LOW CARBON NICKEL AND COBALT PRODUCTION FROM NICKEL SAPROLITE ORES USING THE ATLAS MATERIALS PROCESS

By

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ABSTRACT

The demand for nickel and cobalt battery materials for transport is poised to increase exponentially. The natural resource to meet this demand is the large global resource base of saprolitic nickel ores.

Atlas Materials have developed an innovative hydrometallurgical extraction process using hydrochloric acid leaching. The application of hot hydrochloric acid produces a residue that can be used as a supplemental cementitious material. The nickel, cobalt and magnesium containing leachate can be processed through a series of precipitation steps including (1) iron and aluminum removal, (2) mixed hydroxide precipitation for recovery of nickel and cobalt, (3) manganese rejection by oxidation/precipitation and finally (4) magnesium hydroxide precipitation. The precipitating agent is sodium hydroxide. At the end of the circuit, the spent electrolyte is essentially concentrated sodium chloride solution. This solution may be used as an input to a chlor-alkali facility to produce chlorine and hydrogen and caustic (NaOH). The chlorine and hydrogen are burned to make hydrochloric acid for recycle to leach. In this way, the chemical consumption of the process is low (mainly makeup NaCl). The process requires supply or renewable electricity for salt splitting. The overall process produces low carbon nickel and cobalt to supply the EV battery sector.

The bench and pilot plant results for this process will be presented.

Keywords: Nickel, cobalt, MHP, saprolite, low carbon, chlor-alkali

INTRODUCTION

The decarbonization of the global energy and transport sectors is accelerating. The decarbonization of the transport sector is in full swing with accelerating uptake of electric and hydrogen powered vehicles. Power generation from wind and solar sources is increasing, and storage of electricity to stabilize grid power dependent on renewables is advancing.

The demand for raw materials to enable many of the emerging transformative technologies is increasing rapidly. Specifically, lithium, nickel, cobalt, and manganese are required for lithium-ion battery manufacture, and rare earth elements are needed for electric vehicle traction motors and wind turbines. Further, when recovering critical raw materials for future use, the extraction industry must focus on zero waste production. All by-products/co-products should be considered for use rather than storing in liquid or solid waste impoundments. Lastly, and perhaps most importantly, recovery of critical materials should be performed to produce a "low carbon" product, i.e. the best outcome would be to provide for future supply while creating pathways to remove carbon from the atmosphere.

Atlas Materials was founded to develop innovative technologies for critical materials supply, with by-products to enable an overall low carbon outcome. Technology development has focused on treatment of nickel saprolite ores. Nickel saprolite ores contain magnesium silicate or magnesium hydroxy silicate minerals in addition to nickel and cobalt, iron. and other minor elements. The vision of Atlas is to process these materials for nickel and cobalt battery material supply, silica products carrying iron and aluminum for material substitution in the cement industry, and magnesium hydroxide. Magnesium hydroxide from the NEM process may be used in the future to sequester atmospheric carbon dioxide using a variety of processes.

The NEM general process flowsheet is shown below (Figure 1). The process involves a series of mineral processing and hydrometallurgical steps.

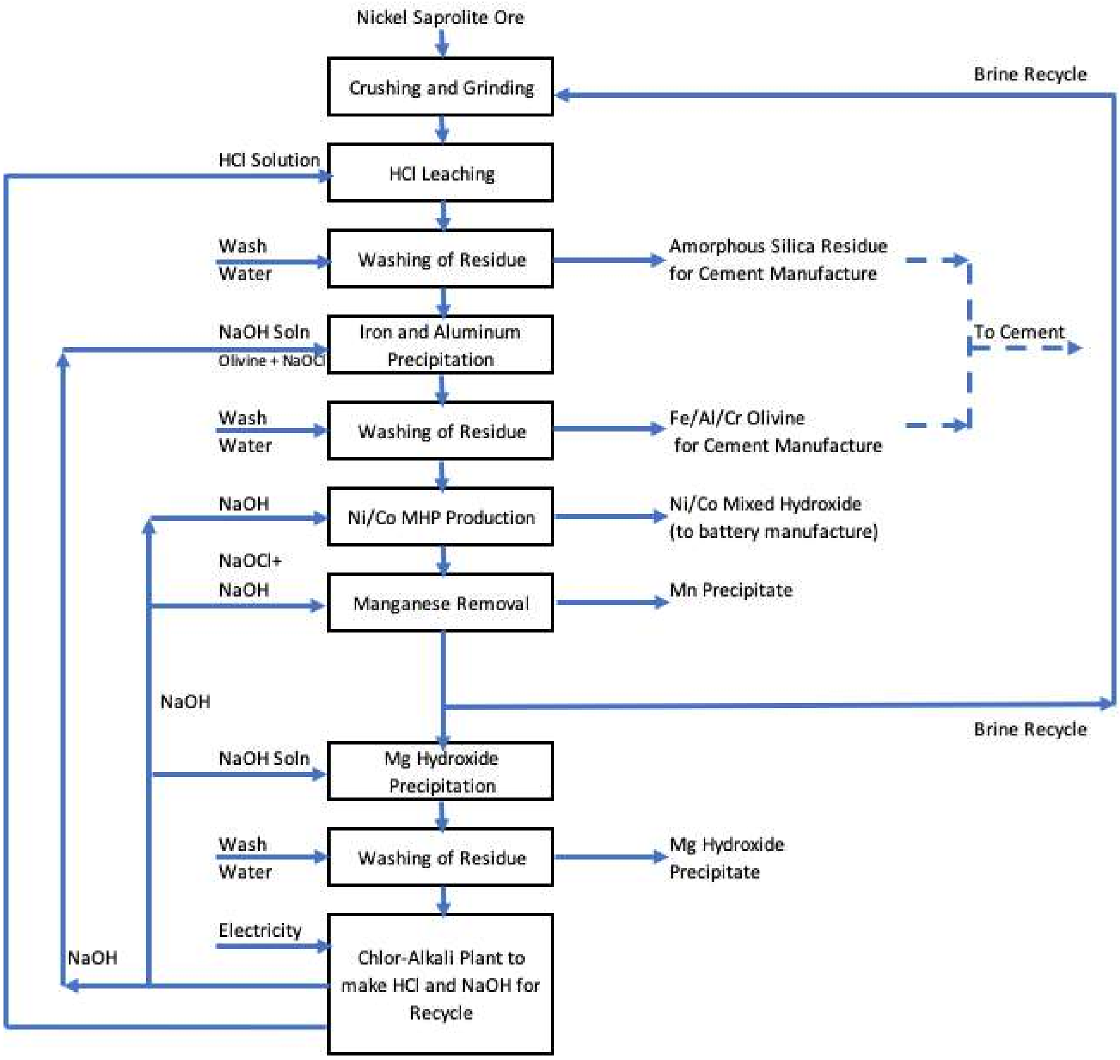

Figure 1: The ATLAS Simplified Process Flowsheet

Crushing and Grinding

Crushing and grinding in recycle brine solution containing a variety of chloride salts including magnesium chloride and sodium chloride. The purpose of recycle of a brine solution is to avoid the addition of water which can only be managed by evaporation which is expensive in terms of energy.

