

Hydro-Pyro integration for the leaching of cobalt and nickel from converted nickel pig iron matte

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The production of nickel and cobalt materials from nickel laterite ores has increased significantly over the past 10 years and progressed from the expansion of nickel pig iron (NPI) in China to mostly in Indonesia because of the constraints imposed on the export of these ores as well as economic considerations. The process for producing synthetic matte from FeNi dates back to developments in New Caledonia and the application to NPI followed its increased application to stainless steel production to utilise the additional iron units where this is justified including the largest producer, Tsingshan and the recent 3 Mt/a plant in the Morowali Industrial Park (IMIP) in Indonesia (1). The potential flexibility to use laterite ores for both battery materials and stainless steel offers significant potential advantages with respect to both market and technical developments. The smelting and leaching options offer synergies based on considerations such as the optimum use of different laterite ore types and process flow sheet design and hydro-pyro integration. However, Indonesia is considering a plan to restrict construction of smelters producing nickel pig iron or ferronickel in order to optimise use of its limited nickel ore reserves for higher-value products such as battery materials. The development of nickel and cobalt projects in Sub-Saharan Africa, Central Asia and South Korea as well as Brazil using appropriate technologies is a matter that is receiving also increasing attention with this paper.

INTRODUCTION AND PROCESSING OPTIONS TO PRODUCE BATTERY MATERIALS FROM SULPHIDE AND OXIDE ORE TYPES WITH BOTH PYROMETALLURGY AND HYDROMETALLURGY PROCESSING STAGES

Nickel and cobalt sources fall into three main categories, namely sulphide and oxide ores plus recyclable materials from various catalyst and battery plus other applications. Sulphide ores can normally be beneficiated in mineral processing plants that produces a bulk concentrate with nickel, cobalt plus copper and in some instances also PGM's and gold that normally means that they need to be smelted to produce a matte that can be treated in a downstream mostly hydrometallurgical process. However, nickel laterite oxide ore types normally contain mostly nickel and some cobalt but can in some instances also contain copper and PGM's too. These additional components normally imply that the production of a ferronickel alloy for stainless steel production is probably not appropriate because the specification for this application can't be met and the potential value of these elements can't be realised. The conversion of the metallic phase from smelting certain laterite ores into a matte by adding sulphur has been practised for over hundred years and this approach has become the one if not most rapidly implemented technology approaches in the past ten years. The environmental considerations related to the chemical and energy requirements for processing are based on carbon and sulphur and these need to be addressed more effectively too!

Nickel and cobalt laterite ore types vary considerably in composition, especially the iron, magnesium and silicon contents in the various mineral phases as well as the most important nickel and cobalt grades. These are present as quite complex mineral multi-compound phases (2) that impact the downstream process stages including ore type and nickel and cobalt separation and their potential pre-upgrading during the mining and stockpiling stages. The Fe/Ni and Ni/Co ratios and the MgO, SiO₂ as well as the Al₂O₃ contents also affect the downstream pyrometallurgical and hydrometallurgical processing considerations. The cost-effective recovery and separation of the battery metal elements is a critical aspect in the development and implementation of nickel laterite ore-based projects where energy demand is also a very important factor. Ferronickel (FeNi) produced from a low Ni (1%) source requires around 50 MWh/t nickel whereas a 2% Ni feed grade is around half this amount. However, a high Fe oxide content in certain limonitic laterite ores of around 40 and up to even over 80% can increase this MWh/t by around 25 to 50%. The increase in iron reduction is normally because the need for increased recovery of the cobalt in particular. This is since a higher extent of Fe reduction from the slag into the metallic phase is needed to reduce the cobalt from the slag. The approach to this aspect where the Ni is the main component for stainless steel has been over many years to produce nickel pig iron (NPI) with only 10 to 15% nickel instead of 20 to 45% in FeNi so that the technology for this is very well established but its more energy intensive per nickel unit produced but having the additional iron units to produce stainless steel in a close-by facility can justify this to some extent. The recent 3Mt/a largest stainless-steel plant in Indonesia, Tsingshan is largely based on this aspect. However, the Ni/Co ratio needs to be over 30 to 40 for most grades of stainless steel so the ore composition needs to be compatible with this requirement.

The technology for adding the sulphur to the metallic phase in the smelting process can be applied during the start of the converter process stage to facilitate the removal the iron by oxidation into a fayalite slag so that it avoids the leaching and need for downstream iron removal by precipitation and separation in the hydrometallurgical stages. The sulphur can alternatively be added in the primary smelting stage to lower the liquidus of the metallic phase by around 100°C which is of benefit in cases where the furnace slag has a low liquidus temperature too so that the furnace operating temperature is also lower and this can also reduce the heat losses as well as lower the energy consumption. However, the option to add the sulphur to the molten alloy in the converter would allow the plant to produce both metallic alloys and well as matte so that a wider range of ore types can be processed, and battery products and stainless-steel alloys can be produced.

PYRO AND HYDRO TECHNOLOGIES

The metallurgical plant design and operating considerations are based on the characteristics of the ore types that can be mined from the specific deposits at the location and their management so that the best approach to producing the relevant products can be achieved. The options to implement pre-concentration and sorting of the ore types based on their variability in composition and particle size distribution should be evaluated as part of the mine plan so that the optimal downstream pyrometallurgical and hydrometallurgical processing options can be decided upon.

