

EFFECT OF SALINITY ON NICKEL LATERITE PROCESSING

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ABSTRACT

The effect of salinity on the processing of various nickel laterite ores is discussed. In particular, the presence of high concentration chloride, sulphate, sodium, calcium and magnesium is addressed. Key unit process operations affected by these ions include ore preparation, pressure acid leaching, counter-current decantation and product purification and precipitation. Some of the process implications of these dissolved species are discussed in terms of rheology and process chemistry.

Laterite slurries that display good natural flowability are less influenced by salinity, as the maximum decrease of yield stress ranges from 15% to about 20%. Heating these slurries to 120°C and higher can however reduce the yield stress up to 98%.

The yield stress of some laterite slurries that display poor rheology can be reduced by over 83% due to the presence of high concentrations of total dissolved solids, mainly as sodium chloride. The combined effect of temperature, i.e. over 130°C, and salinity can in fact render some of these slurries almost free flowable.

Unfortunately, the presence of chloride ions in the downstream process intermediates can cause serious engineering problems such as corrosion, unmet product specifications and difficult water balance management. The use of high throughput continuous precipitators was found to improve chloride rejection. Test products assayed 0.02-0.07 wt.% Cl⁻ compared to 0.4-1 wt.% Cl⁻ in the conventional precipitation products.

INTRODUCTION

In the last 5-7 years, the world nickel producers have been focused on furthering nickel laterite processing utilising high-pressure acid leaching (HPAL) technology. The process water used or recommended for this technology has often been saline, ranging from moderately low to very high concentrations of total dissolved solids.

Examples of chemical compositions of some laterite ores are given in Table I. Due to the differing geneses of the ores, the main differences between the various ore types are the moisture, aluminium, iron and silica content. The silica content of the Cawse ore is mainly present as iron-rich quartz, whereas in Bulong and Murrin Murrin ore, it is incorporated into clays. In lateritic deposits, the nickel and cobalt do not usually occur in distinct minerals. Along with manganese, they are released during long periods of weathering of ultramafic rocks, and become enriched

in weathering products such as goethite, limonite and nontronite clays by ion replacement. This enrichment is mainly due to a reduction in volume caused by leaching of magnesium and other minerals from the ultramafics during the weathering process. At Bulong and

Murrin Murrin, most of the nickel occurs in nontronite, a smectite clay rich in nickel and chromium, whereas at Cawse it is included in less hydrophilic limonitic clays. For comparison, the Moa Bay deposit consists mainly of a limonite or iron-rich clay (1).

Table 1 - Chemical Composition of Typical Laterite Ores (wt. %)

SPECIES	BULONG	CAWSE	MURRIN MURRIN	MOA BAY
Ni	1.11	1	1.23	1.3
Co	0.08	0.07	0.069	0.12
Fe	20.8	18	21.3	45
SiO ₂	42.9	42.5	41.7	8.3
Al	2.75	1.71	3.16	4.8
Mg	4.62	1.58	3.28	0.55
Mn	0.36	0.17	0.27	
Cr	0.6	0.92	1.13	2
Ca	0.03	0.03	0.59	
Moisture	Up to 35%	Up to 10%	About 30%	>20%

It has been claimed that the use of saline water has benefits in ore processing (1). The advantages are found mainly in the ore preparation stages, where the use of saline water prevents the swelling of clays, and thereby assists in the settling of the ore slurry allowing higher solids densities to be pumped into an autoclave. However, along with some advantages, there are a number of penalties that have to be considered.

In PAL, the use of saline water offers mainly disadvantages in terms of increased acid consumption (at constant free acidity), as well as higher engineering costs in order to deal with the highly corrosive environments caused by mixing sulphuric acid with saline water at high temperatures.

Precipitation of the nickel and cobalt is carried out to yield an intermediate product in the form of a mixed nickel-cobalt hydroxide precipitate, for either sale to a refinery, or as a process step in an already integrated plant. It is imperative that soluble impurities deleterious to the refining process are eliminated.

The objective of this paper is to focus on the effect of salinity on lateritic ore rheology and to describe a process suitable for the efficient production of an acceptable mixed nickel-cobalt precipitate (i.e. low Cl⁻ contamination, preferably below 0.1%).

EFFECT OF SALINITY ON ORE SLURRY RHEOLOGY

BACKGROUND

There is extensive literature available describing the rheological behaviour of lateritic slurries, both in general terms, as well as with reference to specific ore deposits, processes and applications (2-5). Regarding the general rheological behaviour of lateritic ore slurries, treated as particulate fluids, a brief summary of the concepts and findings described in paper (6) is summarised below.

The effect of slurry flow properties upon nickel laterite processing is perhaps the most relevant example of a rheology-driven metallurgical process. Rheological characterisation of laterite slurries and subsequent modelling can be carried out using experimental flow curves. While the rheology of lateritic ore slurries is complex and deposit-dependent,

practically all of these fluids display a non-Newtonian flow behaviour, which is best described by the Bingham plastic rheological model. The yield phenomenon separates the quasi-solid and quasi-liquid states of the Bingham plastic particulate fluids. The behaviour of Bingham plastic fluids tends to be time-dependent to a certain degree (i.e. until they reach their ultimate flowability), since shearing history generally influences their rheological properties. In terms of flowability, lateritic ore slurry samples were identified as a type "M" and a type "I". Type "M" lateritic ore slurries display relatively poor flowability, and in general may not flow readily at solids densities as low as 29 wt.%, i.e. characterised by yield stress values of 30 Pa or more. Type "I" lateritic ore slurries typically display excellent flowability at solids densities as high as 42 wt.%, i.e. characterised by yield stress values of 30 Pa or less. Comparative flow curves are illustrated in Figure 1. Certain lateritic ores form slurries that display rheological properties intermediate between types "M" and "I". The flowability of these slurries can be improved by ore-blending, optimising the salinity of the process water, controlled dilution during preheating, and the use of rheological additives.