HCl Leaching

This process uses HCl at high strength (typically 36% HCl by weight in water; a typical product from an HCl production facility attached to a chlor-alkali plant). The raw materials contain a variety of silicate minerals including magnesium, iron, nickel, cobalt, and minor impurity elements.

The chemistry is therefore comprised of the following major reactions:
$Mg_2SiO_4 + 4HCl = 2MgCl_2 + SiO_2 + 2H_2O$
$Ni_2SiO_4 + 4HCl = 2NiCl_2 + SiO_2 + 2H_2O$
$Fe_2SiO_4 + 4HCl = 2FeCl_2 + SiO_2 + 2H_2O$

Note other minerals present such as iron oxides or aluminum oxides may also react with HCl to form additional salts in solution.

$FeO(OH) + 3HCl = FeCl_3 + 2H_2O$
$AlO(OH) + 3HCl = AlCl_3 + 2H_2O$

Note that natural minerals are not pure compounds. The minerals may contain a variety of elements (eg. Mg, Ni, Co, Fe in one silicate mineral) and may be hydrated or weathered. Suitable feed materials include;

A. Nickel saprolite ores
B. Olivine ores
C. Asbestos ores and tailings

The leaching temperature is close to the boiling point to ensure rapid extraction. Acid addition ranges from 500 to 1000 kg HCl per dry tonne of solid feed and will vary with the chemical composition of the feed. The brine recycle solution in the flowsheet below ensures that acid leaching is performed with a high total salt content as, for example, NaCl or $MgCl_2$ or both.

The leaching time can vary from 1 hour to 8 hours. The leaching can in principle be arranged as a single stage or two stage process. Single stage means that the acid and ore are added together and allowed to react at temperature to completion, while two stage means that fresh ore is contacted with partly reacted solution to maximize the consumption of acid (low terminal acidity) and in the second stage, the partly leached ore (from the first stage) is contacted with high acid to maximize extraction of Mg/Ni/Co/Fe, etc. The two-stage process requires an additional solid/liquid separation step to ensure countercurrent movement of solids and liquids.

The products of HCl leaching are a weakly acidic solution containing various chloride salts and a silica rich residue recovered as a solid product. This residue is washed to remove salts and excess acid with fresh water and then may be directed to cement manufacture where the silica is used as a replacement for other materials (thus lowering the carbon intensity of cement manufacture) and a strengthener to improve the yield strength of concrete (high performance concrete).

Iron and Aluminum Removal

The iron and aluminum content in the solution may be precipitated in two ways. First, sodium hydroxide may be added to form a mix of oxide and hydroxide solids. Secondly, the pH may be raised by addition of ground olivine mineral to precipitate the metal impurities.

The NaOH solution may be added as a 50% solution and may be diluted with recycle brine solution for process convenience and enhanced pH control (it may be difficult to control pH by adding such a strong base). The NaOH neutralizes the excess acid and precipitates Fe/Al and other trivalent cations if present, according to the following reactions:

$HCl + NaOH = NaCl + H_2O$
$FeCl_3 + 3NaOH = FeO(OH) + 3NaCl + H_2O$
$2FeCl_3 + 6NaOH = Fe_2O_3 + 6NaCl + 3H_2O$

$AlCl_3 + 3NaOH = AlO(OH) + 3NaCl + H_2O$
$2AlCl_3 + 6NaOH = Al_2O_3 + 6NaCl + 3H_2O$
$CrCl_3 + 3NaOH = CrO(OH) + 3NaCl + H_2O$
$2CrCl_3 + 6NaOH = Cr_2O_3 + 6NaCl + 3H_2O$

The pH adjustment is conducted with stoichiometric amounts of NaOH. Over addition will result in precipitation of Ni/Co (undesirable) so careful control of addition must be maintained. The temperature will be 75 °C to the boiling point. Seed (precipitate) may be recycled to ensure growth of suitable sized particles for enhanced solid/liquid separation. Precipitation time can be 1 to 8 hours. NaOH is added progressively through the precipitation tanks (continuous) so as to enhance precipitation of coarser/separable precipitates. The product undergoes S/L separation and washing.

The iron and aluminum removal process with sodium hydroxide addition may be performed in a two stage arrangement to allow recycle of the second stage precipitate to the leaching section to minimize any nickel and cobalt loss and to maximize the removal of iron, aluminum and chromium. Further, if the iron is partly in the ferrous state, a small amount of sodium hypochlorite may be added to oxidize residual ferrous to the ferric state.

The addition of olivine may be used as an alternative to addition of NaOH. Olivine with a high magnesium content is desired.

$4HCl + Mg_2SiO_4 = 2MgCl_2 + 2H_2O$
$4FeCl_3 + 3Mg_2SiO_4 + 2H_2O = 4FeO(OH) + 6MgCl_2 + 3SiO_2$
$4AlCl_3 + 3Mg_2SiO_4 + 2H_2O = 4AlO(OH) + 6MgCl_2 + 3SiO_2$
$4CrCl_3 + 3Mg_2SiO_4 + 2H_2O = 4CrO(OH) + 6MgCl_2 + 3SiO_2$

Olivine often contains nickel, cobalt and iron. These elements will also react with the acidic leachate. Nickel and cobalt extraction from olivine is beneficial to the production of nickel and cobalt as hydroxide. Iron may extract as ferrous iron from olivine and with the addition of sodium hypochlorite may be oxidized to precipitate. Finally, the extraction of magnesium will lead to a higher overall production of magnesium hydroxide.

