/Cu) as MHP
  - Caustic/Bleach to precipitate Mn as MnO_2
  - Caustic to precipitate $Mg(OH)_2$

- Fe/Al/Cr precipitate very fine and difficult to separate from solution.

- New idea – use olivine as a base for precipitation

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Ferrous Oxidation and Olivine Precipitation

$$2FeCl_2 + NaOCl + 2HCl = 2FeCl_3 + NaCl + H_2O \quad (6)$$

$$4FeCl_3 + 3Mg_2SiO_4 + 2H_2O = 4FeO.OH + 6MgCl_2 + 3SiO_2 \quad (7)$$

$$4AlCl_3 + 3Mg_2SiO_4 + 2H_2O = 4AlO.OH + 6MgCl_2 + 3SiO_2 \quad (8)$$

Nickel Precipitation

$$NiCl_2 + 2NaOH = Ni(OH)_2 + 2NaCl \quad (9)$$

Manganese Oxidation and Precipitation

$$MnCl_2 + NaOCl + 2NaOH = MnO_2 + 3NaCl + H_2O \quad (10)$$

Magnesium Hydroxide Precipitation

$$MgCl_2 + 2NaOH = Mg(OH)_2 + 2NaCl \quad (11)$$

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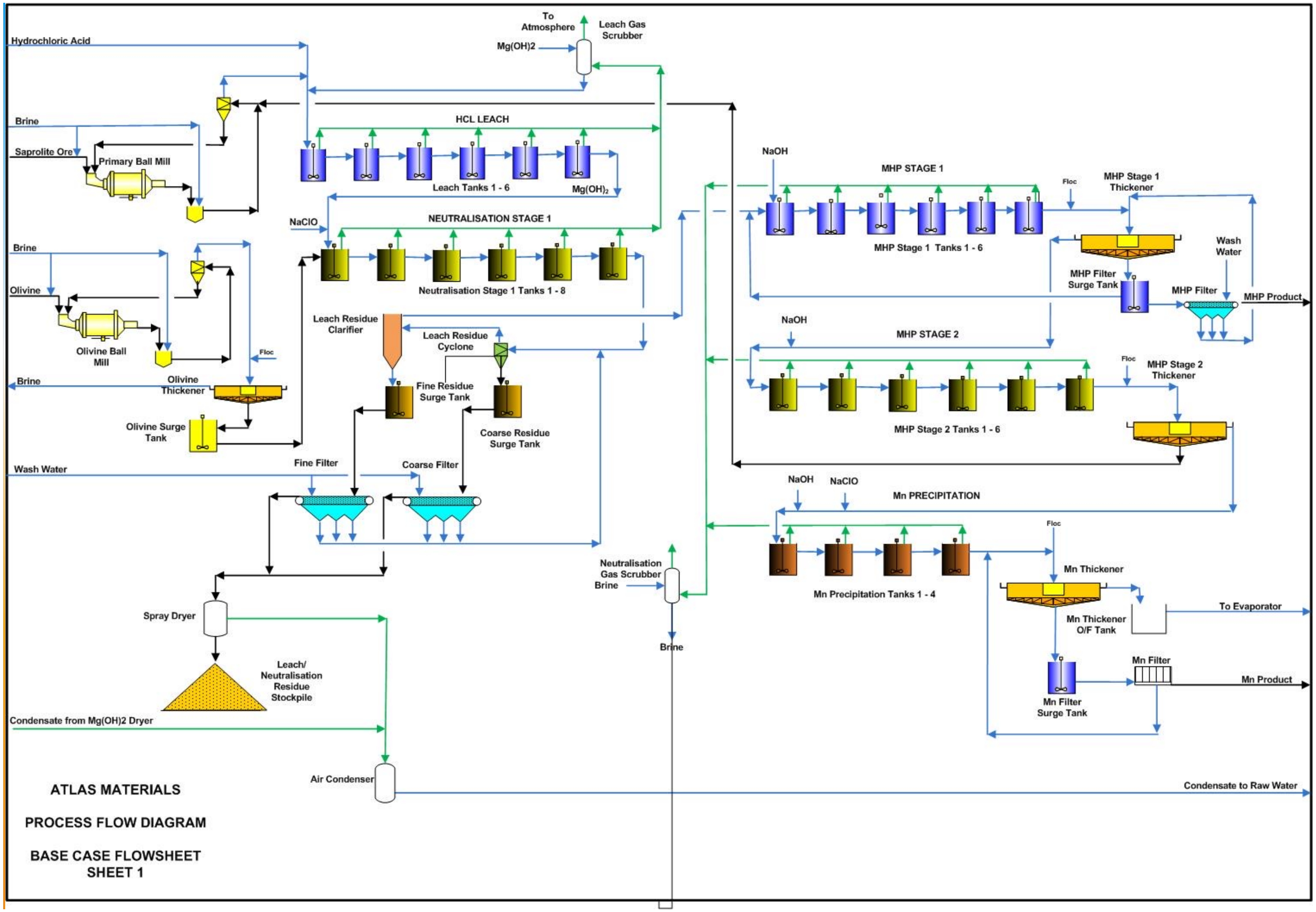
Hydrochloric Acid
To Atmosphere
Mg(OH)2
Leach Gas Scrubber
Brine
Saprolite Ore
Primary Ball Mill
HCL LEACH
Leach Tanks 1 - 6
Mg(OH)₂
NaClO
NEUTRALISATION STAGE 1
Neutralisation Stage 1 Tanks 1 - 8
Brine
Olivine
Olivine Ball Mill
Floc
Brine
Olivine Thickener
Olivine Surge Tank
Leach Residue Clarifier
Leach Residue Cyclone
Fine Residue Surge Tank
Coarse Residue Surge Tank
Wash Water
Fine Filter
Coarse Filter
Spray Dryer
Leach/ Neutralisation Residue Stockpile
Condensate from Mg(OH)2 Dryer
Air Condenser
Neutralisation Gas Scrubber
Brine
Brine
NaOH
MHP STAGE 1
Floc
MHP Stage 1 Thickener
MHP Stage 1 Tanks 1 - 6
Wash Water
MHP Filter Surge Tank
MHP Filter
MHP Product
NaOH
MHP STAGE 2
Floc
MHP Stage 2 Thickener
MHP Stage 2 Tanks 1 - 6
NaOH
NaClO
Mn PRECIPITATION
Floc
Mn Thickener
Mn Precipitation Tanks 1 - 4
Mn Thickener O/F Tank
To Evaporator
Mn Filter
Mn Product
Mn Filter Surge Tank
Condensate to Raw Water
ATLAS MATERIALS
PROCESS FLOW DIAGRAM
BASE CASE FLOWSHEET
SHEET 1