The actual specific gravity of the solids contained in laterite slurries and various derived process slurry samples has been found to be dependent on the solids content (pulp density) of the respective slurries and was related to their Bingham yield stress.

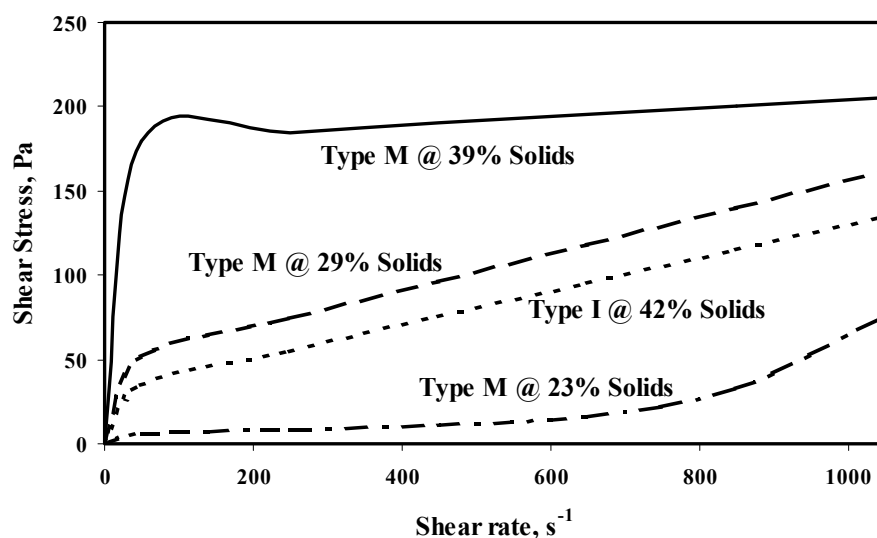


Figure 1 - Comparative Flow Curves: Slurries Type "M" and "I"

EFFECT OF TDS AND TEMPERATURE ON FLOWABILITY

Rheology tests were carried out on type "M" and "I" laterite slurry samples in order to quantify the effect of temperature and Total Dissolved Solids (TDS). The TDS was adjusted by using a salt mixture containing 26.3 wt.% Na⁺, 47.5 wt.% Cl⁻, 3.2 wt.% Mg²⁺, 1 wt.% Ca²⁺, 6.6 wt.% SO₄²⁻, and insignificant amounts of K⁺, HCO₃⁻, and other watersensitive, and hence most species. The rheological measurements were carried out using a high accuracy Haake RS75 concentric cylinder rotational rheometer, which features extremely sensitive torque measurement (10⁻⁶ - 10⁻¹ Nm range), high temperature capability, controlled shear/stress modes, and the ability to generate numerous data points with the option for linear or logarithmic plotting.

The effect of the temperature on yield stress for a slurry type "M" is illustrated in Figure 2. Accordingly, the yield stress at 0 g/L TDS in solution was reduced by 92% (from 108 Pa to 9 Pa) at 36 wt. % solids by heating from 31 to 131°C.

The combined effect of temperature and salinity on a laterite type "M" slurry is illustrated in Figure 3. Accordingly, the yield stress at 31°C was reduced by 83% (from 108 to 19 Pa) by increasing the solution TDS from 0 to 41 g/L. A further increase of salinity to 78 g/L TDS only reduced the yield stress at 31°C by an additional 6%. The relative decrease in yield stress due to the effect of heating from 31 to 131°C at 41 g/L TDS and 78 g/L TDS was 71% and 66%, respectively.

The combined effect of temperature and salinity on a laterite type "I" slurry is illustrated in Figure 4. Accordingly, the yield stress at 34°C was reduced by about 98% (from 10 to 0.2 Pa) by heating to 121°C (i.e. with or without salt addition). The addition of 37 g/L TDS reduced the yield stress at 34°C by 15% (from 10 Pa to 8.5 Pa). A further increase of salinity to 76 g/L TDS only reduced the yield stress marginally throughout the temperature range (from 34 to 121°C) tested.

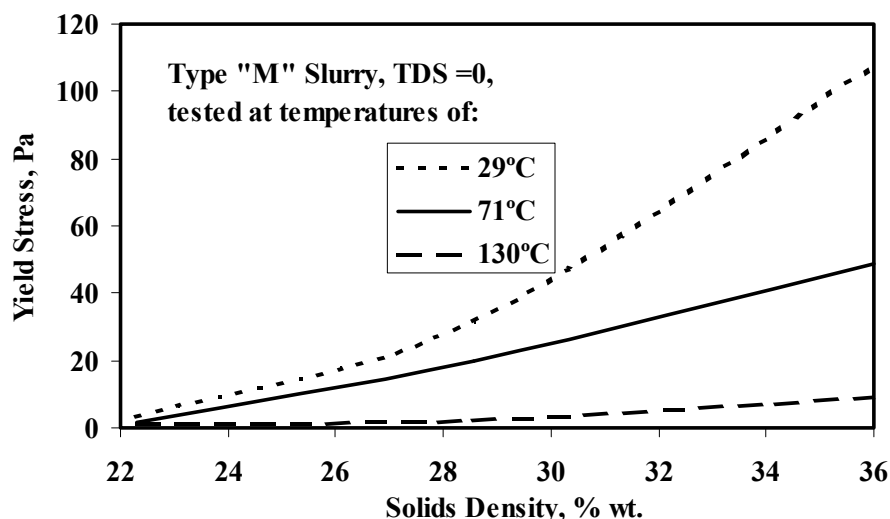


Figure 2 - Effect of Temperature on Yield Stress: Slurry Type "M"

