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The Past and the Future of Nickel Laterites

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Abstract

Production of nickel from laterite ores has occurred for over 100 years beginning with processing of garnieritic ores from New Caledonia. However, until now the world nickel supply has been predominantly from sulfide sources. Going forward, the authors project that the production of nickel from sulfide ores will remain more or less constant. Most of the expansion in nickel production capacity over the next ten years will come from processing of laterite ores. Thus the capital and operating costs of new laterite projects will have significant impact on the nickel supply and therefore price.

The authors have reviewed the history and capital and operating costs of various recent laterite projects and of those "on the drawing board". The authors have also evaluated the risk associated with such projects. The paper will discuss the impacts of this and the recent history on the future development of laterite nickel projects.

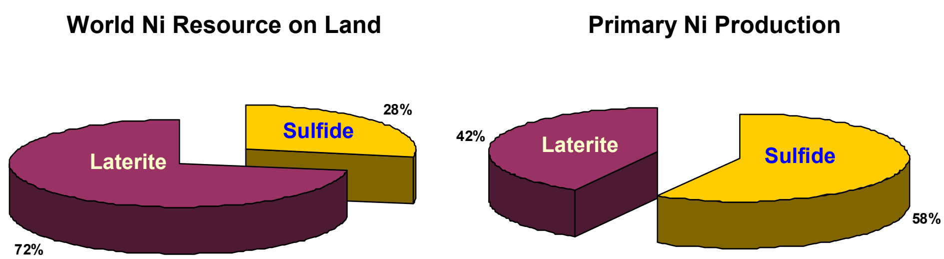
Introduction

Laterite ores were the major source of early nickel. Rich laterite deposits of New Caledonia were exploited starting the end of the nineteenth century to produce white metal ("alliage blanc"). The discovery of sulfide deposits of Sudbury during the early part of the 20th century shifted the focus to sulfides [Ref 1]. This dominance of the sulfide ores as the major source of nickel has not been challenged until now. Thus, while about 70 % of world land based nickel resources are contained in laterites, they currently account for only about 40 % of the world nickel production (Figure 1). Nickel production and demand has continued to increase since 1950. The total increase in production from 1950 to 2003 has been about 8 fold from about 140 kt/yr in 1950 to 1200 kt/yr (forecast) in 2003 [Ref 2,3]. In 1950 laterite source nickel formed only a small fraction of the production (<10%). In 2003, nickel from laterite sourced accounted for 42 % or about 510 kt Ni. By 2012 the share of laterite source nickel is expected to rise to 51 %. The growth in nickel supply has followed economic cycles and other world events. However on the whole nickel production has risen at a rate of about 4% p.a. (Figure 2). This is higher than the average increase in the World GDP.

Figure 1

World's Land Based Nickel Resources and Primary Nickel Production

(Resources Distribution by Contained Nickel)

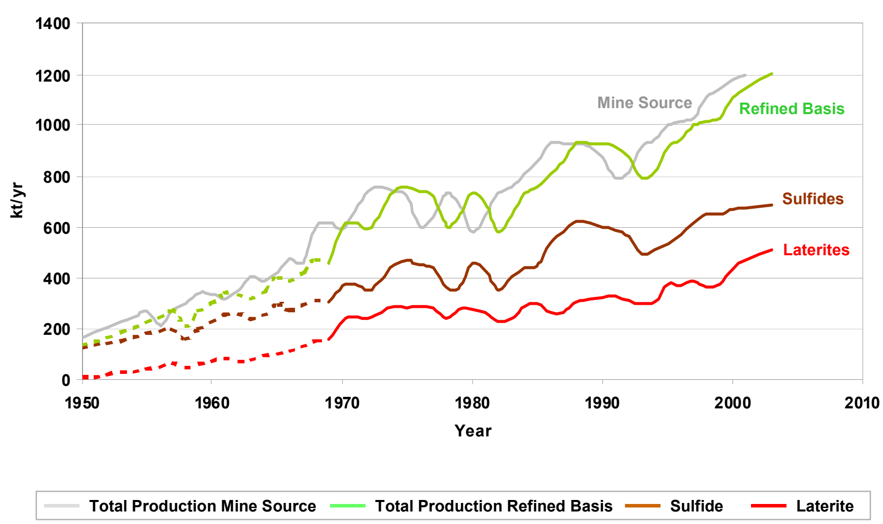


	MT Resource	% Ni	Mt Ni	% of Total
Sulphide	10500	0.58	62	27.8%
Laterite	12600	1.28	161	72.2%
Total	23100	0.97%	223	100

Figure 2

Nickel Production, kt/yr

1950 – 2003



Nickel Laterite Geology, Mineralogy and Resources

A general description of nickeliferous laterite has been provided by Golightly [4] and Alcock [5]. Other reviews include those by Burger [6]. Geology and mineralogy of individual deposits has been discussed in AIME 1979 and other symposia and seminars [7-13].