Pyrometallurgy

Ore types containing nickel-copper-cobalt and Platinum Group Metals (PGM's) sulphides can normally be pre-concentrated by mineral processing and oxide laterites with various iron to nickel (Fe/Ni), nickel to cobalt (Ni/Co) and silica to magnesia (SiO₂/MgO) ratios that can in principle be pre-concentrated by sensing and sorting based on larger particle size separation and conveyer belt sorting and diverting whereas finer sized feed needs to be carried out somewhat differently (mine front end loader bucket sensing and sorting or continuous belt sensing per metre length and downstream diverting into stockpiles).

The smelting of sulphide concentrates produces a matte that is processed in a converter to remove most of the reduced iron prior to leaching whereas the laterite ores can be smelted to produce FeNi with nickel contents of 15 to 45% but the cobalt content needs to be low enough to meet a Ni/Co ratio of over 30 for production of suitable alloy grades and target less than a ratio of 10 for potential cobalt recovery.

Laterite ores can also be smelted normally using the Rotary Kiln Electric Furnace (RKEF) process to produce FeNi and NPI with the Ni content less than 15% due to higher Fe contents especially from ores with Fe/Ni ratios of over 15 and up to 30. The NPI can be used to produce stainless steel where the higher Fe units would reduce the amount of steel scrap needed or it can be changed into a synthetic matte by adding sulphur and then removing the iron in a staged converter process prior to casting and crushing for leaching to extract the nickel, cobalt, copper and any PGM's present.

The ore types shown in table 1 below have been used in the normal process applications for smelting for Saprolite and leaching for Limonite ore compositions and the related ratios shown. However more recent technologies have changed the process options to some extent, namely where lower SiO₂/MgO ratio ores and higher MgO contents can be used to contribute to increasing the pH in acid neutralising stages to precipitate the sulphates as residues from the leach solution and also pre-leach some of the nickel and cobalt. The laterite ores can also be smelted to produce NPI and matte in spite of the higher Fe/Ni ratios as long as the higher iron is justified in the production of stainless steel or can be removed in a converter process where sulphur is added to form a synthetic matte (syn-matte).

The higher SiO₂/MgO ratios of over 2.5 especially where the Al₂O₃ is over 5% results in a lower slag liquidus temperature so that the slag superheat could be as high as around 200°C to ensure the FeNi alloy can be tapped from the furnace with a superheat of around 50°C. The furnace lining to contain this type of slag requires special design and operational considerations so that the potential option to use ESS furnace technology where the required metal temperature can be obtained via heating using induced energy from a channel induction heater system in the hearth as explained below.

ESS technology is based on the combustion of the reduction products and fossil fuel to pre-heat, calcine and reduce nickel and iron oxides in the laterite (3,4,5). It differs from the RKEF process in that it achieves, in a single stage-based furnace operation, a higher calcine temperature and almost complete nickel reduction at the required iron reduction. Electrical channel induction heating provides the additional energy needed to produce molten FeNi or NPI and slag.

The electrical energy is used to supplement the combustion energy. When compared with an RKEF, this reduces the electrical energy consumption (SEC) by around half producing FeNi. Moreover, the SEC is almost independent on the degree of iron reduction when producing NPI. The requirement is that the slag liquidus temperature must be similar or below that of the alloy phase. The slag does not need to be super-heated, expanding the related range of laterites that can be smelted.

Table 1. Process Options based on laterite ore types as examples (Ni/Co > 30 to 40 is needed for FeNi alloy production with the indicative values shown

| Examples | Types Laterites | Ratios SiO ₂ /MgO | Ratios Fe/Ni | Process Normal | Process Alternatives |
|----------|-----------------|------------------------------|--------------|----------------|-------------------------------|
| 1 | Limonite | 2.2 to 7.0 | 18 to 35 | Leach | Smelt NPI and syn-matte leach |
| 2 | Transition | 1.3 to 2.5 | 12 to 18 | Smelt/leach | Smelt/leach |
| 3 | Saprolite | 1.3 to 2.5 | 8 to 12 | Smelt | Leach neutralisation |

Table 2. Example of nickel laterite ores in the Ivory Coast in West Africa

| Ivory Coast (%) | Ratios | | | | | | SiO ₂ /MgO* | Fe/Ni | Ni/Co* |
|-----------------|--------|------|------|--------------------------------|------|------------------|------------------------|-------|--------|
| | Ni | Co | Fe | Al ₂ O ₃ | MgO | SiO ₂ | | | |
| Limonite | 1.5 | 0.14 | 45.0 | 4.1 | 4.4 | 13.7 | 3.1 | 30 | 11 |
| Transition | 1.4 | 0.05 | 19.6 | 2.1 | 25.6 | 37.6 | 1.5 | 14 | 29 |
| Saprolite | 2.1 | 0.07 | 21.2 | 3.9 | 14.8 | 36.6 | 2.5 | 10 | 31 |
| Weighted ave | 1.6 | 0.12 | 37.3 | 3.9 | 8.7 | 21.0 | 2.4 | 23 | 14 |

* Fairly high SiO₂/MgO, Fe/Ni and Ni/Co ratios suggesting NPI to recover cobalt may be necessary or the ESS furnace technology may be considered.