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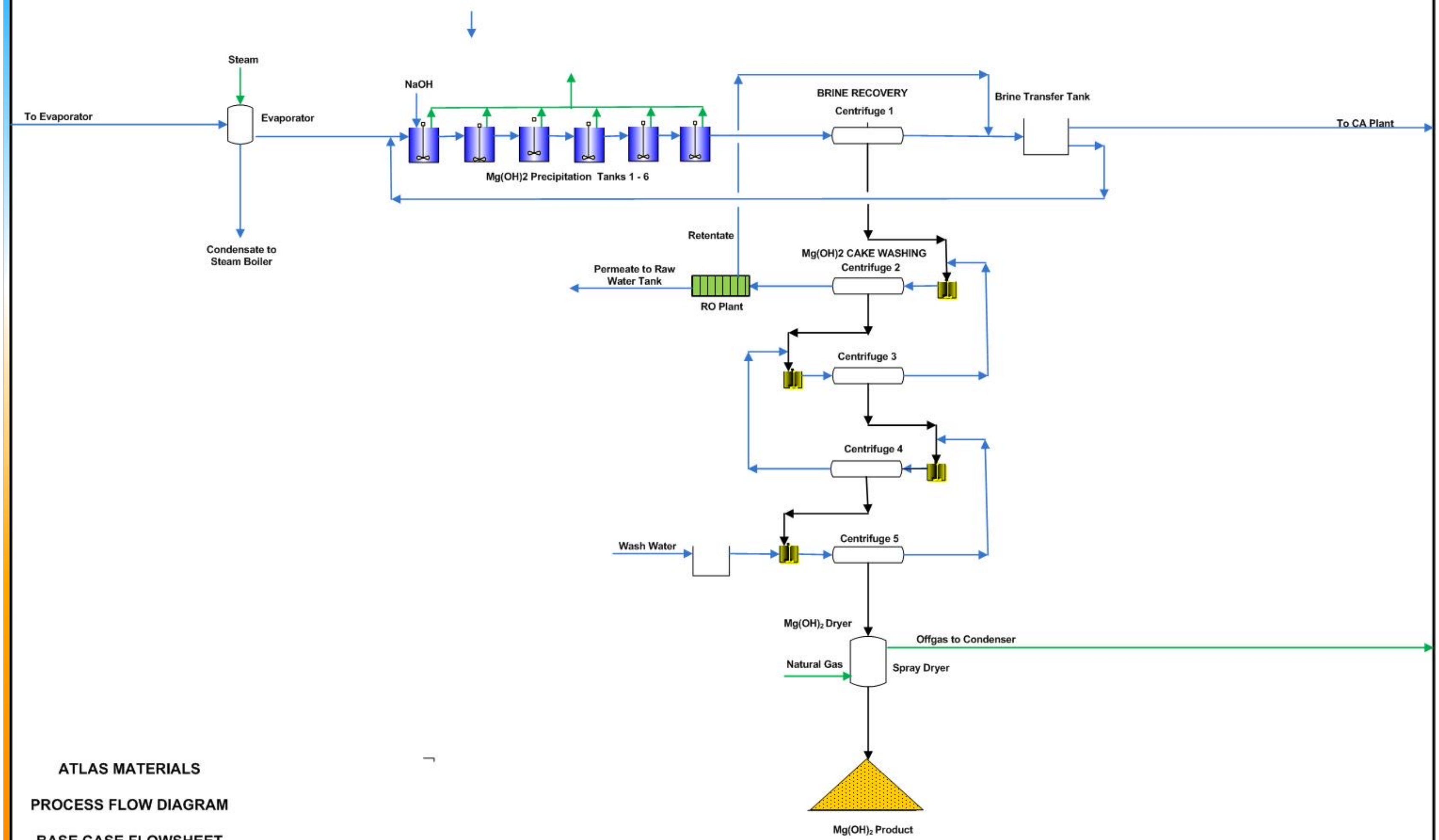