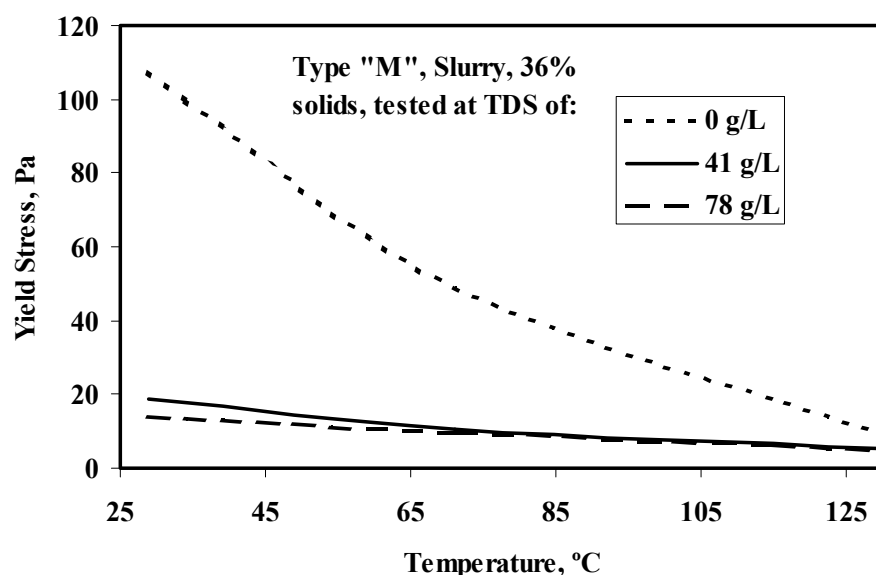


Figure 3 - Effect of Temperature and Salinity on Yield Stress: Slurry Type "M"

The effect of saline water upon increasing the flowability of the laterite ore slurries is attributed to the chloride ions preventing the swelling of the hydrophilic clays (1). Additional details summarising the chemical interactions that influence lateritic ore slurry rheology are given below.

The most chemically active fraction of laterite ores consists of colloidal clays. Given their very small size (microns and below), the colloidal particles display a

very large surface area per unit weight. These materials also generally exhibit net negative charge because of cation substitutions in the crystalline structures of the clay. Cations are attracted to these negatively charged particles, allowing for the ionic exchange with a solution. The energy of retention of cations decreases in the following order: Al³⁺, Ca²⁺, Mg²⁺, Ca²⁺, K⁺, Na⁺, H⁺. Accordingly, when fresh water is used for laterite ore slurry make-up, there will be some Ca²⁺ ions readily available, which will occupy the available sites preferentially over Na⁺ ions and subsequently cause swelling.

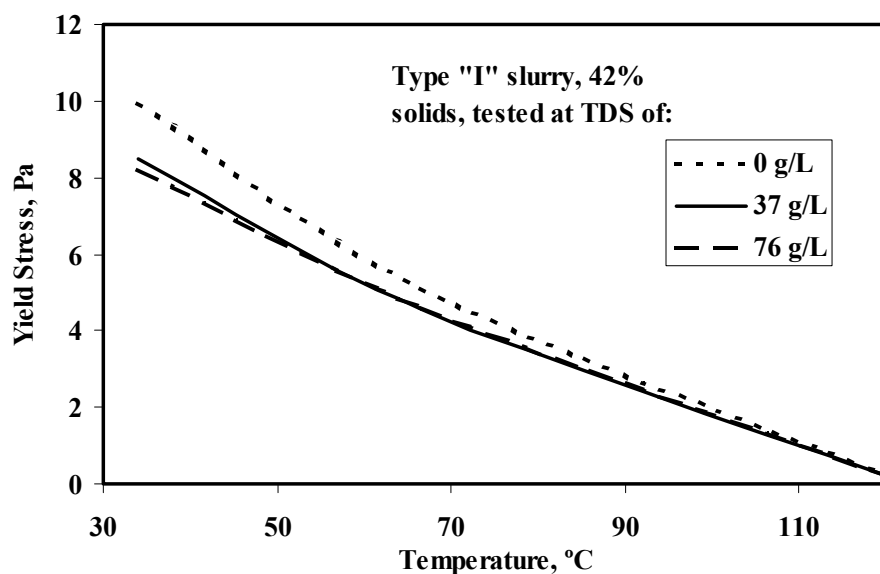


Figure 4 - Effect of Temperature and Salinity on Yield Stress: Slurry Type "I"

Smectite and so-called Mixed Layer (Illite-Smectite) clays are the most watersensitive, and hence most prone to swelling after ion exchange. Saline water containing predominantly Na^+ cations produces better "competing" conditions to occupy some of the available negative sites on the clay particles. Hence, the amount of Ca^{2+} cations adsorbed and exchanged will be lower, causing ultimately a reduction of swelling. Ion exchange induced swelling can cause significant changes in the rheological properties of a given slurry, and furthermore its flowability, settling and thickening properties. Swollen clay particles tend to be prone to flocculation; the resulting underflow however tends to display lower pulp density. Conversely, dispersed clay particles form stable suspensions, thus exhibiting slower settling velocity; the resulting underflow, however, tends to display higher solids densities than the flocculated pulp. As mentioned before, given the particulate fluid character of the laterite slurries, the specific gravity of the particle-aggregates ("flow units") tends to change with the pulp density (6).