The major minerals in laterite nickel ore are FeO(OH) (Goethite), Al(OH)₃ (Gibbsite), and Fe₂O₃. The XRD peaks for the SiO₂ phase are comparatively lower, and those for other minerals with calcium, magnesium, and nickel are not obvious.

Laterite ore compositions from deposits in the Ivory Coast are shown in table 2 above that have quite high Saprolite ore type Ni grades but also high SiO₂/MgO ratios that can affect the slag compositions and its liquidus temperature that would be lower, so the design of the furnace needs to take this into consideration.

Table 3 below shows the indicative range of nickel laterite ores that illustrates the wide range of compositions and related important ratios that affect the selection and design of the process flow sheets as well as the operating parameters.

Table 3. Indicative range of laterite ore compositions

| % | Lower | Average | High | Higher** |
|--------------------------------|------------|------------|------------|----------|
| Ni | 1.0 | 1.5 | 2.5 | 5.0 |
| Co | 0.01 | 0.03 | 0.5 | 15 |
| Fe | 5.0 | 17.5 | 35 | 85 |
| MgO | 5.0 | 17.5 | 25 | 30 |
| SiO ₂ | 10 | 30 | 55 | 50 |
| Al ₂ O ₃ | 1.0 | 1.5 | 5.0 | 15 |
| Cr ₂ O ₃ | 0.5 | 1.0 | 3.5 | 5.0 |
| MnO | 0.25 | 0.5 | 1.5 | 10 |
| ZnO | 0.01 | 0.03 | 0.25 | 1.0 |
| Cu | 0.01 | 0.005 | 0.025 | 2.5 |
| PGM's, ppm | 0.01 | 0.05 | 1.0 | 2.5 |
| Ratios | | | | |
| Fe/Ni | 5 | 12 | 20 | 30 |
| Ni/Co | 100 | 50 | 20 | 5 |
| SiO ₂ /MgO | 2.0 | 1.7 | 3.0 | 7.5 |
| Ratio ranges* | | | | |
| Fe/Ni | 5 to 10 | 6 to 14 | 15 to 25 | 25 to 35 |
| Ni/Co | 10 to 150 | 30 to 100 | 10 to 50 | 5 to 20 |
| SiO ₂ /MgO | 1.2 to 1.4 | 1.5 to 1.9 | 2.5 to 3.5 | 5 to 10 |

* Ratios vary from low to high and visa verse ** e.g. asbolane

Special example of multiple material saprolite and limonite ore types in Central Africa

The Burundi ore composition used for this evaluation of special examples is very different from most Ni laterite ores since it has a very high Fe content in the limonite ore type but also has high other value materials in addition to the nickel, namely cobalt, copper and PGM's that impact the selection of the process flow sheet significantly. The use of both an upfront pyro and downstream hydro process to recover all these value materials is one of the potentially best approaches.

The carbothermic reduction of especially the Fe but to a much lesser extent because of the low contents of the nickel, copper and cobalt plus other reducible oxides contributes significantly to the CO and CO₂ gas emissions from the pre-treatment process flow sheet stages that also require coal for drying and preheating. The electrical energy for the smelting furnace is decreased based on the pre-treatment stages to around 450 to 500 kWh/t of hot calcined ore feed and the use of hydro power also reduces the impact of fossil fuel based electrical power generation. The potential use of hydrogen reduction of the Fe oxides would support the decrease in CO₂ emissions especially in the production of NPI. However, the

methodology for hydrogen production and the cost aspects would need to be realistic and suitable. The availability of hydro power supply is a distinct greenhouse gas advantage for the smelting stage due to the high slag to metal ratio of typically 10 up to 15/1.

The RKEF process can be used to smelt the pre-dried blended ore feed in the rotary kiln calcining and electric furnace smelting stages but instead of atomising the metallic Fe-rich alloy the addition of sulphur would allow the Fe removal to be carried out using a staged converter process and then the syn-matte can be crushed and milled to a suitable size for leaching in H₂SO₄ as explained below.

Figure 1 below shows the gamma graphs for the extent of nickel and cobalt recovery vs iron reduction with chromium and manganese for comparison showing the closer values of the first two and that the latter two are unlikely to be present to any significant extent even though they are around 0.5 to 1% in some laterites. The copper recovery lies between nickel and cobalt as shown and depends on the feed composition but it's much lower in most nickel laterites where its content less than 0.01%.

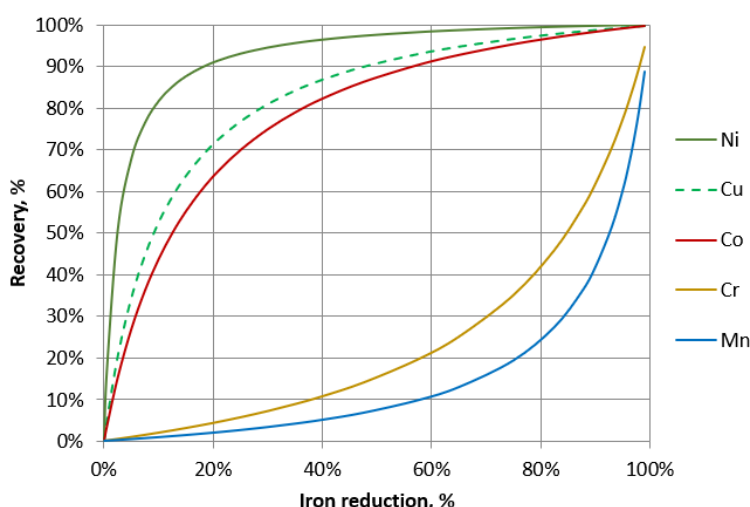


Figure 1. Gamma graphs for the extent of nickel, copper, cobalt and chromium plus manganese recovery vs iron reduction showing that chromium and manganese are much less reducible (the PGM's all deport and collect into the metallic phase).