Nickel and Cobalt Recovery

Nickel and cobalt are present in solution as $NiCl_2$ and $CoCl_2$ salts. The recovery of Ni/Co can be done in many ways including the direct precipitation of mixed hydroxide precipitate. This can be done directly from the solution coming from the iron precipitation.

$NiCl_2 + 2NaOH = Ni(OH)_2 + 2NaCl$
$CoCl_2 + 2NaOH = Co(OH)_2 + 2NaCl$

Other metals will also precipitate with the Ni/Co in minor amounts, such as Mn and Fe (remaining iron in solution). If an excess of sodium hydroxide is added, then magnesium will co-precipitate as magnesium hydroxide. The selectivity of MHP precipitation can be enhanced by using two stage MHP precipitation. The second stage precipitate is recovered and recycled to the first stage MHP precipitation process or to the discharge from the main leaching step (where acid is present to redissolve the Ni/Co and other metals from the second stage leach).

The mixed hydroxide precipitate is recovered by S/L separation and washing. A pressure filter is often used with a “squeeze” cycle to minimize the entrained moisture in the washed MHP cake prior to shipping.

The precipitation is carried out between 25- 90 °C and terminal pH is in the range of 5-8. Note that pH measurement is difficult in a strong salt solution, and sodium hydroxide addition may also be controlled by stoichiometry. The precipitation time is 1-8 hours. Seed recycling is used to maximize particle size and minimize contamination. The process (as in all steps) is conducted continuously.

Manganese Removal

Manganese is an undesirable impurity in magnesium hydroxide, and cannot be selectively precipitated as a hydroxide in the presence of magnesium hydroxide. Accordingly, oxidation and precipitation is used to remove manganese from solution.

$MnCl_2 + NaOCl + 2NaOH = MnO_2 + H_2O + 3NaCl$

The manganese dioxide precipitate is filtered and washed.

Magnesium hydroxide precipitation

The remaining magnesium in solution is precipitated by addition of NaOH to form $Mg(OH)_2$.

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

This can be done by adding NaOH to $MgCl_2$ solution or by reversing the order of addition. The goal is to provide a near complete removal of Mg as $Mg(OH)_2$ from solution, requiring a near stoichiometric addition of NaOH.

Chlor-Alkali plant

The final solution is NaCl and H_2O with some minor contaminants in solution. This solution is directed to a chlor-alkali plant for manufacture of NaOH, Cl_2, and H_2. This involves many steps. The Cl_2 and H_2 can be burned and water-scrubbed to form strong HCl solution for recycle to leaching.

The excess heat from combustion may be recovered as steam and used to evaporate excess water from solution.

EXPERIMENTAL RESULTS

Raw Materials for Leaching

The three types of raw materials used in this study were obtained from various sources. Table 1 shows the elemental composition of the raw materials tested. The asbestos tailing was obtained from a tailing deposit in Quebec. Olivine (used as a foundry sand material) was provided by Essix Resources under the trade name Incast75.

The nickel and cobalt content of the material increases from asbestos tailing to olivine to nickel saprolite samples. Iron levels are variable from ~5% for the olivine sample up to 18% for the saprolite. The magnesium content was highest for olivine at 29.79% and only 12.2% for nickel saprolite. The silicon content varied over a narrow range of 15.6 to 19.49% Si.

Table 1. Composition of Raw Materials for Extraction

Analysis(%)	Asbestos Tailing	Olivine	Nickel Saprolite #1	Nickel Saprolite #2
Ni	0.239	0.34	1.81	1.83
Co	0.011	0.011	0.052	0.02
Cu	0.0019	0.002	0.005	NA
Zn	0.0019	0.004	0.02	NA
Fe	7.51	5.13	18.0	8.39
Mg	22.2	29.79	12.2	17.4
Al	0.5	0.19	2.19	0.50
Cr	0.25	0.28	0.78	0.43
Mn	0.07	0.08	0.65	0.14
Ca	0.26	0.08	0.33	0.22
Si	16.5	19.49	15.6	18.1
Na	0.06	0.04	0.02	0.03
S	NA	NA	0.02	NA

The samples were either used as received or ground to finer size as required.

HCl Leaching Test Results

A series of HCl leaching tests was performed to assess the extraction of the key elements (Ni/Co/Mg/Fe/Al) and the quality of silica residue produced as a product.

The leach extractions were most sensitive to the acid addition reported as kg HCl/tonne of material. The basis is kg HCl on a 100% basis and per tonne of dry ore (Figure 2). The nickel extraction for the saprolite sample (Figure 2) approached 100% at ~750 kg HCl/t of ore. Iron and magnesium extractions were slightly lower. It was feasible to produce ≥75% SiO_2 content in the residue at the 750 kg HCl/t addition rate.

The olivine extraction results (Figure 3) showed very similar extractions of Ni/Mg/Fe, consistent with the uniform mineralogy of the olivine sample. The acid required to reach maximum extraction was nearly 1200 kg HCl/t ore due to the more basic character of the olivine. The SiO_2 grade of the leach residue exceeded 80%.

The results of the leaching of asbestos tailings (Figure 4) showed very high Ni/Mg/Fe extractions at +800 kg HCl/t. The SiO_2 grade again exceeded 80% in concert with high base metal extractions.

The batch leaching results showed that a variety of raw materials could be treated with suitable levels of HCl to maximal extraction of the key metals and production of a silica rich residue.

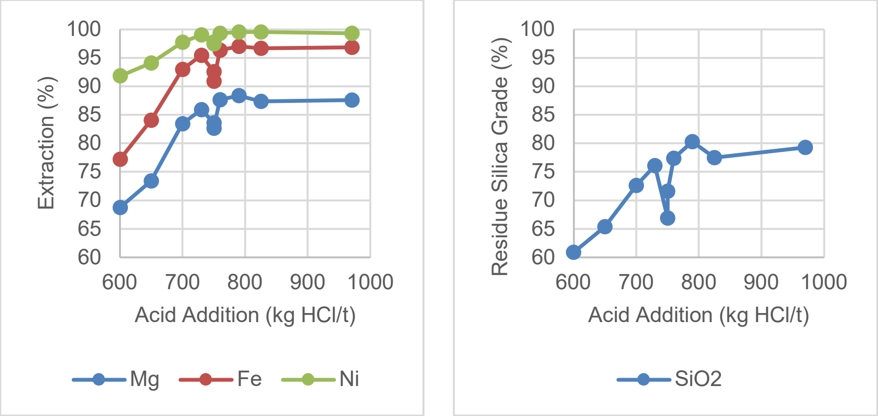

Figure 2. Batch leaching of saprolite #1. Typical conditions: Temperature 100 °C, 4 h, 87 g/L Mg (as $MgCl_2$)