ATLAS MATERIALS

PROCESS FLOW DIAGRAM

BASE CASE FLOWSHEET
SHEET 2

Demonstration Pilot Plant Results

- Pilot plant 1 (PP1) - acid leach and olivine neutralization process
- Pilot plant 2 (PP2) - precipitation of MHP and scavenger MHP
- Pilot plant 3 (PP3) manganese removal + $Mg(OH)_2$ pptn
- Saprolite ore from Societé des Mines de la Tontouta (SMT) and Société Minière Georges Montagnat (SMGM). Olivine from Sibelco

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Element	Analysis (%)	
	Saprolite (SMT)	Olivine
Ni	1.75	0.28
Co	0.07	0.01
Fe	8.67	5.27
Mg	16.1	28.7
Al	0.18	0.33
Cr	0.42	0.25
Mn	0.16	0.08
Ca	0.04	0.20
Si	21.7	19.4
LOI	14.7	2.19

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Pilot Plant 1 (Leach and Olivine Neutralization)

Continuous testing for 5 days (24/7)

The ground ore (34% solids) added at a rate of 2 kg/h (dry basis) to a series of four stirred leaching reactors that overflowed in a cascade fashion.

32% HCl was added to the first reactor at dosage of 640 kg HCl/t ore (dry basis).

Temperature of 102 °C.

The leach residence time was 4 hours.

Five olivine neutralization reactors. The olivine slurry (60% solids) addition rate of 0.28 g/g ore feed.

Bleach (11% NaOCl) added to the third reactor to oxidize ferrous ion.

ORP control

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Pilot Plant 1 (Leach and Olivine Neutralization)

Leach Extractions (Average): 98% Ni, 95% Fe, 95% Mg, 46% Al, 14% Cr, 97% Mn, 84% Ca were achieved with residual free acid at 1-6 g/L HCl.

Final solution after olivine neutralization: 5.1 g/L Ni, 0.197 g/L Co, 7.9 mg/L Fe, 60.4 g/L Mg, 0.9 mg/L Al, <0.3 mg/L Cr, 0.37 g/L Mn, 0.34 g/L Ca, 23 mg/L Si.

High extraction and effective purification

Residue analysis: 30.9% Si (66.1% SiO_2), 11.4% Fe, 4.24% Mg, 0.31% Al, 0.51% Cr, 0.13% Ni, 0.01% Co.

This material is under evaluation as a fly ash replacement for cement making.

The solutions were recovered by filtration and wash water addition.

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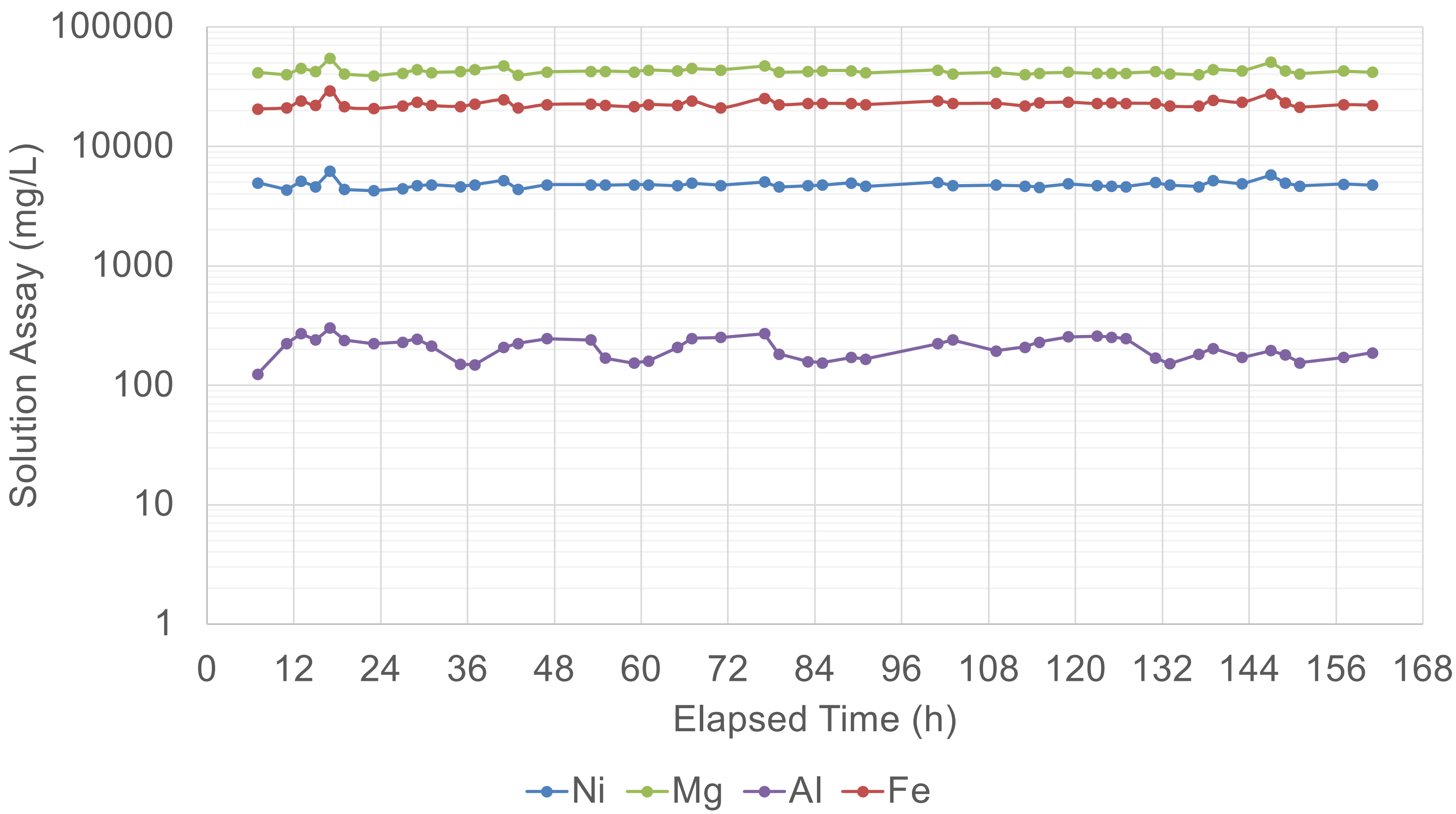
Pilot Plant 1 (Leach and Olivine Neutralization)