The copper recovery cannot directly be calculated using this model and is therefore only an approximation based on a closely related reference from Mintek that also supports the other relationships shown in Figure 1 (5).

The tables referred to below are based on the indicative compositions and related mass and energy balance calculations for the two Burundi ore types and include the RKEF process as well as the ESS furnace technology under development and include the electric energy consumptions.

Table 4 shows the Burundi compositions for limonite and saprolite ore types

Table 4. The indicative Burundi laterite ore compositions

| Burundi (%) | Ni | Co | Cu | Fe | Al ₂ O ₃ | MgO | SiO ₂ | PGM's (ppm) | Fe/N | | |
|-------------|-----|------|-----|------|--------------------------------|------|------------------|-------------|-----------------------|------|-------|
| | | | | | | | | | SiO ₂ /MgO | i | Ni/Co |
| Limonite | 1.2 | 0.18 | 0.4 | 43.4 | 5.9 | 1.2 | 7.8 | 1.1 | 6.7 | 37.7 | 6.3 |
| Saprolite | 2.0 | 0.07 | 0.2 | 17.1 | 3.1 | 16.1 | 32.4 | 0.6 | 2.0 | 8.5 | 30.1 |

Table 5. RKEF and ESS smelting of Burundi saprolite and limonite for both RKEF and ESS processes with the calculated alloy composition and energy consumption values

| Technology | RKEF | | | | ESS | | | |
|----------------|-----------|------|----------|------|-----------|------|----------|------|
| | Saprolite | | Limonite | | Saprolite | | Limonite | |
| Grade (%) | High | Low | High | Low | High | Low | High | Low |
| Fe | 62.2 | 78.3 | 85.3 | 91.6 | 63.2 | 78.6 | 85.8 | 90.3 |
| Ni | 33.4 | 17.5 | 10.3 | 4.6 | 32.5 | 17.3 | 9.9 | 5.6 |
| Co | 0.8 | 0.6 | 1.2 | 0.7 | 0.8 | 0.5 | 1.2 | 0.8 |
| Cu | 3.1 | 2.0 | 2.7 | 1.5 | 3.0 | 1.9 | 2.6 | 1.7 |
| SEC, kWh/t ore | 394 | 443 | 456 | 578 | 252 | 248 | 210 | 175 |
| MWh/t Ni | 22.2 | 24.0 | 45.1 | 55.0 | 14.1 | 13.0 | 20.6 | 16.1 |

Table 6 shows the NPI alloy composition produced from a Burundi ore type that is then used to sulphidise the metal to 10 and 15% sulphur-containing synthetic mattes with high iron contents prior to converting to 2% Fe for leaching.

Table 7 shows the slags formed during the two converter stages to remove most of the iron in the matte phase (6,7).

Table 6. The primary smelter alloy and synthetic and converted matte compositions produced from indicative Burundi ore compositions

| | Alloy composition | | Matte 1 | | Matte 2 | | Converted Matte 1 | | Converted Matte 2 | |
|----|-------------------|----------|-----------|----------|-----------|----------|-------------------|----------|-------------------|----------|
| | Saprolite | Limonite | Saprolite | Limonite | Saprolite | Limonite | Saprolite | Limonite | Saprolite | Limonite |
| Fe | 62.2 | 85.3 | 56.0 | 76.8 | 52.9 | 72.5 | 2.0 | 2.0 | 2.0 | 2.0 |
| Ni | 33.4 | 10.3 | 30.1 | 9.3 | 28.4 | 8.7 | 78.8 | 63.8 | 74.3 | 60.2 |
| Co | 0.8 | 1.2 | 0.7 | 1.1 | 0.7 | 1.0 | 2.0 | 7.5 | 1.8 | 7.1 |
| Cu | 3.1 | 2.7 | 2.7 | 2.4 | 2.6 | 2.3 | 7.2 | 16.6 | 6.8 | 15.7 |
| S | 0.0 | 0.0 | 10.0 | 10.0 | 15.0 | 15.0 | 10.0 | 10.0 | 15.0 | 15.0 |

Table 7. Converter slags with estimated increased cobalt contents as iron is removed from the matte in two stages

| Converter slags | Stage 1 | Stage 2 |
|------------------|---------|---------|
| | % | % |
| FeO | 51.0 | 49.9 |
| NiO | 0.26 | 0.50 |
| CoO | 1.28 | 1.49 |
| CuO | 0.26 | 1.00 |
| SiO ₂ | 44.6 | 43.6 |
| CaO | 2.60 | 2.50 |

HYDROMETALLURGY

Some of the more recent developers of hydrometallurgical processes for extracting nickel and cobalt from several oxide and sulphide ore and concentrate types refer to aspects of pyrometallurgical processes that are potential concerns but may also be the result of some ignorance or misunderstanding. It is suggested that both be considered together towards an over-all optimum in performance as well as

environmental and economic considerations. The various options for up and down stream integration is a matter for extensive future research, development and evaluation on existing plant operations as well as new projects as suggested in the conclusions and recommendations below.