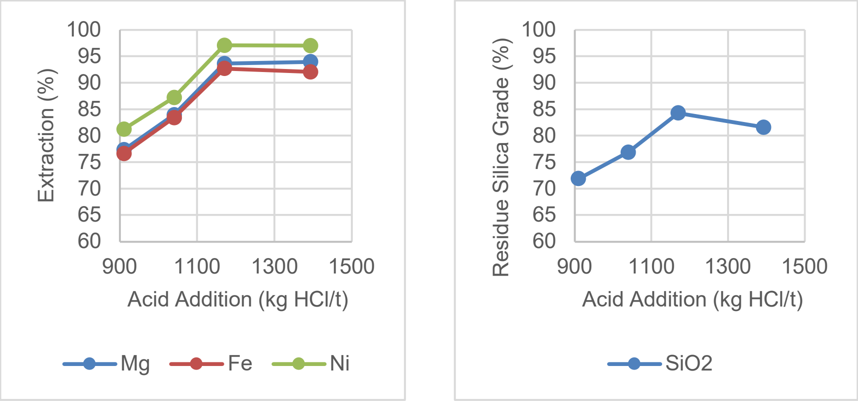

Figure 3. Batch leaching of olivine. Typical conditions: Temperature 100 ºC, 4 h, 87 g/L Mg (as $MgCl_2$)

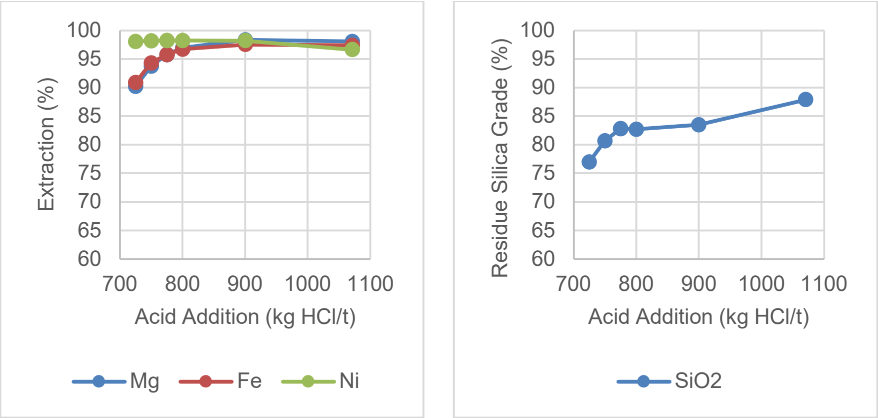

Figure 4. Batch leaching of asbestos tailings. Typical conditions: Temperature 100 ºC, 4 h, 87 g/L Mg (as $MgCl_2$)

Cementitious Properties of the Leach Residues

An extensive study of the cementitious properties of the leach residues is currently being conducted by the LMC laboratory EPFL (Lausanne, Switzerland). The micro-silica leach residue product has a reactivity similar to fly ash. This is important as fly ash availability will decrease over time with reduced use of carbon-based fuels. Micro-silica can be used to replace fly ash. Further testing has shown that with up to 30% substitution for Ordinary Portland Cement (OPC) the compressive strength of mortars is unaffected, the compressive strength of concrete is increased 14-19% and the concrete containing Atlas micro-silica has a 10-fold improvement in chloride penetration resistance compared to reference OPC.

Batch Testing of the Downstream Process Operations

In addition to an extensive series of batch leach tests, the downstream operations were also tested step by step in a series of further experiments. **Error! Reference source not found.** below shows the changing composition of solutions within the sequential unit operations in the NEM flowsheet.

Table 2. Solution Compositions (mg/L) Through Downstream Unit Operations (Leach = HCl Leach, IR = Iron Removal with NaOH addition, MHP = Mixed Hydroxide Precipitation, MnR = Manganese Removal, MP = Magnesium Hydroxide Precipitation)

Operation	Leach	IR	MHP	MnR	MP
Mg	69600	63000	68800	62300	3.1
Ni	3370	2210	300	1.7	0.6
Fe	36900	3.6	0.3	0.2	0.5
Al	3470	10	0.2	0.2	0.2
Mn	750	640	630	0.05	0.05
Na	24	25500	27400	25200	125000

The leach solution contains over 3 g/L of Ni and high levels of Mg, Fe, and Al. The IR solution shows very low terminal Fe and Al concentrations and somewhat reduced Ni concentration, a consequence of some dilution due to base addition and some co-precipitation of Ni. The sodium level is increased due to NaOH addition, while manganese is diluted to 640 mg/L Mn in solution. The MHP (primary) solution shows very low Fe/Al and significant reduction in Ni. This experiment produced a high grade MHP product (+40% Ni on a dry basis). The MnR solution shows an excellent rejection of Mn from solution (to 0.05 mg/L of Mn) by oxidation and pH adjustment. Further, the MP precipitation results show very low residual content of Mg, Ni, Fe, Al, and Mn. The final concentration of Na was 125 g/L Na, corresponding to 318 g/L NaCl. This brine would undergo further treatment in a conventional chlor-alkali circuit to polish minor contamination before electrolysis.

In more recent testing of the iron removal process using olivine addition with hypochlorite addition to oxidize iron, excellent results were obtained with respect to extent of removal of iron, aluminum and chromium. A leach filtrate was mixed with ground olivine mineral slurry (40% solids) at 70 °C for 2 h. A small amount of sodium hypochorite solution (11% NaOCl) was added to maintain +700 mV ORP. The results are summarized in Table 3.

The nickel content of the solids dropped from 0.34% Ni to 0.19% Ni with approximately 17% weight gain due to iron and aluminum precipitation. There was net extraction of nickel from olivine. Iron was reduced from 24.2 g/L to 0.2 mg/L, aluminum dropped from 571 to <0.2 mg/L and chromium dropped from 274 to <0.2 mg/L indicating quantitative removal of the three impurities. Accordingly, the residue composition increased in iron, aluminum, and chromium while the magnesium content dropped from 29.79% to 13.4%.