Leach Solution Analysis



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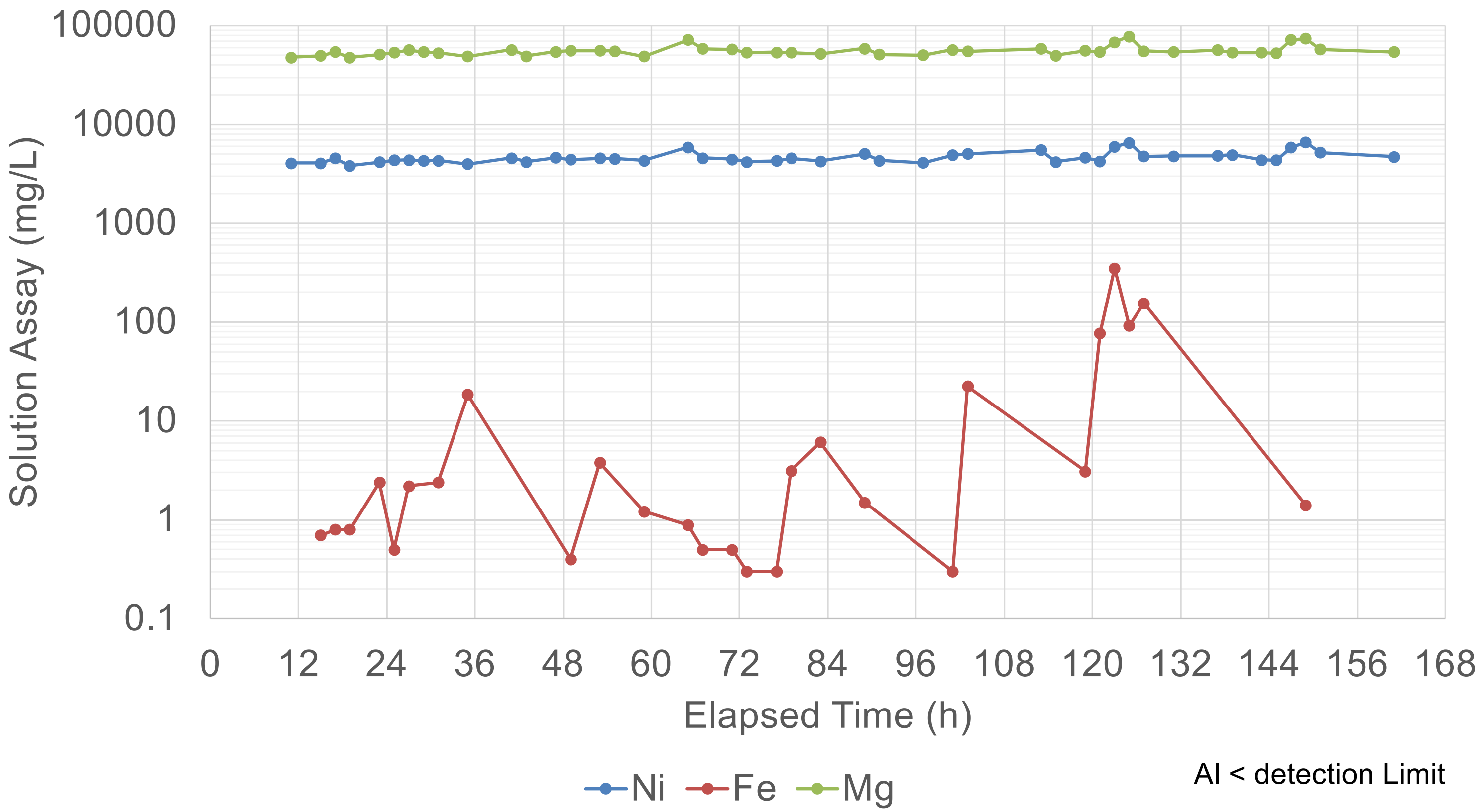
Pilot Plant 1 (Leach and Olivine Neutralization)