In this paper, the synergies of mineral processing, pyrometallurgy and hydrometallurgy for nickel cobalt as well as some copper and PGM containing-laterite ores are referred to so that this approach is supportive of what would be best for both the battery materials industry and other applications.

Leaching of cobalt and nickel from synthetic matte produced from the sulphidising and converting of Nickel Pig Iron (NPI)

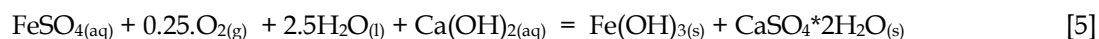
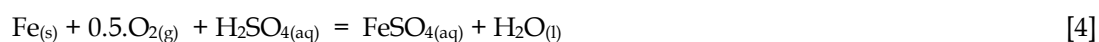
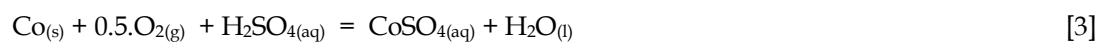
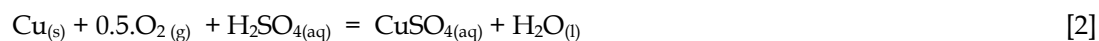
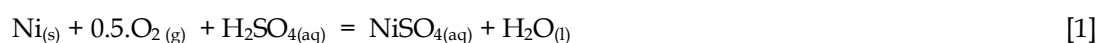
The leaching of cobalt and nickel from refined nickel pig iron (NPI) produced from various laterite ore types requires the removal of silicon and carbon prior to sulphidising (7). The amount of sulphur to sulphidise the metallic phases can be controlled to lower sulphur in a synthetic matte to 10 to 15% sulphur vs around 25 to 30% in typical mattes. The synthetic matte can be converted to remove most of the iron down to 2% or less and also to increase the percentages of the value elements. This approach normally allows the matte to be ground instead of atomised as is the normally case with low sulphur and high Fe contents such as those produced using the Mintek ConRoast that was also applied to low sulphur containing oxide feed materials in some extensive pilot scale operations at Mintek (5) even though some aspects of the process have constrained the extent of its commercial applications.

The laterite ores in some deposits contain other components that can increase the potential value significantly. However, those elements could also impact on the production of FeNi from it because of the relatively high cobalt and copper values that could be lost unless they are separated by leaching. This would be particularly true if there are PGM's as is the case in some laterite ores in Burundi as an example and referred to below.

Process Flow Sheet Methodology

To compare the feasibility of different possible pyro- and hydrometallurgical treatments of the furnace products, a high-level economic analysis was performed. The comparison was made on the basis of Opex only since that is the recurring item in the cash flow and is hence expected to contribute more significantly to the net present value than the Capex which is incurred only once.

The emphasis is on the effect of the iron-content in the furnace products and the manner in which iron is rejected from the hydrometallurgical circuit. The two generic flowsheets being considered are shown in Figure 2 distinguished by a low-redox and low-temperature leach in diagram (a) and a high-redox and high-temperature leach in diagram (b). In the former, all iron leached is assumed to remain in solution as Fe²⁺ and the leach residue is therefore assumed to be free of iron. The leaching step needs to be followed by a separate Fe-removal step using Ca(OH)₂, producing Fe(OH)₃ adsorbed onto gypsum. The relevant reactions are:



In this case, the Fe-leaching reaction [4] is acid-consuming while the Fe-removal reaction [5] consumes lime (Ca(OH)₂) to produce a combination of Fe(OH)₃ and CaSO₄·2H₂O as Fe-bearing residue. However, this residue is separate from the leach residue and hence does not dilute PGM's that might be contained in the leach residue.

In the latter case, the nickel, copper and cobalt leaching reactions remain the same, but all iron is assumed to precipitate out of solution as Fe_2O_3 in the leaching step according to reaction [6]:



This yields a combined Fe-leaching and Fe-removal reaction that consumes neither acid nor lime and produced Fe_2O_3 as iron-bearing residue combined with the leach residue. Copper is assumed to be produced as cathode by SXEW, which generates an acidic raffinate which can be recycled to the leach for economising on the consumption of H_2SO_4 . The nickel and cobalt are assumed to be produced as a mixed hydroxide, precipitated using $\text{Mg}(\text{OH})_2$. For the comparison of the cost/revenue differential between the options, the revenues/costs associated with only the items shown in Table 6 were considered. The cost of O_2 /air has been considered in terms of an energy cost to generate and disperse O_2 into the leach, from prior experience assumed as 0.6 kWh/kg_ O_2 and 0.1 USD/kWh.