Continuous Pilot Plant Results

A continuous pilot plant was established at SGS Canada to integrate the key elements of the process, from ground ore feed to the production of silica residue, iron/aluminum precipitate, mixed hydroxide of nickel and cobalt, manganese precipitate, and finally magnesium hydroxide precipitate. The barren solution after magnesium removal is also a product but in this case for recycle through a chlor-alkali facility for manufacture of sodium hydroxide and hydrochloric acid supply.

Table 3. Olivine Precipitation of Iron, Aluminum and Chromium from Laterite Leach Solution

Sample	Leach Soln (mg/L)	INCAST75 (%)	Filtrate (mg/L)	Wash (mg/L)	Residue (%)
	520 mL	60 g	508 mL	1902 mL	70 g
Ni	5670	0.34	4920	358	0.19
Fe	24200	5.13	0.2	0.2	21.8
Mg	64600	29.79	71300	4910	13.4
Al	571	0.19	<0.2	5.2	0.58
Cr	274	0.28	<0.2	<0.2	0.41
Si	40.7	19.49	37.1	7.1	16.08
Na	17300	0.04	15600	1170	0.05

The pilot plant was run on a prepared sample of ground saprolite (Table 1) with grinding performed in recycle brine solution. Leaching was performed with ~750-800 kg HCl/t feed material and 95 °C for 10 days total (two periods of 5 days). The leach slurry was collected and filtered in a pressure filter to recover the silica residue and the leach solution was directed to primary neutralization. A hematite-rich seed slurry was added to the feed solution as it entered four stages of neutralization with NaOH solution. The slurry product was thickened and the thickener UF was divided into seed recycle and final product. The primary neutralization thickener overflow was sent through secondary neutralization (four stages followed by thickening), where additional NaOH solution was added. The secondary neutralization thickener UF was recycled to leaching and the OF was directed to MHP production. MHP production was performed in two stages (primary and secondary), and the second stage MHP thickener UF was recycled to leaching. The MHP thickener OF was sent to manganese removal. This was performed by oxidation with NaOCl and pH adjustment (with caustic addition) to form a manganese oxide product. Finally, the manganese free filtrate advanced to magnesium hydroxide precipitation with sodium hydroxide addition.

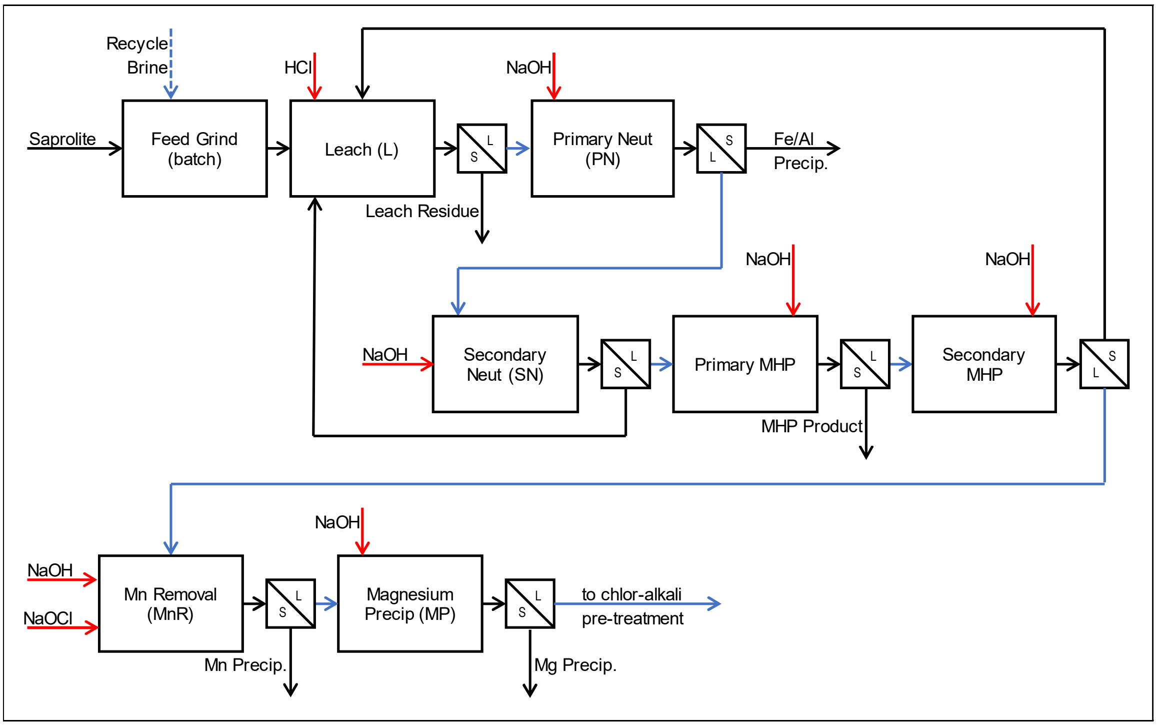

Figure 5. Overall flowsheet of the continuous pilot plant

Saprolite Leaching. The pilot plant operation was divided into 18 periods over which data was collected and mass balances calculated. **Error! Reference source not found.** shows metal extraction version time over these periods. The extraction of Ni in the saprolite leaching process was generally in the range of 96-99%. The Fe extraction was slightly lower and the Mg lower again. The acid addition rate was varied during the run and the changing extraction results are reflected by an increase or decrease in acid addition. The reported extractions are calculated by the Si-tie method where Si is assumed to be insoluble.