Tropical weathering (laterization) comprises a prolonged process of mechanical and chemical weathering that produces profiles of great variability in thickness, grade and chemistry and ore mineralogy.

Nickel laterites occur in present or past zones of the earth that have experienced prolonged tropical weathering of "ultramafic" rocks containing ferro-magnesian minerals (olivine, pyroxene, and amphibole) associated with a variety of geological settings spanning the Precambrian to the Tertiary. Ultramafic rocks comprising of dunite (essentially monomineralic olivine), peridotite (olivine, pyroxene, and hornblende), pyroxenite (orthopyroxene or clinopyroxene), hornblendite (monomineralic hornblende) and serpentinite (essentially serpentine $2H_4Mg_3Si_2O_9$). Serpentine is the most common product of hydrothermal alteration of olivine in the presence of water at temperatures between 200 to about 500^{O}C. The process of serpentinization occurs without a significant volume change due to the removal of large quantities of magnesia and lesser silica. During this process some of the nickel is mobile in solution and some remains in the serpentine, or combines with magnetite that is a co-product of serpentinization. The presence or lack of serpentine has a profound influence on the character of the weathering profile. The latter may be upgradable for nickel content by rejecting low-grade boulders, however with a subsequent change in "ore" chemistry and quantity.

The chemistry and mineralogy of ultramafic rocks has changed over geologic time as the Earth's crust thickened, mantle mixing occurred, and sea floor spreading moved the continents with some ocean floor material obducted on to the continental margins. Alteration in the form of regional or contact serpentinization (hydration) and other metamorphic overprinting is typical of the older, thinner ultramafic terrains. The younger ultramafics obducted from the ocean floor, formed larger, thicker sheets that have either an extensive or a structurally controlled local serpentinization with no other metamorphic overprint. The deleterious trace elements Cu, Pb, Zn, are compositionally higher in the older shield ultramafics compared to the more recent large, obducted mid-ocean derived ophiolite. The structural character and the chemical and mineralogical variability of the various bedrock sources lead to variable and unique laterite weathering profiles.

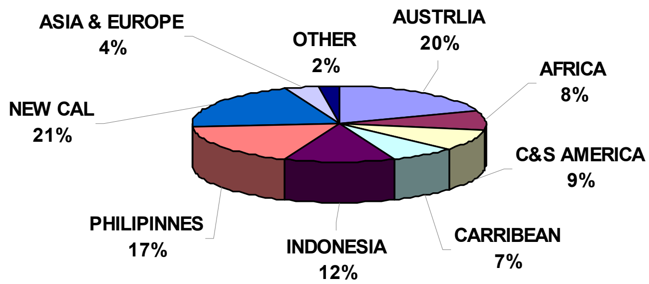
Some of the oldest and most highly deformed ultramafics to undergo laterization are found in the complex Precambrian shields in Brazil and Australia. Smaller highly sheared alpine-type intrusives have formed laterite profiles on favourable topographic landforms in Guatemala, Columbia, Central Europe, India, and Burma. Large thrust sheets of obducted ophiolite in Tertiary to Mesozoic island arcs and continental collision zones underwent laterization in plateau, crest and spur landforms in New Caledonia, Cuba, Indonesia and the Philippines. A period of very active laterization extended from about the mid-Tertiary to the mid-Quaternary. Weathering in the tropical climes continues to this day but at a much lower rate and in an ever-decreasing scale because the footprint of the world's population, with some notable exceptions, is quickly removing the forests that protect the tropical soils from erosion, cropping, or other cultural activities.

Distribution of laterite resources by region is shown in Figure 3.

Figure 3

World Nickel Laterite Resources

(Distribution by Contained Nickel)



	Mt	%Ni	Mt Ni	% of Total
AUSTRLIA	2452	0.86	21	13.1%
AFRICA	996	1.31	13	8.1%
C&S AMERICA	1131	1.51	17	10.6%
CARRIBEAN	944	1.17	11	6.9%
INDONESIA	1576	1.61	25	15.7%
PHILIPINNES	2189	1.28	28	17.4%
NEW CALEDONIA	2559	1.44	37	22.9%
ASIA & EUROPE	506	1.04	5	3.3%
OTHER AUSTRALASIA	269	1.18	3	2.0%
TOTAL LATERITES	12621	1.28	161	100%