Solution assays from Olivine Neutralization Reactor 5



Al < detection Limit

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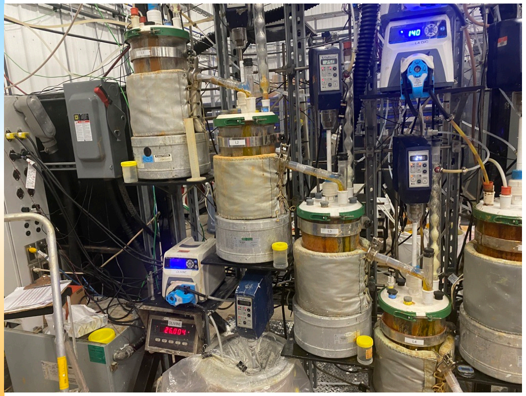
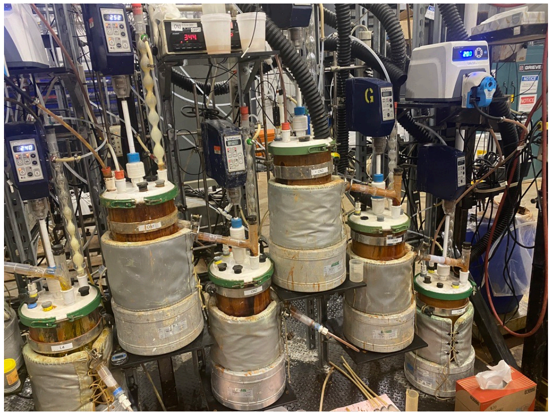
Pilot Plant 1 (Leach and Olivine Neutralization)



Leaching
(4 reactors)



Olivine Neutralization +
Bleach Addition
(5 reactors)

Filter Press and Washing

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Pilot Plant 2 (MHP Stages 1 and 2)

10% NaOH in brine solution to precipitate Ni/Co at 75 °C with three reactors for each of MHP and SHP.

The circuit was gradually fine-tuned to precipitate approximately 90% of the Ni in the incoming solution.

The average grade of the MHP product was 45% Ni, 1.79% Co, 4.5% Mg, 0.01% Fe, 0.02% Al, <0.01% Cr and 0.3% Si.

The SHP circuit was quickly tuned to achieve <10 mg/L Ni in solution.

The SHP solids averaged 29.1% Ni, 0.64% Co, 15.3% Mg, 0.02% Fe, 0.01% Al, 4.97% Mn, <0.01% Cr, 0.06% Si.

This material recycles to the leach circuit discharge to ensure high recovery of nickel and cobalt to the primary MHP product.