EFFECT OF SALINITY ON PRODUCT RECOVERY

BACKGROUND

Recovery processes of nickel and cobalt from pregnant leach solutions include precipitation of nickel and cobalt using magnesia or lime suspensions (7-9). Subsequent treatment of the resulting

mixed nickel/cobalt hydroxide product requires dissolved salt levels within certain specifications, which are dictated by process and equipment restraints. Processes such as ammonia re-leaching followed by solvent extraction and electrowinning require strict limits on the concentration of chloride, calcium, magnesium and manganese. Equipment constraints are mainly related to the potential of chloride induced corrosion.

High concentration gradient precipitation using magnesia and/or lime suspensions are generally preferred because of the increased solids loading. According to conventional wisdom, the expectation is that the throughput would increase proportional to the solids loading. Recent pilot plant testing campaigns on various nickel laterite projects indicated however that the throughput achieved was significantly lower than anticipated due to the high retention time requirements, generally several hours. Diffusion appeared to be the rate-limiting factor, causing the mobility of both the reactants and products to be restricted. High retention times caused increased reagent consumption, due to mainly co-precipitation of manganese and magnesium. The excess of precipitation reagents caused increased impurity uptake. The impurities were present as partly soluble chlorides and sulphates, presumably retained both physically and chemically. Physically entrapped soluble salts could be removed by washing, depending on factors such as

precipitate grain size and morphology. Chemical compounds encountered in the mixed hydroxide included mainly basic salts, especially sulphates, which are practically impossible to remove economically.

The magnesia milk produced precipitates assaying typically from 38-45 wt. % Ni at average Ni:Mn ratios of about 12:1. They also contained relatively high levels of impurities, especially chloride, sulphate and magnesia. These precipitates required further purification. For example, alkaline washing was considered to reduce the chloride contamination, thereby yielding increased operating cost.

The precipitates produced by lime slurry precipitation assayed relatively low nickel grades, i.e. 13-17 wt. % Ni at average Ni:Mn ratios of about 4:1. The main anionic impurities consisted of sulphates, including gypsum.

Similar results were found in the case of several other processes based on high gradient precipitation from solutions. A typical example in that respect is the production of high purity metal salts (10). However, this paper will focus on exemplifying the application of thermodynamics in understanding the nickel precipitation process chemistry, in order to develop a suitable alternate process.

PROCESS CHEMISTRY AND THERMODYNAMICS

Relevant stoichiometric reaction equations on the precipitation of nickel using lime and magnesia under various conditions are listed in Table II. The respective free enthalpy (ΔG^{60}) values at 60°C are also given (11). The reactions are sorted in reverse order of their ΔG^{60} values for the equations as written (from left to right). Accordingly, the most thermodynamically favourable reaction to occur is the precipitation of nickel with CaO (calcium oxide, quick lime), as illustrated by equation 1. At the bottom of the table, the positive ΔG^{60} value indicates that the direction of reaction illustrated by equation 15 is reversed, thus this reaction will occur from right to the left at 60°C.

According to the thermodynamic data, lime as CaO is the most reactive precipitating agent. However, the reaction illustrated by equation 1 does not occur in practice, since the lime is generally brought into the system as a suspension (equation 5). Therefore, the lime reacts as calcium hydroxide (Ca(OH)_2) to precipitate nickel (via equation 2). With a few exceptions, (i.e. Na, K), the lime is also capable of precipitating most other cations from solution (Ni, Co, Mn, Mg, Al, etc), as well as anions such as sulphate, yielding gypsum. Thus, lime has a limited selectivity. On the other hand, some of the co-precipitated species, such as Mn(OH)_2 can precipitate Ni as illustrated by equation 11.

Calcium hydroxide can generate magnesia in situ, primarily as Mg(OH)_2 (equation 6) as well as MgO (equation 12). Therefore, in the case of a lime-based process, the freshly produced Mg(OH)_2 and MgO could become available to precipitate nickel. However, the tendency to react is greater for the MgO (equation 3) than for Mg(OH)_2 (equation 8). The unreacted Mg(OH)_2 tends to precipitate instantly due to its low solubility, thus it would become unavailable for nickel precipitation, while becoming essentially an impurity.

If a magnesia milk-based system is used, the MgO would react with Ni preferentially (equation 3) instead of reacting with water (equation 9). The magnesia system tends to be dependent on the saturation concentration of MgSO_4 . As indicated by equation 10, the MgO reacts with nickel sulphate at 60°C when the resulting MgSO_4 "salts out"; under the same conditions, the Mg(OH)_2 will not react at all, as the equilibrium is rather forced towards its formation (equation 15).

The above considerations are also valid in the case of cobalt, with the only observation that the precipitating tendency of cobalt is slightly greater than that of nickel.