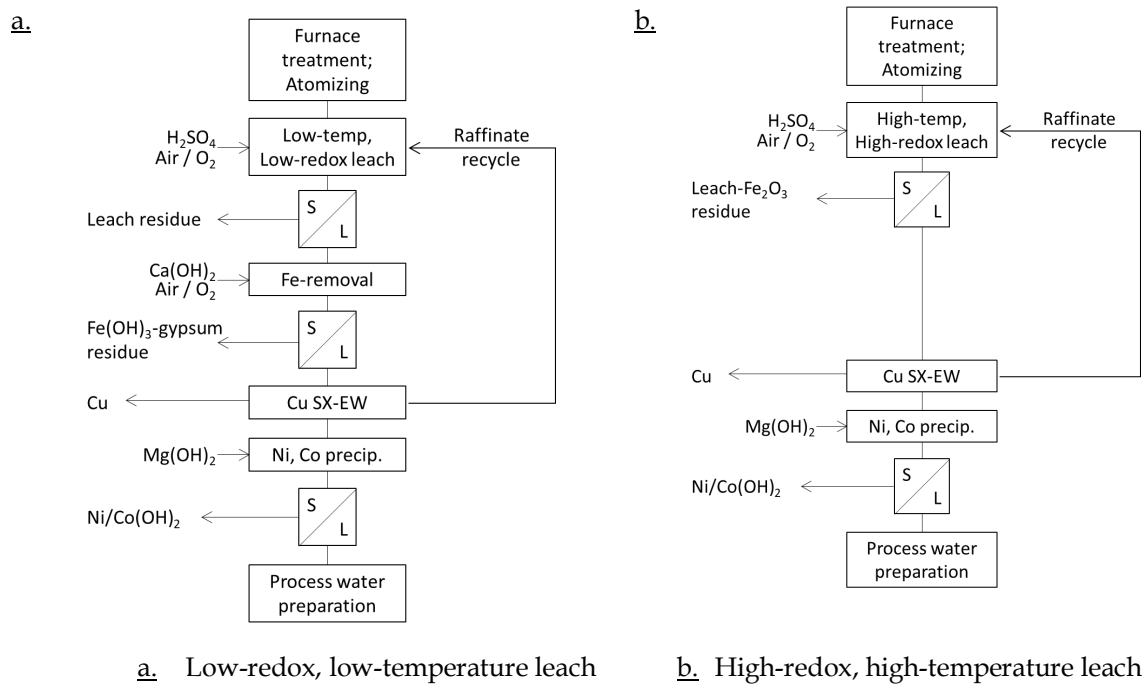


Figure 2. Generic hydrometallurgical process flow sheet examples

Table 8. Revenue and cost parameters considered

| Item | Unit cost ¹ , USD/kg |
|--------------------------------|---------------------------------|
| O ₂ | 0.06 |
| H ₂ SO ₄ | 0.25 |
| Ca(OH) ₂ | 0.20 |
| Mg(OH) ₂ | 0.50 |
| Cu | -8.82 |
| Ni(OH) ₂ | -10.2 |
| Co(OH) ₂ | -26.6 |

¹Revenues are shown as negative costs using average metal prices of the 12 months preceding May 2022 and assuming 70% of contained metal value is received for hydroxides.

The results of the analysis appear in Table 9. All costs, revenues and residue sizes are reported per kg Ni in the product, since nickel constitutes the major source of revenue.

Table 9. Results of economic analysis

| | Alloy-Lim | Alloy-Sap | Mat1_Lim | Mat1_Sap | Mat2_Lim | Mat2_Sap | C_Mat1_Lim | C_Mat1_Sap | C_Mat2_Lim | C_Mat2_Sap |
|---|-----------|-----------|----------|----------|----------|----------|------------|------------|------------|------------|
| ELEMENTAL COMPOSITION, % | | | | | | | | | | |
| Fe | 85.0 | 65.0 | 76.5 | 58.5 | 72.3 | 55.3 | 2.0 | 2.0 | 2.0 | 2.0 |
| Ni | 10.0 | 30.0 | 9.0 | 27.0 | 8.5 | 25.5 | 62.7 | 77.0 | 60.5 | 72.2 |
| Co | 1.2 | 1.0 | 1.1 | 0.9 | 2.6 | 0.9 | 7.5 | 2.6 | 7.3 | 2.4 |
| Cu | 2.5 | 2.5 | 2.3 | 2.3 | 2.1 | 2.1 | 15.7 | 6.4 | 15.1 | 6.0 |
| S | - | - | 10.0 | 10.0 | 15.0 | 15.0 | 10.0 | 10.0 | 15.0 | 15.0 |
| PGM | 1.0 | 1.1 | 0.8 | 1.0 | 0.9 | 1.0 | 2.0 | 1.8 | 2.0 | 1.7 |
| LOW TEMPERATURE LOW REDOX LEACH, 100% Fe REMAINS IN LEACH SOLUTION, SEPARATE Fe REMOVAL POST-LEACH AS Fe(OH)3-GYPSUM | | | | | | | | | | |
| Marginal cost, USD/kg_Ni | 8.0 | 2.5 | 8.0 | 2.5 | 8.0 | 2.5 | 1.1 | 1.0 | 1.1 | 1.0 |
| Oxidation | 0.3 | 0.1 | 0.3 | 0.1 | 0.3 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| H2SO4 | 4.7 | 1.4 | 4.7 | 1.4 | 4.7 | 1.4 | 0.5 | 0.4 | 0.5 | 0.4 |
| Ca(OH)2 | 2.5 | 0.6 | 2.5 | 0.6 | 2.5 | 0.6 | 0.0 | 0.0 | 0.0 | 0.0 |
| Mg(OH)2 | 0.6 | 0.5 | 0.6 | 0.5 | 0.6 | 0.5 | 0.6 | 0.5 | 0.6 | 0.5 |
| Residue size, kg/kg_Ni | 47.6 | 4.1 | 19.5 | 4.5 | 20.2 | 4.7 | 0.2 | 0.2 | 0.3 | 0.3 |
| PGM upgrade factor | 247.5 | 247.6 | 9.9 | 9.9 | 6.6 | 6.6 | 9.7 | 9.8 | 6.7 | 6.5 |
| Marginal profit, USD/kg_Ni | 16.5 | 15.7 | 16.5 | 15.7 | 16.5 | 15.7 | 23.4 | 16.7 | 23.4 | 17.0 |
| HIGH-TEMPERATURE HIGH REDOX LEACH, 100% Fe PPT IN LEACH AS Fe2O3 | | | | | | | | | | |
| Marginal cost, USD/kg_Ni | 1.3 | 1.0 | 1.3 | 1.0 | 1.3 | 1.0 | 1.1 | 1.0 | 1.1 | 1.0 |
| Oxidation | 0.3 | 0.1 | 0.3 | 0.1 | 0.3 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| H2SO4 | 0.5 | 0.4 | 0.5 | 0.4 | 0.5 | 0.4 | 0.5 | 0.4 | 0.5 | 0.4 |
| Ca(OH)2 | - | - | - | - | - | - | - | - | - | - |
| Mg(OH)2 | 0.6 | 0.5 | 0.6 | 0.5 | 0.6 | 0.5 | 0.6 | 0.5 | 0.6 | 0.5 |
| Residue size, kg/kg_Ni | 13.7 | 3.1 | 14.9 | 3.4 | 15.6 | 3.6 | 0.2 | 0.2 | 0.3 | 0.2 |
| PGM upgrade factor | 0.8 | 1.1 | 0.8 | 1.1 | 0.8 | 1.1 | 7.6 | 7.6 | 5.6 | 5.4 |
| Marginal profit, USD/kg_Ni | 23.2 | 17.2 | 23.2 | 17.2 | 23.2 | 17.2 | 23.5 | 16.7 | 23.5 | 17.0 |