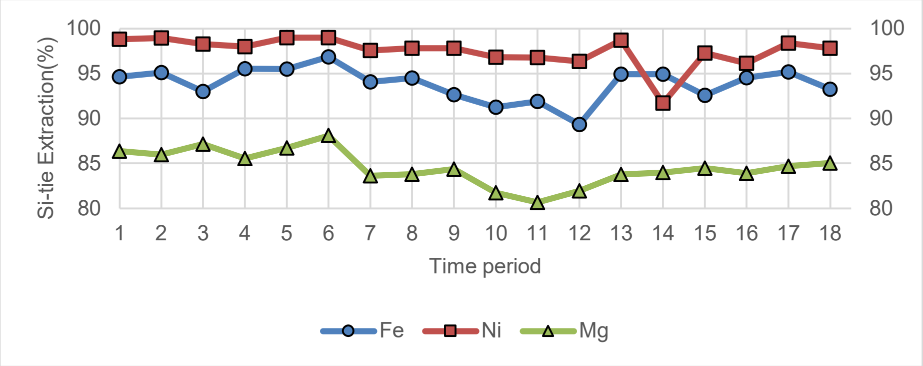

Figure 6. Saprolite leaching results over the 18 time periods of the pilot plant operation

Primary Neutralization. The primary neutralization results are shown in **Error! Reference source not found.** and **Error! Reference source not found.**. The iron removal results are consistent at nearly 100% efficiency. The aluminum removal results showed an increase toward the end of the pilot plant with a commensurate rise in nickel coprecipitation. The nickel in the primary neutralization residue is lost from the circuit so better control is required to avoid a nickel loss while still removing sufficient Al in this step. Aluminum precipitation is an indicator of potential nickel loss. It is important to not over-add NaOH at this stage, otherwise nickel loss will increase. The solid assay from the primary neutralization circuit showed a plateau of approximately 80% Fe_2O_3 with 5.5% Al_2O_3 and 4% Cl. The iron and aluminum precipitates are hydrated and the chloride in the residue is likely due to formation of hydroxy chloride precipitates of iron and aluminum.

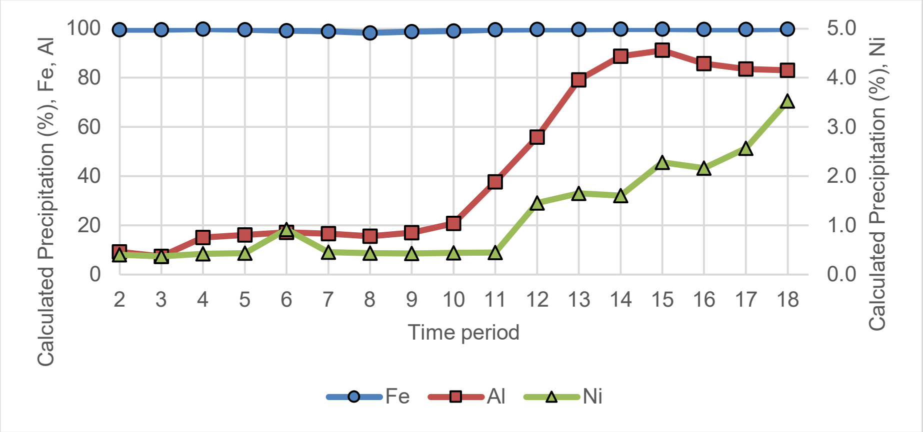

Figure 7. Primary neutralization calculated precipitation

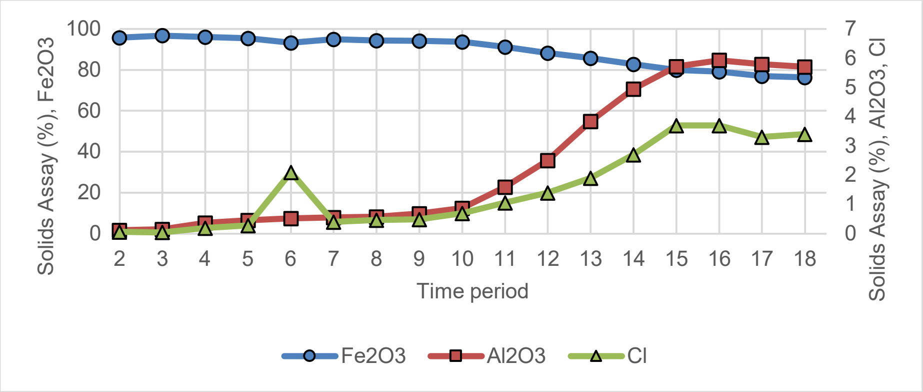

Figure 8. Primary neutralization solids assay

Secondary Neutralization. The secondary neutralization results (**Error! Reference source not found.** and **Error! Reference source not found.**) show excellent removal of iron and aluminum. However, if aluminum removal is too efficient, the precipitation of nickel increases. This is not a problem in the sense that the secondary neutralization residue is recycled and nickel is releached. However, the nickel needs to move downstream to MHP precipitation, and therefore nickel coprecipitation and aluminum removal have to be kept in balance to avoid excessive nickel buildup in the Leach-Secondary Neutralization part of the circuit. This was an important learning from the pilot plant.