Equilibrium curves were calculated for the case of a typical feed solution produced in a laterite pilot plant. The

Table II- Free Enthalpy Values at 60°C

NO.	CHEMICAL REACTION EQUATION	ΔG (KCAL)
1	$\text{CaO} + \text{NiSO}_4(\text{a}) + 3\text{H}_2\text{O} = \text{Ni(OH)}_2 + \text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	-33.5
2	$\text{Ca(OH)}_2 + \text{NiSO}_4(\text{a}) + 2\text{H}_2\text{O} = \text{Ni(OH)}_2 + \text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	-19.9
3	$\text{MgO} + \text{NiSO}_4(\text{a}) + \text{H}_2\text{O} = \text{Ni(OH)}_2 + \text{MgSO}_4(\text{a})$	-14.8
4	$\text{Ca(OH)}_2 + \text{MnSO}_4(\text{a}) + 2\text{H}_2\text{O} = \text{Mn(OH)}_2 + \text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	-14.4
5	$\text{CaO} + \text{H}_2\text{O} = \text{Ca(OH)}_2$	-13.6
6	$\text{Ca(OH)}_2 + \text{MgSO}_4(\text{a}) + 2\text{H}_2\text{O} = \text{Mg(OH)}_2 + \text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	-11.4
7	$\text{MgO} + \text{MnSO}_4(\text{a}) + \text{H}_2\text{O} = \text{Mn(OH)}_2 + \text{MgSO}_4(\text{a})$	-9.3
8	$\text{Mg(OH)}_2 + \text{NiSO}_4(\text{a}) = \text{Ni(OH)}_2 + \text{MgSO}_4(\text{a})$	-8.5
9	$\text{MgO} + \text{H}_2\text{O} = \text{Mg(OH)}_2$	-6.3
10	$\text{MgO} + \text{NiSO}_4(\text{a}) + \text{H}_2\text{O} = \text{Ni(OH)}_2 + \text{MgSO}_4 (*)$	-5.8
11	$\text{Mn(OH)}_2 + \text{NiSO}_4(\text{a}) = \text{Ni(OH)}_2 + \text{MnSO}_4(\text{a})$	-5.5
12	$\text{Ca(OH)}_2 + \text{MgSO}_4(\text{a}) + \text{H}_2\text{O} = \text{MgO} + \text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	-5.1
13	$\text{Mg(OH)}_2 + \text{MnSO}_4(\text{a}) = \text{Mn(OH)}_2 + \text{MgSO}_4(\text{a})$	-3
14	$\text{MgO} + \text{MnSO}_4(\text{a}) + \text{H}_2\text{O} = \text{Mn(OH)}_2 + \text{MgSO}_4 (*)$	-0.3
15	$\text{Mg(OH)}_2 + \text{MnSO}_4(\text{a}) = \text{Mn(OH)}_2 + \text{MgSO}_4 (*)$	6

ΔG - free enthalpy at 60°C (*) indicates the presence of solid MgSO_4
Thermodynamics data were calculated using Outokumpu HSC for Windows, Release 4.1.

curves suggest that in the case of these stoichiometry based Ca(OH)_2 and MgO precipitation systems, there is a certain domain where selectivity versus co-precipitation of Mn(OH)_2 and Mg(OH)_2 appears possible. The extent of that selectivity would be dependent on the degree of sub-stoichiometry at which the precipitating reagent is added. The corresponding equilibrium composition curves given in Figure 5 for the case of the Ca(OH)_2 based system, suggest that the maximum nickel hydroxide concentration, achievable in terms of strict stoichiometry theory would be about 87%. That is 55 wt.% Ni compared to about 15 wt.% produced in testwork. An identical calculation for the case of the magnesia based system would return a nickel precipitate containing about 61 wt.% Ni, compared to about 41 wt.% average produced by testwork.

It is obvious that the real lime and magnesia-based processes are more complicated than suggested by the fundamentals discussed above. The main deviation from the theory consists of the formation of multiple-salts, such as for example basic sulphates. Beside chemical co-precipitation, physical entrapping of solution containing dissolved salts is a common occurrence. Washing efficiency tends to be generally

low, mainly due to the amorphous nature of the metal precipitates.

Additional factors contributing to the process chemistry and kinetics of the two precipitation systems (magnesia and lime-based) discussed are solubility data. Lime is more soluble in water compared to magnesia. At 60°C, the saturated lime solution contains about 1.2 g/L Ca(OH)_2 , or, about 1 g/L equivalent CaO (12). Under the same conditions, the solubility of magnesia at saturation is about 0.005 g/L equivalent MgO; thus the CaO/MgO solubility ratio is about 160. Regarding the reaction products, a saturated aqueous solution contains about 2 g/L gypsum at 60°C, corresponding to 1.6 g/L equivalent CaSO_4 . The solubility of magnesium sulphate under identical conditions is about 46 g/L MgSO_4 ; thus the $\text{Mg}^{2+}/\text{Ca}^{2+}$ solubility ratio by weight is about 25. The presence of halide anions in solution, such as chloride, tends to increase the solubility of gypsum (12).

The reactivity trends suggested by the thermodynamic data presented above can be used to design alternative processes that allow controlling the process chemistry to a significant degree, such as the Incremental Flash Crystallisation Precipitation process.

INCREMENTAL FLASH CRYSTALLISATION-PRECIIPITATION PROCESS

The idea of incremental flash crystallisation is based upon process chemistry thermodynamics and reaction kinetics. As detailed earlier, it is necessary to ensure that a given reaction will occur under certain conditions, characterised in this case by temperature and reagents availability per unit of volume/mass, i.e. concentration. From a kinetic point of view, most precipitation processes can be practically assimilated to a very fast crystallisation. Crystallisation consists of three stages: supersaturation, nucleation and growth (13, 14).