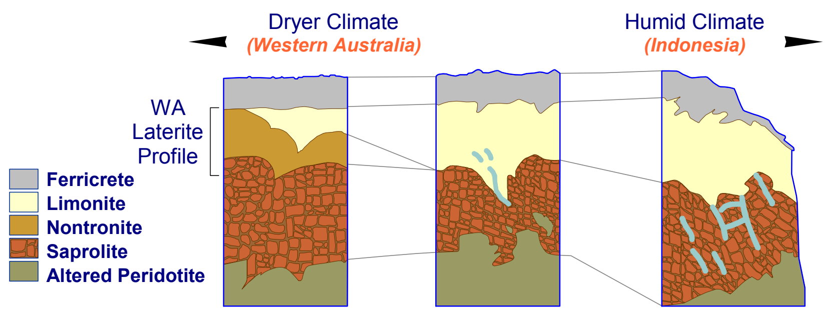
The favourable topographic landforms are gentle crests, spurs, and plateaus of hills in humid environments. It is rare that economic concentrations of nickel laterite form on the steeper flanks of hills or on the sedimentary out-wash plains below the ultramafic hills of tropical rainforests. However, in Australia the Precambrian rocks were deeply eroded to produce broad semi-desert plains and low relief hills to set the stage for a unique laterite development in which smectite clay (nontronite) is the predominant mineralized layer. In Australia these are the so-called "dry laterites" where water circulation was either restricted or intermittent with incomplete flushing of the silica from the laterized soil. These "silica-excess" profiles in some instances may be upgraded for nickel content with selective mechanical removal of the silica. As yet, none of the Australian projects have been profitable due to low grade or less than economical throughput.

A simplified picture of the complex suite of nickel laterite profiles has been published widely in the literature (for example Ref 5). Figure 4 illustrates the range of profiles from the dry West Australian type to the wet tropical laterites, all of which have either colluvium or ferricrete (iron cap) at the top, followed by a limonite or ferruginous layer comprised primarily of goethite and few residual mineral/rock fragments, followed by a transitional zone of limonite (or smectite in the case of the "dry laterites"), and a basal boulder saprolite transitional to weathered bedrock. The boundaries are generally gradational between the layers. The individual layer thicknesses are highly variable and are influenced by relic faults extending upwards in the weathering profile from the bedrock.

From the project perspective, nickel laterites are either sensitive to cut-off grade (no economically rejectable boulders in the clay) or are sensitive to recovery factors if the saprolite is upgradable. In most cases the limonite portion of the "ore" profile cannot be upgraded. Figure 5 illustrates a typical scenario when a cut-off grade is raised in a non-upgradable saprolite. Conversely, the laterite resource expands exponentially as the cut-off grade is dropped.

Figure 4

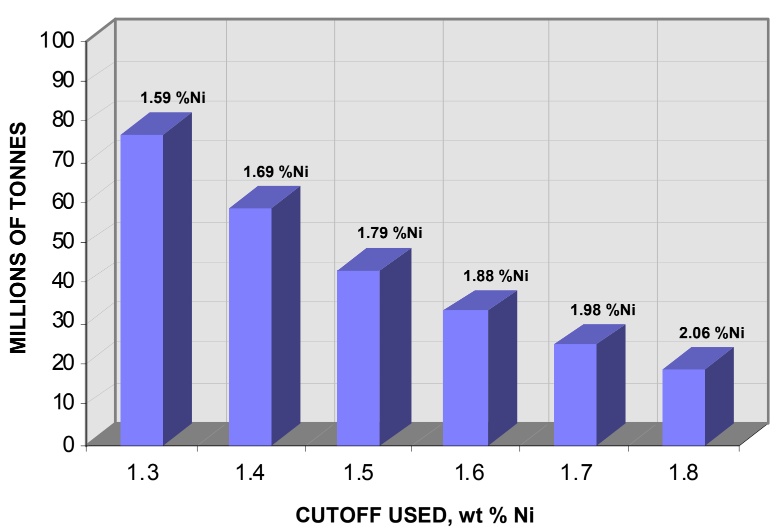
Laterite Profiles: Wet and Dry Laterites



	%Ni	%Co	%Mg	%Fe	%Ni	%Co	%Mg	%Fe	%Ni	%Co	%Mg	%Fe
Ferricrete	.2 -.5	.02	.6	35+	.2 -.5	.02	.6	35+	.2 -.5	.02	.6	35+
Limonite	.6-1.4	.1-.2	1-2	45	1.2-1.7	.1-.2	1-2	45	1.2-17	.1-.2	1 -4	45
Nontronite	1.2	.08	3.5	18								
Saprolite	.4	.02	12.0	9	1.5 -3	.05-.1	10-20	10-25	1.5-3	.05-.1	10-30	10-20

Figure 5

Serpentine Saprolite Ore Reserves and Ni Cutoff



Estimates of the global nickel laterite resource vary. For example, some of the Australian "resources" are defined at 0.5% Ni cut-off. A global resource estimate is therefore open to review and editorial comment especially during times of medium term price instability that may draw new entrants to the industry. There is risk in defining and declaring resources and reserves because the lag from exploration to exploitation is generally 8 to 10 years.