OTHER PROJECTS

Shevchenko Project Kazakhstan

The development work carried out on the Shevchenko Nickel project in Kazakhstan at Mintek between 2005 and 2010 involved the pre-treatment and smelting in a DC furnace pilot plant with twin cathodes as well as direct leaching of the nickel laterite ore samples in both heap and tank process options to produce nickel cobalt intermediates MHP (Mixed Hydroxide Products). These could be either redissolved and purified to produce high battery materials or calcined and smelted to produce high grade FeNi with around 80 to 90% Ni but the cobalt content would need to be controlled to be less than about 1.5 to 2% for several of the stainless and alloy steel applications (8). The MHP contains typically around 40 to 45% Ni and can include up to 3 to 4% cobalt so that their separation can be considered if the economy of scale justifies this downstream processing stage or the MHP can be sold but normally at a discount to the LME price. The Southern Urals Nickel Plant (SUNP) in Orsk installed a 15 MVA (12 MW) DC arc furnace based partly on the Mintek DC furnace design but with only a single cathode electrode. The DC furnace was intended as a demonstration scale to install two or three larger 80 to 90 MW DC furnaces with twin electrodes. However, the first two twin electrode 80 MW DC arc furnaces were installed at Koniambo in New Caledonia in around 2014 so their performance was awaited before the furnaces at Shevchenko were to be progressed with following the campaign at Mintek in 2005(9).

Unfortunately, the 80 MW DC furnaces at Koniambo have experienced some significant equipment and operational difficulties so the Shevchenko project was placed on hold in 2015 pending the outcomes at Koniambo. Nevertheless the 12 MW DC furnace quite close to Shevchenko was evaluated as an option to process calcined MHP in 2012 to 2014 that indicated that between 20 and 30 kt/a of high grade FeNi could be produced based on MHP produced from some of the Shevchenko ore types (10,11). This approach is still being considered along with using advances for ore sending and sorting technology to increase the Ni content in the ore feed and control the Ni/Co ratio as well as the SiO₂/MgO and Fe/Ni ratios to optimise the process flow sheet and economic parameters. The option to produce NPI using the DC furnace process would also be a potentially good approach in a single electrode furnace up to around 60 MW especially where the ore is predominantly fine and when the smelting with a shielded arc is difficult to achieve which in a conventional three phase three electrode AC furnace would lose a significant amount of thermal energy from the related open arcs and bath conditions or immersed arcs and high side wall and roof heat flux loading conditions. The NPI produced in the DC furnace could also be sulphidised to produce mattes for converting and leaching. DC furnace developed in South Africa that was initiated by Mintek has been implemented for HCFer production by KazChrome in Aktobe on four DC arc furnaces at the 72MW power level that is now a good reference (12).

Other project examples - Indonesia and South Korea plus Brazil

- Indonesian FeNi and NPI developments plus battery nickel products.

Tsingshan is now the world's largest stainless steel producer and has a large production capacity in China and recently in Indonesia totalling close to ten million tons. Tsingshan's involvement in the recent 3 Mt/a plant in the Morowali Industrial Park (IMIP) in Indonesia resulted in the application of the Rotary Kiln Electric Furnace (RKEF) process to produce relatively low-cost nickel pig iron (NPI). This recent project is now a leader in the Indonesian NPI industry and globally in NPI processing technology. The integration with the stainless-steel plant involved the implemented the AOD decarburisation process for hot transfer of NPI into the stainless-steel production process.