The principle of the Incremental Flash Crystallisation Precipitation ("IFCP") process consists of limiting the presence of raw materials in the reaction mass, defining and controlling the allowable residence time and minimising the co-precipitation of unwanted reaction products. Well-dosed additions, with controlled deficit of one reagent (thus causing concomitant excess of the antagonistic reagent) are used to ensure fast reaction rate, instant impurity rejection and high recovery. The net result is that the reaction product is generated on a gradual but fast-paced basis, i.e. "growing like a crystal, but growing fast". Optimum operating conditions allow sufficient time for the impurities to be "forced out" from the diffusion layer. At the same time, the particles tend to grow sufficiently in size as to display good settling, washing and rheological characteristics. The main advantages of this method are significantly lower reagent consumption, control and use of non-conventional stoichiometry, increased productivity due to extremely short residence time requirements and high purity ensured by the incremental, discrete reagent additions. Commercial applications could include production of metallic and non-metallic compounds from solutions, such as salts and pigments as well as various intermediate products.

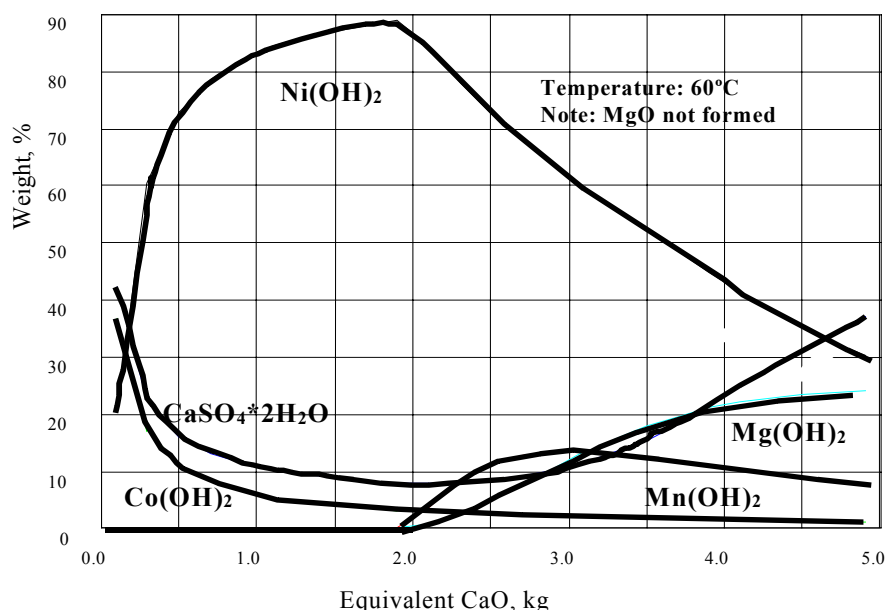


Figure 5 - Equilibrium Composition: $\text{Ca}(\text{OH})_2$ Precipitation System

IFCP PROCESS APPLICATION EXAMPLE

This example illustrates the process of obtaining a nickel-cobalt mixed hydroxide precipitate from a pregnant leach solution produced by the HPAL leaching of a laterite ore. The details provided below focus on process efficiency, reagent consumption and rejection of chloride, which is the main impurity.

The solution composition is provided in Table III. Preliminary testing using magnesia and lime indicated that only the lime was suitable to be used in the IFCP process. This result was not surprising, in the light of the process chemistry fundamentals described above.

The solution was subjected to a three-stage co-current precipitation process using aqueous lime at the desired concentration, 55°C, and 9.8 minutes total residence time. A flowsheet of the process is shown in Figure 6. Several hours of operating time were allowed to reach steady state conditions and produce sufficient quantity of product. Representative samples were retrieved during steady state operation and subjected to particle size and chemical analyses. The targeted incremental stoichiometric additions of calcium hydroxide were 70%, 23% and 18%

in stages 1, 2 and 3, respectively. They were calculated versus the sum of the Ni and Co requirements for the formation of their respective stoichiometric hydroxides.

The test conditions are summarised in Table IV. Based on the amount of nickel and cobalt precipitated, it was concluded that the actual (realised) stoichiometric additions of calcium hydroxide were 81%, 15% and 3% in stages 1, 2 and 3, respectively, thus suggesting a non-conventional precipitation stoichiometry.

These values were calculated versus the sum of Ni and Co requirements for the products formed, according to the molar stoichiometry matrix shown in Table V. Assuming that the product washing was efficient, it could be postulated that basic mixed sulphates were formed. Given its low concentration, it could not be ascertained whether the co-precipitated chloride was chemical or physical in nature.

The precipitates assayed from 35-41 wt.% Ni, compared to the 13-17 wt.% Ni content range produced by the conventional lime-slurry based system and to the 38-45 wt.% Ni content range produced by the magnesia based precipitation system.

Table III - Feed Solution Composition (ppm)

ELEMENT	Ni	Co	Cu	Zn	Fe	Al	Cr	Mg	Mn	SO ₄	Cl	Si
mg/L	2,042	71	0.4	13	1	<1	<1	16,650	451	61,060	20,500	67

The dehydration ("chemical drying") of the precipitate was illustrated by the profile of the crystallization water content from stages 1 through 3. Since dehydration is associated to the ageing process, the test results also substantiated that the phenomenon was underway even from the incipient stage of the reaction.

The particle size profile versus reaction progress (Figure 7) indicated that particle growth occurred. Possible mechanisms could have been agglomeration and/or crystallisation and/or releach-recrystallisation. Product purity comparison versus the existing processes is provided in Figure 8. Accordingly, the chloride content of the ICFP product ranged from 0.02-0.07 wt.%, throughout three incremental stages, compared to 1 wt.% Cl⁻ and 0.4 wt.% Cl⁻ content of the final products precipitated using the conventional magnesia-slurry and lime-slurry based systems, respectively.