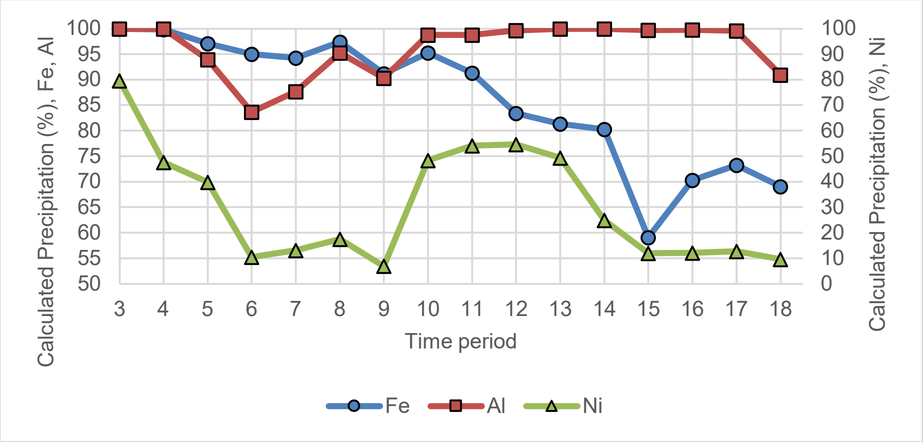

Figure 9. Secondary neutralization precipitation efficiency

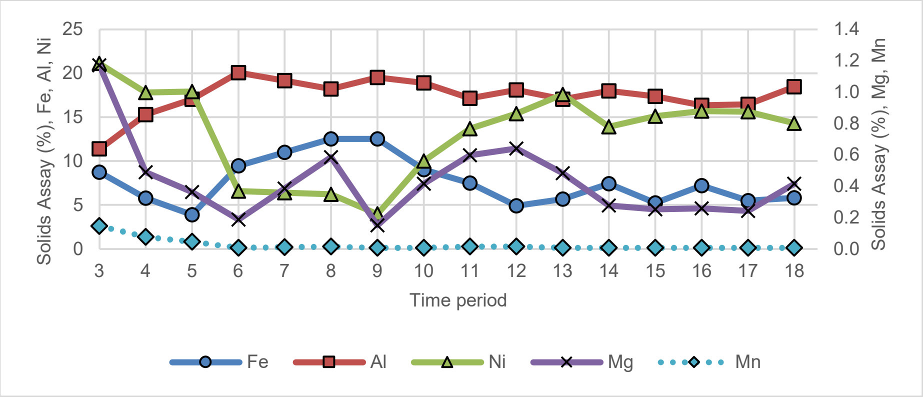

Figure 10. Secondary neutralization solids assay

Primary and Secondary Mixed Hydroxide Precipitation. The primary mixed hydroxide precipitation results (**Error! Reference source not found.** and **Error! Reference source not found.**) showed that nickel could be precipitated to form high grade MHP at as high as ~40% Ni on a dry basis (periods 5-8). The results also show the need for effective control of NaOH addition. During periods 9-18, excess NaOH was added, leading to increased precipitation of Mg and some Mn. The stability of this circuit is impacted by the upstream process steps and especially by the recycles of nickel and cobalt back to leach. Further, the measurement of pH in the strong brine solution as a measure of control is difficult and impacts the control of the MHP circuit. Future pilot plant operations will have improved pH electrode sensors and control.

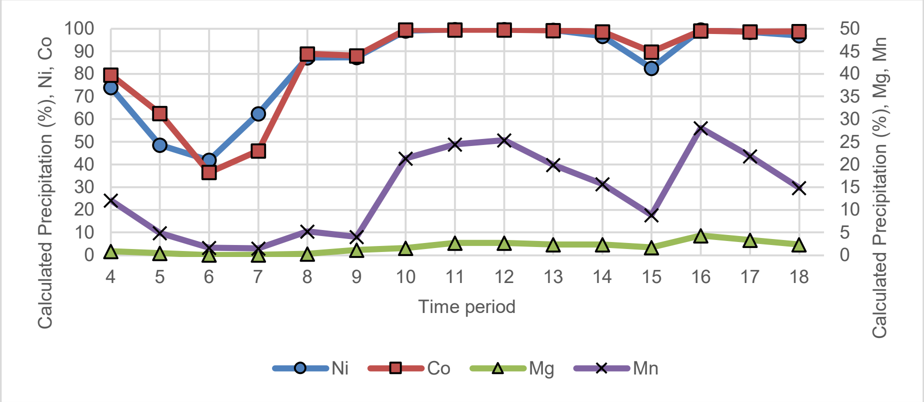

Figure 11. Primary mixed hydroxide precipitation efficiency

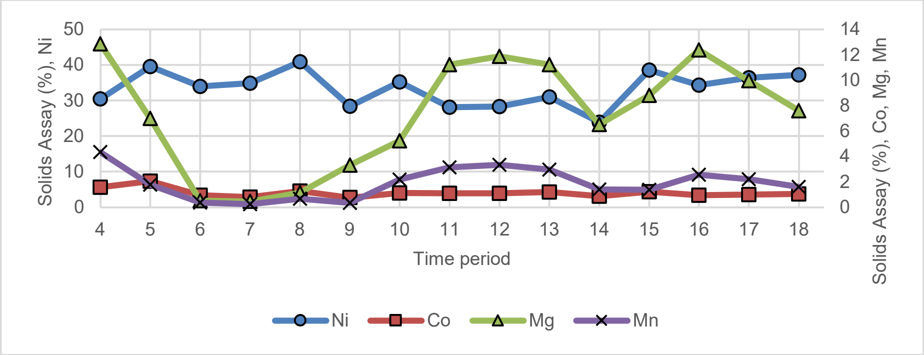

Figure 12. Primary mixed hydroxide precipitation solid assay

The secondary mixed hydroxide precipitation results (**Error! Reference source not found.** and **Error! Reference source not found.**) generally show the effective capture of residual nickel arriving from the primary mixed hydroxide circuit. Again, the correct dosage and control of NaOH addition is a critical issue moving forward with the process scaleup. Under-addition of NaOH will result in loss of soluble Ni and Co to the manganese removal circuit while over-addition will cause the precipitation of Mg and Mn.

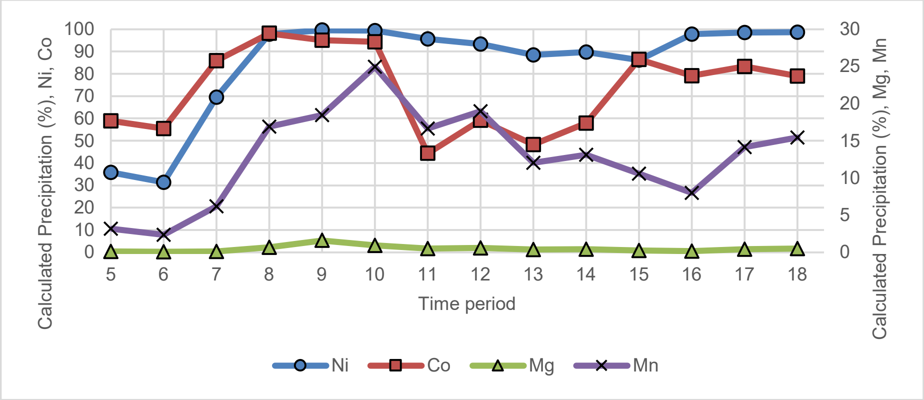

Figure 13. Secondary mixed hydroxide precipitation efficiency

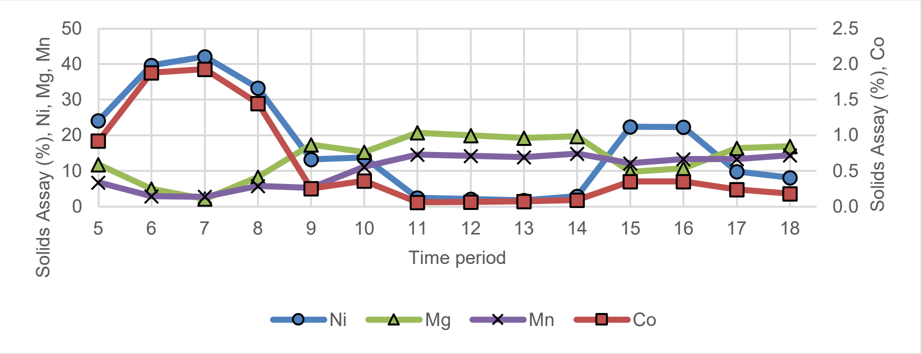

Figure 14. Secondary mixed hydroxide precipitation solids assay

Manganese Precipitation. The manganese removal circuit (**Error! Reference source not found.** and **Error! Reference source not found.**) was stable and yielded very high levels of manganese removal by effective oxidation and pH adjustment. Small levels of magnesium precipitation occurred through the operation, unavoidable due to the elevated pH used for manganese removal. The operation between period 5 and 10 showed some nickel in the manganese precipitate, due to incomplete nickel removal in the secondary mixed hydroxide precipitation circuit. Beyond this point (periods 11 and beyond), the nickel in solution in the feed to manganese precipitation was very low and hence the content of the manganese precipitate was very low.