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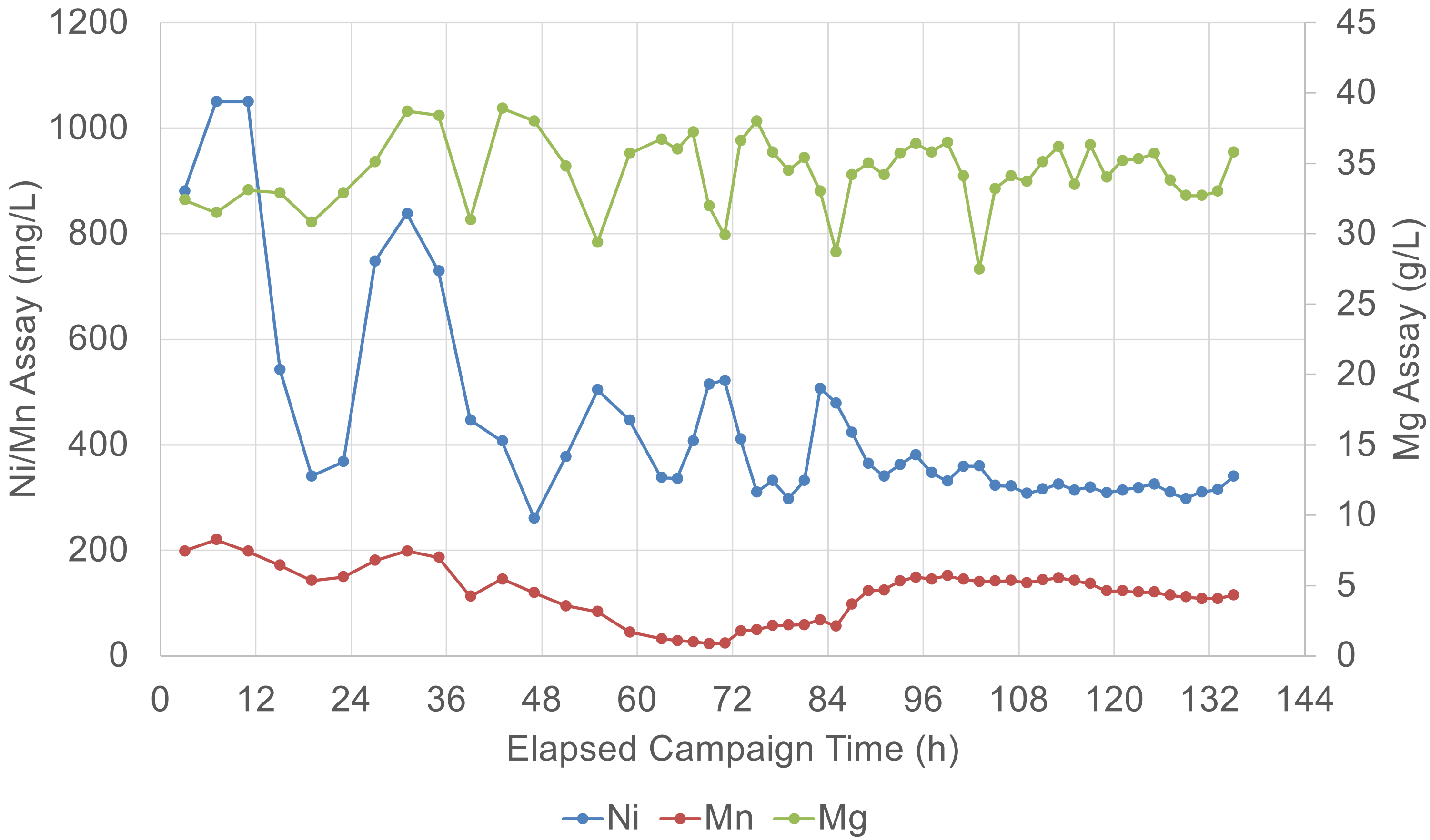
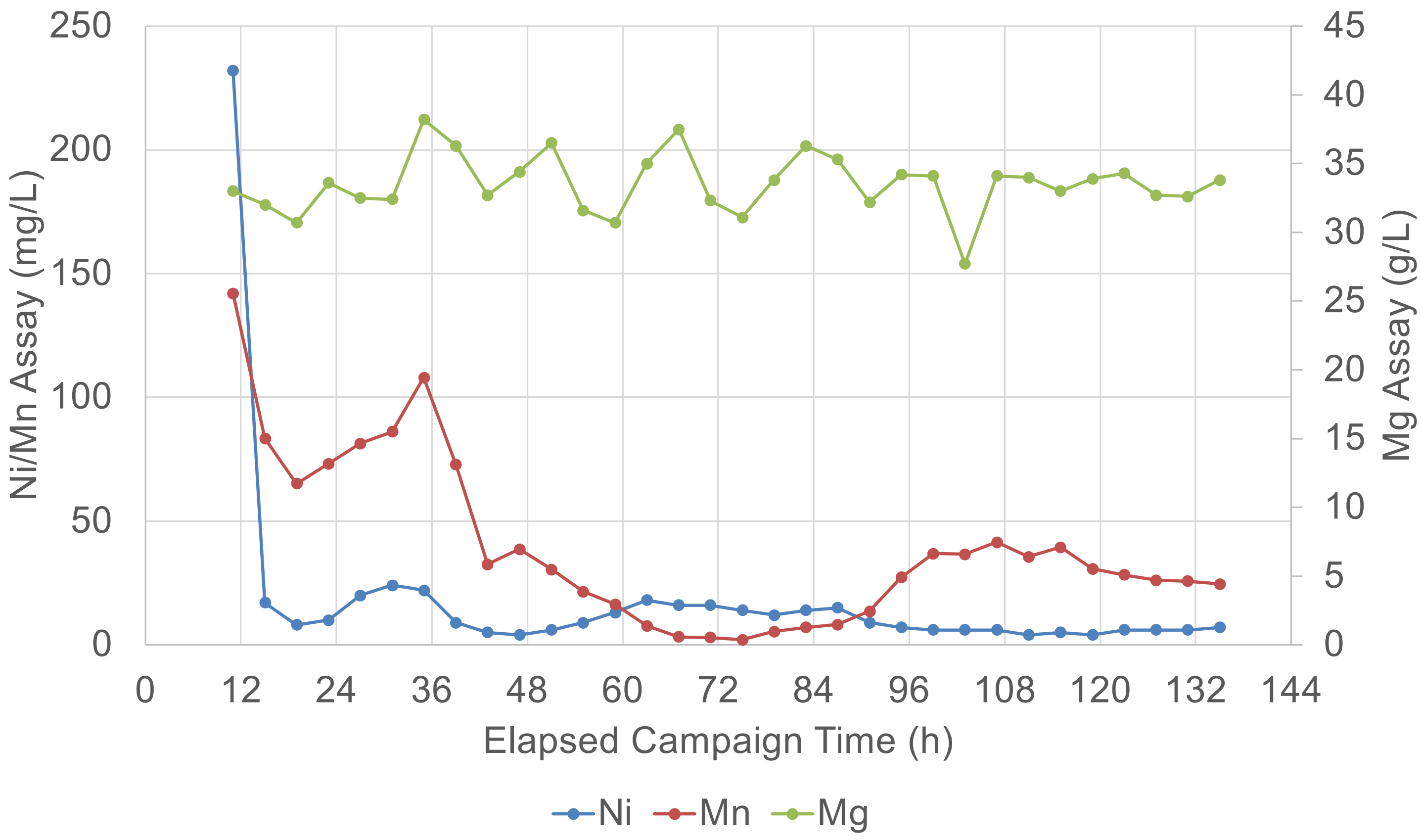
Pilot Plant 2 (MHP Stages 1 and 2)

Solution assays from MHP 1 Precipitation



Pilot Plant 2 (MHP Stages 1 and 2)

Solution assays from MHP 2 Precipitation



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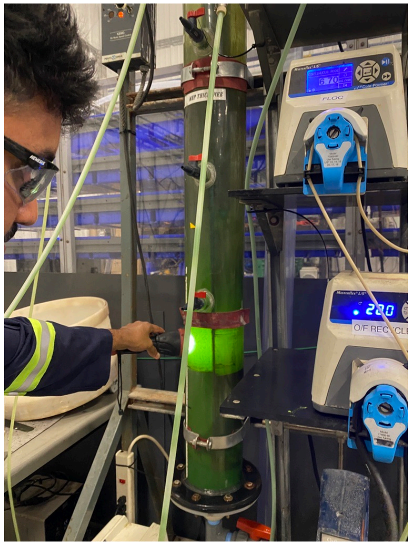
Pilot Plant 2
(MHP Stages 1 and 2)

MHP Stages 1 and 2
4 + 3 reactors



MHP 1 Thickener

MHP Filter Cake

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Pilot Plant 3 (Mn Removal and $Mg(OH)_2$ Production)

Mn Removal: three stages at 75 °C with addition of 11% NaOCl to oxidize manganese followed by 10% NaOH solution in brine to pH ~6 to precipitate manganese.