The process efficiency data (Table VI) indicate that the reaction progressed incrementally, as both precipitation and co-precipitation increased proportionally to the incremental reagent addition. Correlating the grade-purity data to the precipitation efficiency data allows defining key ICFP process variables such reagents concentration as well as the frequency and value of the stoichiometry addition increments. Practically, the ICFP process can be realised using either conventional MSMPR ("mixed suspension mixed product removal") type of equipment or, alternatively, tubular reactors with static mixers.

Table IV - Test Conditions Summary

STAGE NUMBER	1	2	3	TOTAL
Retention time (minutes)	3.8	3.2	2.9	9.8
Conventional stoichiometry Ca(OH) ₂ addition, %	70.2	23.3	17.9	111
Non-conventional stoichiometry Ca(OH) ₂ addition, %	80.7	14.8	3.2	98.7

*Stoichiometry calculated versus the sum of Ni and Co.

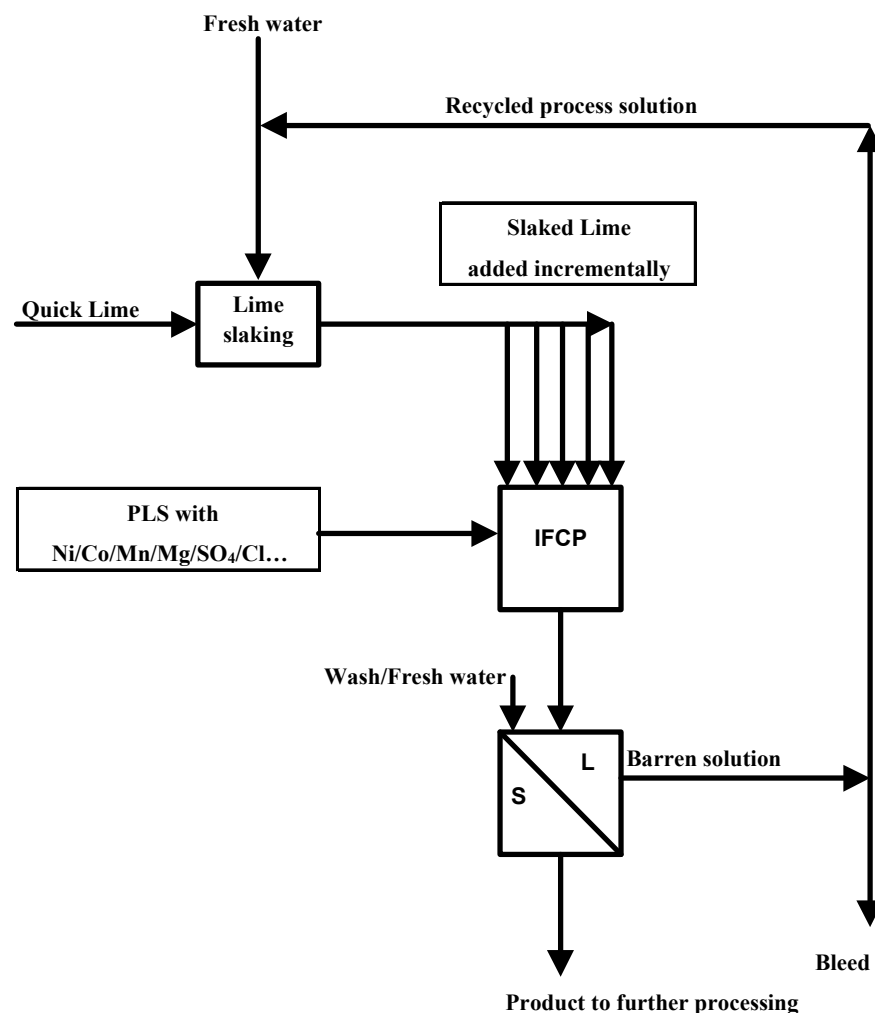


Figure 6 - ICFP Process Flow Sheet

Table V - Composition and Molar Stoichiometry Matrix of the Precipitates

METAL STAGE	METAL COMPOSITION OF RESIDUES, %			*STOICHIOMETRY MATRIX OF RESIDUES		
	1	2	3	1	2	3
Ni	40.8	38.4	34.7	0.70	0.65	0.59
Co	1.93	1.48	1.3	0.03	0.03	0.02
Mn	3.01	4.74	5.68	0.05	0.09	0.10
Ca	0.03	0.38	0.99	0.001	0.01	0.02
Mg	0.36	0.98	2.03	0.01	0.04	0.08
Cl	0.02	0.02	0.07	0.0006	0.0007	0.0019
SO ₄	3.10	6.8	9.2	0.03	0.07	0.10
OH	21.44	22.54	23.45	0.63	0.66	0.69
H ₂ O	29.31	24.66	22.58	1.63	1.37	1.25

*Corresponding example of compound, i.e. stage 1: $\text{Ni}_{0.7} \text{Co}_{0.03} \text{Mn}_{0.05} \text{Mg}_{0.01} \text{Ca}_{0.001} (\text{SO}_4)_{0.0} \text{OH}_{0.63} \text{Cl}_{0.0006} * 1.63\text{H}_2\text{O}$

Table VI - Test Results Summary

METAL/ STAGE	METAL IN BARREN SOLUTION, mg/L			PRECIPITATION EFFICIENCIES, %		
	1	2	3	1	2	3
Ni	404	89	21	80	96	99
Co	6	7	7	93	91	90
Mn	300	190	113	33	57	75