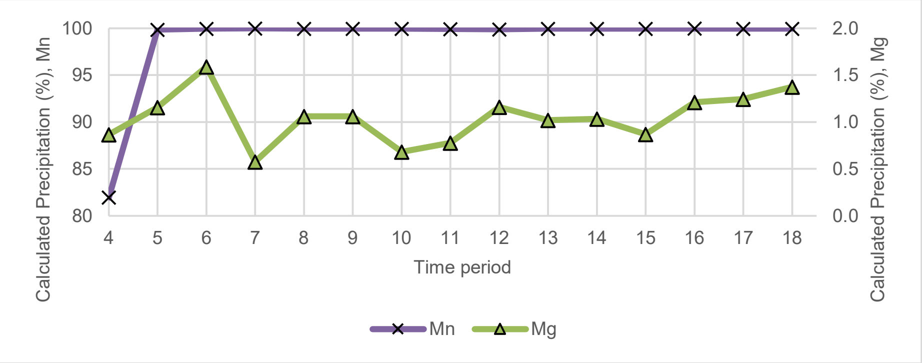

Figure 15. Manganese precipitation efficiency

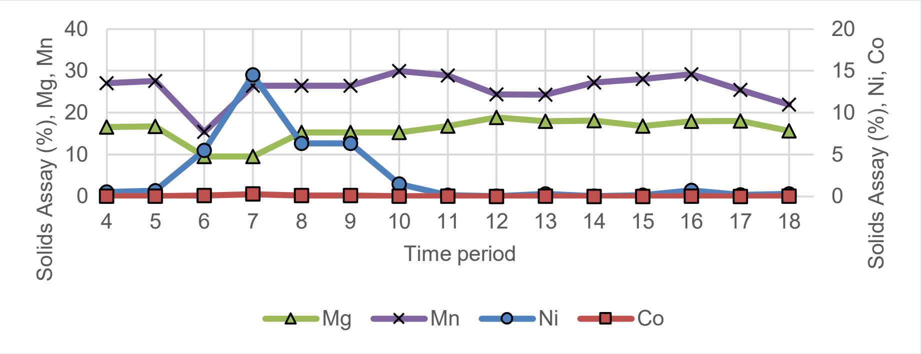

Figure 16. Manganese precipitation solids assay

Magnesium Precipitation. The magnesium precipitation results were excellent (Table 3). The magnesium precipitation circuit operated toward the end of the 10 day pilot plant run. The key impurity elements were generally very low except for chloride, which likely formed magnesium hydroxy chloride precipitates under startup conditions. Any of the other di- or tri-valent metals present in the feed to magnesium precipitation will co-precipitate with the magnesium. Magnesium precipitation efficiency was ~100%. The brine formed as a product from this process step is ideal as a feed to brine softening ahead of the chlor-alkali plant operation.

Table 4. Magnesium precipitate analysis.

Chemical Analysis (%)							
Sample	Fe	Al	Cl	Ni	Co	Mn	MgO

16	<0.01	0.02	4.4	<0.01	<0.01	<0.01	61.3
17	0.01	0.04	0.2	0.11	<0.01	0.01	63.1

CONCLUSIONS

Following an extensive bench test program, the Atlas Materials process was piloted on a sample of nickel saprolite ore for a total of 10 days. All the key metrics were achieved in the pilot plant operation.

- The leach extractions of nickel and cobalt were in the range of 96-99% in the primary HCl leach.
- The primary neutralization circuit removed iron and aluminum effectively with minimal co-precipitation of nickel and cobalt.
- The secondary neutralization circuit was effective at polishing residual iron and aluminum content from the solution prior to mixed hydroxide precipitation.
- The primary mixed hydroxide precipitation produced product grading up to 40% Ni on a dry basis. Under controlled conditions, co-precipitation of magnesium and manganese could be avoided. The testing highlighted the need to develop improved measurement of pH in the strong brine solutions used in this process so as to enhance control and selectivity of the key process steps.
- The secondary mixed hydroxide precipitation was effective at precipitating residual value metals.
- The manganese removal circuit utilizing oxidation and pH adjustment for precipitation was outstanding in performance with virtually 100% removal of manganese from solution.
- The magnesium precipitation process product was high grade and low in metallic impurities. The magnesium precipitation process is dependent on all of the upstream processes to produce a suitable precipitate product. The brine from the magnesium precipitation process was virtually free of any impurities and suitable as a source of NaCl brine to proceed to brine softening and chlor-alkali processing to regenerate HCl and NaOH for the process.

The silica leach residue from batch leaching of saprolite, olivine and asbestos tailing was evaluated as an additive to cement. The results confirmed that the leach residues were reactive and suitable for cement making.

A new unit operation has recently been developed and has been incorporated into the base flowsheet. Olivine may be added to the iron/aluminum removal stage to precipitate these elements. Excellent results have been achieved in batch testing. Residual iron/aluminum and chromium levels are in the range of <5 ppm in solution with negligible nickel co-precipitation.

The overall recovery of nickel and cobalt from the process is expected to be in the range of +95%. The MHP product is suitable for further post processing to produce battery material precursor materials to support the rapidly increasing demand in the electric vehicle space. The magnesium hydroxide product from the process is an ideal material to support decarbonization.

Atlas Materials will operate an extended Demonstration Pilot Plant later in 2023. The Demonstration Pilot Plant will confirm process chemistry, provide engineering data for a feasibility study for a 100,000 tonne per annum ore treatment facility and provide larger samples of products for off-take evaluation.