Indonesia Weda Bay Industrial Park (IWIP) started being constructed in 2018 and is located on Halmahera Island in Indonesia's North Maluku province and could potentially become one of the world's largest nickel production regions together with IMIP (1). IWIP nickel pig iron is expected to supersede production from China that is more costly. Tsingshan is collaborating with a number of different partners across a range of IWIP projects - this including Eramet that has been involved with RKEF nickel project in New Caledonia for many years and alternative technologies in Indonesia including the smelting of nickel intermediates. The nickel plants often have 12 to 15 RKEF lines with 15 to 30 MW furnaces but are progressing to larger-scales to have the necessary economy of scale. The

installation of 750 MW of power plants is part of the infrastructure including logistics that has been implemented in the region.

The impressive infrastructure and operational facilities at the Indonesia Morowali Industrial Park (IMIP) comprise the following:

The 3.0 Mt/a stainless steel capacity and 0.5Mt/a carbon steel capacity that is being increased to 3.5Mt/a
A 0.6Mt/a high carbon ferrochrome smelter
A 3.0Mt/a nickel pig iron facility with 36 operating RKEF lines
A 2.0GW power plant that is being expanding to close to 3GW) and
An HPAL facility with an acid plant, a lime and a coke plant

- Brazil and South Korea

Brazil and South Korea are expanding their nickel industries using their own ore resources or importing them respectively using mostly RKEF technology to produce FeNi in Brazil and more recently also NPI in South Korea for the battery metals industry. Brazilian Nickel has recently installed a Heap Leach Plant to produce a nickel intermediate product (NIP) and also potentially cobalt too. New RKEF and HPAL plants are under consideration and a new RKEF FeNi plant is being constructed in Brazil by Horizonte Minerals Plc.

CONCLUSIONS

The two main options for pyro-hydro and hydro-pyro process flow sheet integration to produce battery nickel and cobalt materials allow a wider range of nickel laterite ore types to be processed. The selection of the pyrometallurgical process for producing NPI for stainless steel production vs battery materials depends on composition of the laterite ore type and the specifications and market values of the respective products as well as the capital and processing costs. There is very good flexibility in cases with variable ore types and compositions to produce NPI for both stainless steel and synthetic mattes for leaching by adding the sulphur after the smelting stage to the metallic phase. The decision can be based on the criteria that justifies the recovery of nickel and cobalt as leached phases for downstream hydrometallurgical processing. The conclusions for the approach optimisation of the smelting, sulphidising and converting process stages based on the ore type and composition as well as the downstream leaching phase are as follows:

- 1) The more extensive reduction of iron oxides with the laterite ore feed than is normally used to produce FeNi with typically 20 up to 40% nickel but is decreased to around 15% in NPI and used for syn-matte conversion. This needs to be justified based on the potential benefits of mostly higher cobalt and in some instances nickel too vs the increased energy requirement and need to refine the NPI before sulphidising and then remove most of the iron in the converter stages prior to leaching the syn-matte.
- 2) With the relatively high-Fe furnace products, the marginal cost of leaching is much higher when the iron remains essentially in solution, as was assumed for the low-temperature low-redox potential leach. That requires the addition of H_2SO_4 during the leach stage followed by the addition of $Ca(OH)_2$ in the iron removal stage, producing a large $Fe(OH)_3$ -gypsum residue. The only advantage of such an approach is that a higher upgrade in PGM concentration in the leach residue is achieved for possible further processing or sale.
- 3) Using a high-temperature high-redox leach where the iron is assumed to precipitate 100% in the leach step as Fe_2O_3 , a saving is effected on H_2SO_4 and $Ca(OH)_2$ consumption, the need for a separate iron removal step post-leach is eliminated and a much smaller and denser Fe_2O_3 residue is produced. The high-temperature high-redox potential option yields in all cases a higher marginal profit per kg nickel for a given furnace product. However, this difference becomes insignificant with the converted mattes.
- 4) The removal of most of the iron from the synthetic matte with the optimum sulphur content in two or three stages of converting in progressively smaller converter vessels as the mass

decreases allows the management of the overall cobalt recovery to be carried out so that the final smaller quantity of converter slag with the highest cobalt content associated with the low Fe content matte can be recycled to the alloy smelting stage and recovery the cobalt that has the trend to follow the iron content as it is reduced as well as when it is oxidised.

- 5) The alternatives for hydro-pyro integration include in situ, heap, tank and HPAL leaching with the production on Ni-Co intermediates that can be further processed in either pyro and or hydro metallurgical processes to produce various separate nickel and cobalt products based on the required economy of scale to justify this but with the added flexibility to send the intermediates to a facility that meets this requirement.
- 6) Whether alloy or matte is leached has very little effect on the marginal profit of the leaching step. Converting the matte improves the profitability for the limonite compared to the production of unconverted matte, but not for the saprolite because the iron content is normally lower.
- 7) Southern and sub-Saharan Africa has reasonable nickel and the largest cobalt resources to exploit for battery materials and has the world's largest chromium sources as chromite ores and by-products from the PGM industry and manganese and vanadium ore deposits that can also supply the battery materials industries as well as alloy and stainless steels. However, the nickel laterites discovered so far have not been developed in any significant manner but the applications for battery materials and related advanced technologies could in principle change hopefully this situation.

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