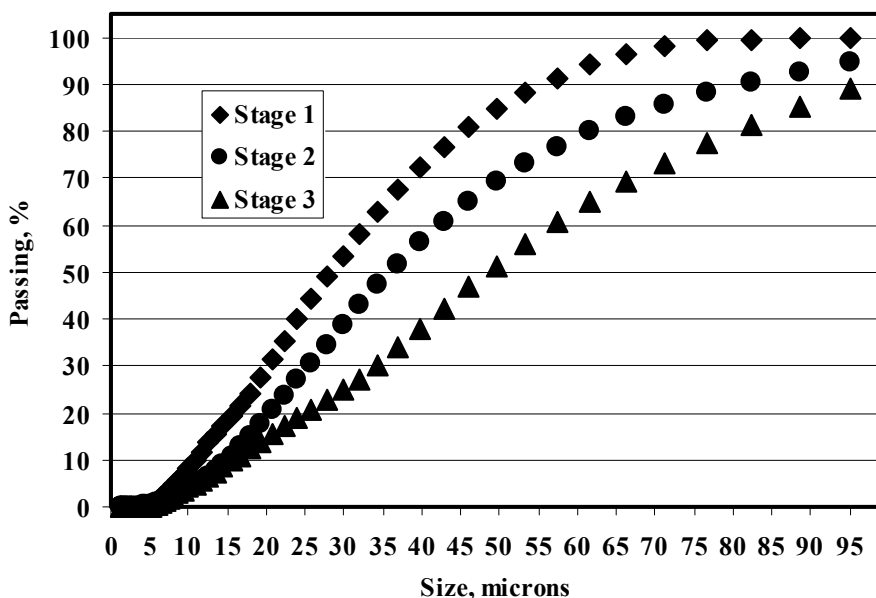


Figure 7 - IFCP Particle Size Profile versus Reaction Progress

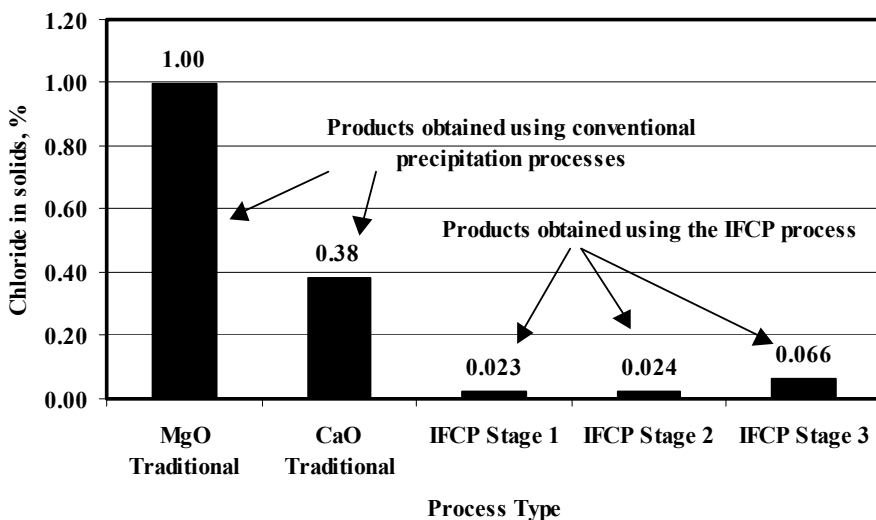


Figure 8 - Comparative Chloride Rejection Data: Conventional vs. IFCP Process

CONCLUSIONS

- The rheological properties of typical "M" and "I" laterite ore slurry samples tested were dependent upon temperature and Total Dissolved Solids (TDS).

- The yield stress of a type "M" slurry was reduced by 92% by heating from 31°C to 131°C. The yield stress of a type "M" slurry at 31°C was reduced by 83% by increasing the solution TDS from 0 to 41 g/L. A further increase of salinity to 78 g/L TDS reduced the yield stress only marginally. The relative decrease in yield stress of a type "M" slurry due to the effect of heating from

31°C to 131°C and in the 41 to 78 g/L TDS range amounted to 71% and 66%, respectively. The yield stress of a laterite type "I" slurry was reduced by about 98% by heating from 34°C to 121°C, and without salt addition. The addition of 37 g/L TDS in solution reduced the yield stress at 34°C by 15%. A further increase of salinity to 76 g/L TDS reduced the yield stress only marginally.

- The effect of saline water upon increasing the flowability of the laterite ore slurries is attributed to the sodium-salinity preventing the ion exchange induced swelling of the hydrophilic clays. 2002-6
- High concentration gradient precipitation from highly saline solutions, by using magnesia and/or lime suspensions is detrimental to the process throughput and resulting product quality.
- The main advantages of the "Incremental Flash Crystallisation Precipitation" (IFCP) process are significantly lower reagent consumption, control and use of non-conventional stoichiometry, increased productivity due to extremely short residence time requirements and high purity precipitates as a result of incremental, discrete reagent additions.
- IFCP tests using lime as a reagent produced precipitates assaying from 35-41 wt.% Ni, compared to the 13-17 wt.% Ni content range produced by the conventional lime-slurry based system, and to the 38-45 wt.% Ni content range produced by the magnesia based precipitation system. The chloride content of the IFCP product ranged from 0.02-0.07 wt.%, throughout three incremental stages, compared to 1 wt.% Cl⁻ and 0.4 wt.% Cl⁻ content of the final products precipitated using the conventional magnesia-slurry and limeslurry based systems, respectively.

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