Manganese and nickel levels less than 1 mg/L in the final solution.

The average solid assays were 22.4% Mn, 11.7% Mg.

The magnesium hydroxide precipitation by direct addition of 50% NaOH.

three stages of precipitation were used with caustic addition to stage 1 and all reactors maintained at 80 °C.

Magnesium was reduced from ~ 30 g/L to ~1 g/L toward the end of the pilot plant.

Calcium was not precipitated.

The residual magnesium and calcium would be removed in the chlor-alkali pre-treatment circuit (conventional technology).

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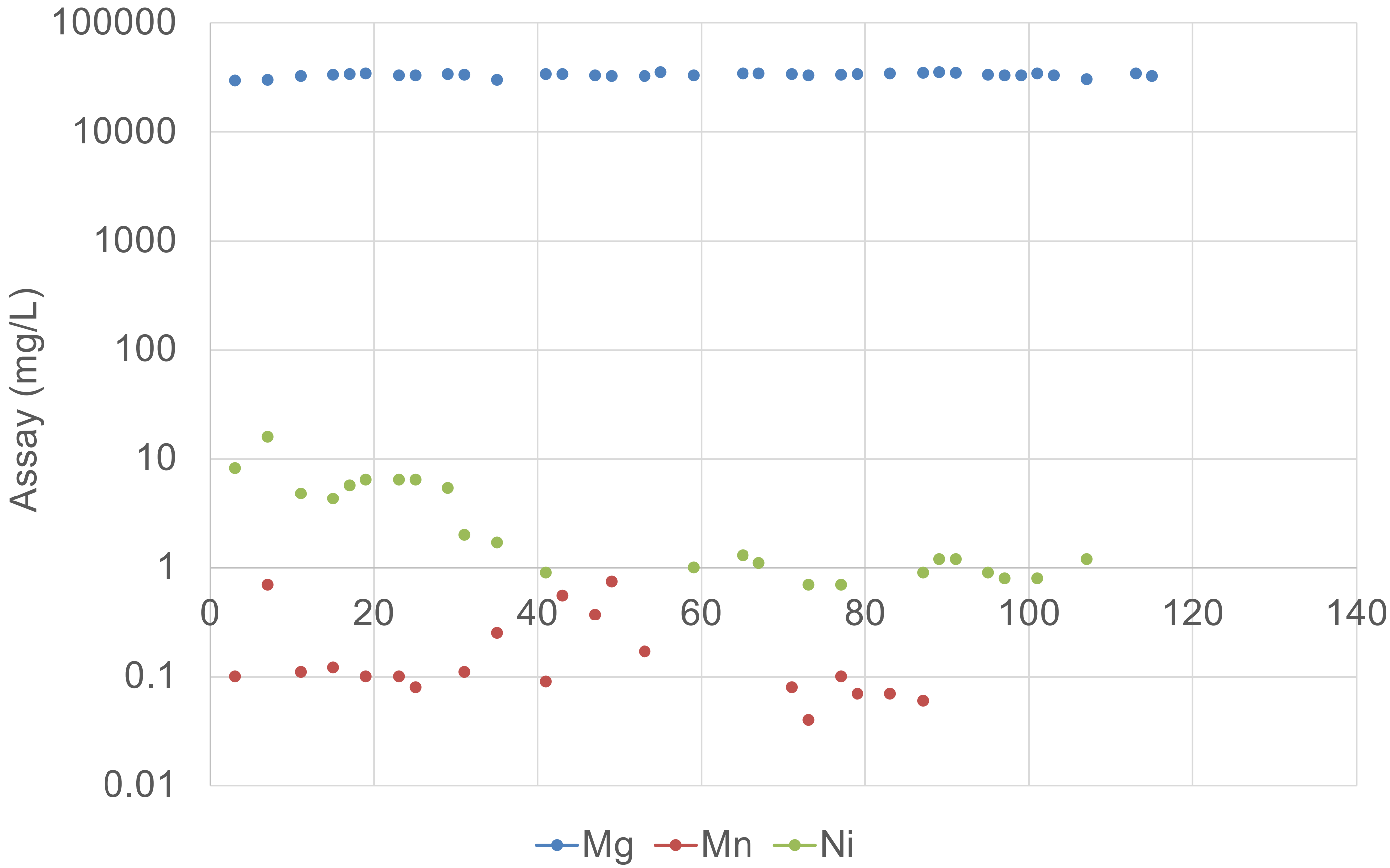
Pilot Plant 3 (Mn Removal and $Mg(OH)_2$ Production)

Solution assays for the Mn precipitation process



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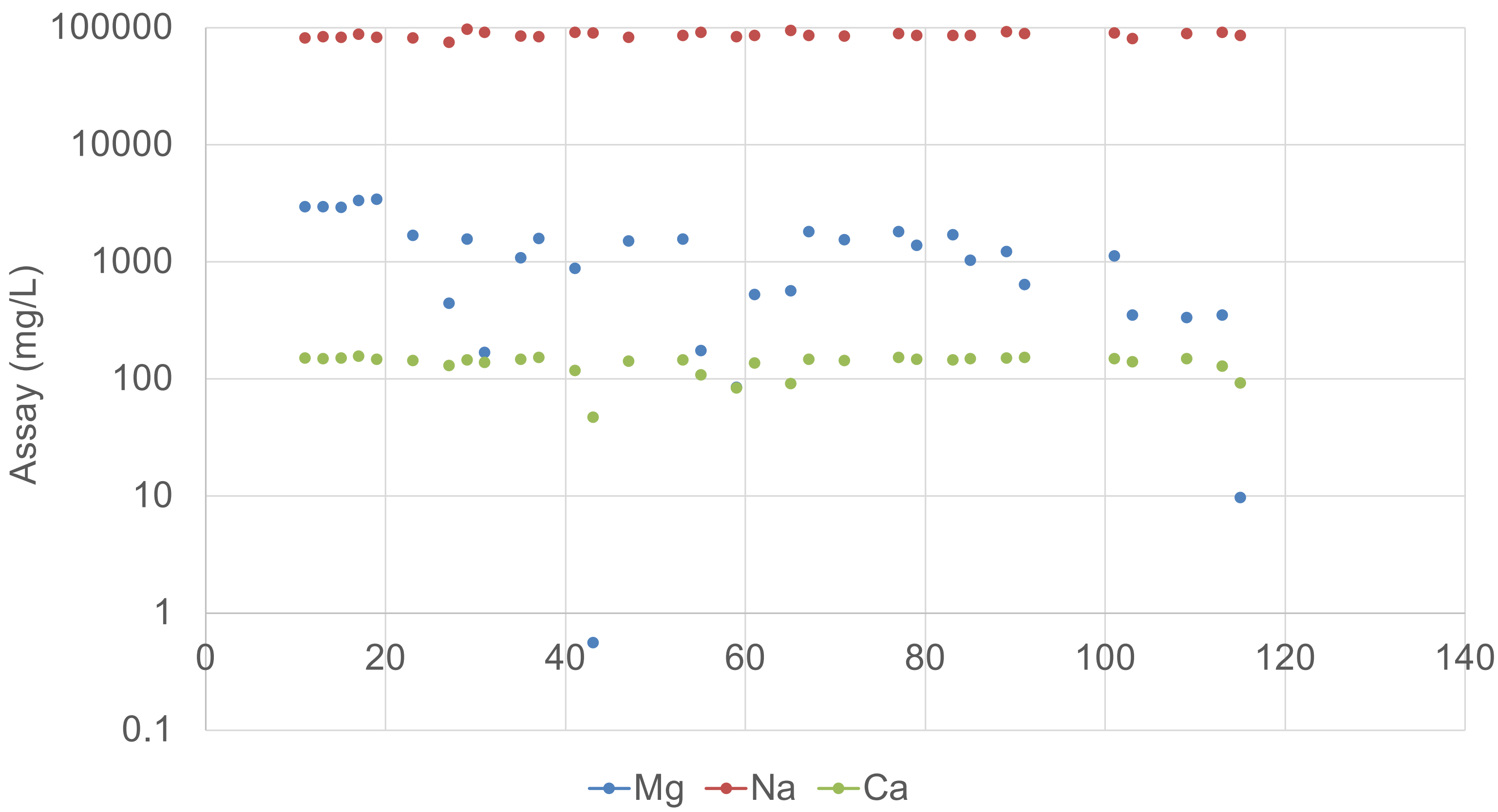
Pilot Plant 3 (Mn Removal and $Mg(OH)_2$ Production)

Solution assays for the Mg precipitation process



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Pilot Plant 3 (Mn Removal and $Mg(OH)_2$ Production)

Magnesium Hydroxide Pptn (3 reactors)

Magnesium Hydroxide Slurry

Magnesium Hydroxide Centrifugation

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$Mg(OH)_2$ Product Analysis

Element	Analysis (% or g/t)
Ni	11 g/t
Co	<3 g/t
Fe	11 g/t
Mg	39.9 %
Al	4 g/t
Cr	<1 g/t
Mn	<0.4 g/t
Ca	388 g/t
Cl	357 g/t

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Progress Toward Commercialization

- Completed FEL 3 Studies for Electra – 100,000 tpa (dry) of nickel saprolite ore treatment plant
- + 28,000 tpa of olivine
- ~1,800 tpa of Ni in MHP
- ~70,000 tpa of siliceous material as SCM
- Makes ~25,000 tpa of Mg in products

- Business plan integrates costs (Capex and Opex) and revenues.

- Now the 12 principles of circularity are meeting Warren Buffett's rules of investing.

- Warren Buffett once said, "The first rule of an investment is don't lose money. And the second rule of an investment is don't forget the first rule. And that's all the rules there are." (www.marketwatch.com, accessed September 3, 2024)

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Conclusions and Next Steps

The Atlas Materials base case process has advanced significantly from the early proof of concept pilot plant.

The challenges that were apparent in the 2022 proof of principle pilot plant have been addressed through further bench work and are now being confirmed in the demonstration pilot plant at SGS Canada.

The development of the olivine neutralization process for iron/aluminum and chromium removal has been a breakthrough in development.

The leach solution purification can be achieved in one step to produce solutions with < 1 mg/L Fe, Al, Cr content => +45% Ni in MHP

In addition, the production of high purity magnesium hydroxide has been demonstrated in the pilot plant program

Crystallize economic feasibility to bring circularity to life!

Contact

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Thank you

Simplified NEM Original Hydromet Process (HCl + NaOH Basis with NaCl to C-A Plant)