The resources shown in this paper include Measured, Indicated and Inferred resource categories and in some instances Reserves. These data are obtained from various public sources. Care was taken to select the most appropriate resource estimate from the various sources that would best reflect the current knowledge of the various deposits.

An estimate of the global resource for nickel laterite is given below, from the perspective of the processes employed to extract nickel (pyrometallurgical or hydrometallurgical), in millions of metric tonnes:

	Resource Mt	Assay %Ni	Ni Content Mt	Distribution %
Total Pyromet	4,000	1.55	62	39
Total Hydromet	8,600	1.15	99	61
Total Laterites	12,600	1.28	161	100

Thus, there is almost twice as much laterite resource that is amenable to hydrometallurgical processing (limonite, nontronite/smectite) as that amenable to pyrometallurgical processing (saprolite, garnierite).

Figure 6

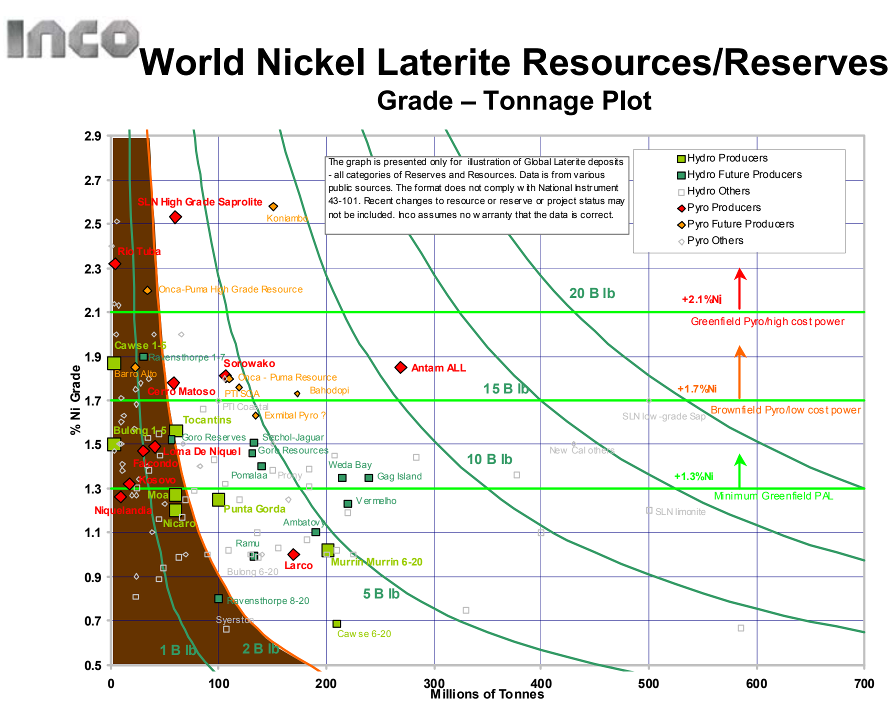


Figure 6 shows various major laterite deposits in the form of a grade-tonnage plot for mostly limonitic (high iron) deposits (suitable mainly for hydrometallurgical processing - shown in green) and mostly saprolitic or garnieritic deposits (suitable mainly for pyrometallurgical processing - shown in red). An economic project would have at least 40 kt nickel per year capacity requiring 800 kt (~2 billion pounds) of nickel deposit for a mine life of 20 years. For a PAL process, a minimum process plant feed grade of 1.3 % Ni is required for an economic project. Similarly, for a smelter a minimum grade of 1.7 % Ni (with low power cost) or 2.1 % Ni (with high power cost) is required, as shown in Figure 6.

Different nickel laterite profiles include following mineral types:

- Limonite, asbolite: (1 to 1.7% Ni, 0.1 to 0.2 % Co) These are suitable for pressure acid leach and Caron process
- Nontronite: (1 to 5% Ni, 0.05 to 0. % Co) These are suitable for pressure acid leach and smelting
- Serpentine: (1.5 to 10% Ni, 0.05 to 0.1 % Co) Typical composition is in the range 1- 2 % Ni and 0.05 to 0.07% Co. These ores are suitable for pyrometallurgical processes (ferronickel and matte smelting)
- Garnierite: (10 to 20% Ni, 0.05 to 0.1 % Co) Typical composition is in the range 2-3 % Ni and 0.05 to 0.1% Co. These are suitable for pyrometallurgical processes (ferronickel and matte smelting, but especially high carbon ferronickel)

Laterite Processes

A general description of laterite (and sulfide) nickel processes has been provided by Bacon [14], Simons [15] and Taylor [16]. Descriptions of individual operations and processes have been provided in various symposia and proceedings [7-13]. A variety of flowsheets are used to process laterite ores. They generally fall into two categories:

(1) pyrometallurgical processes, and (2) hydrometallurgical processes.

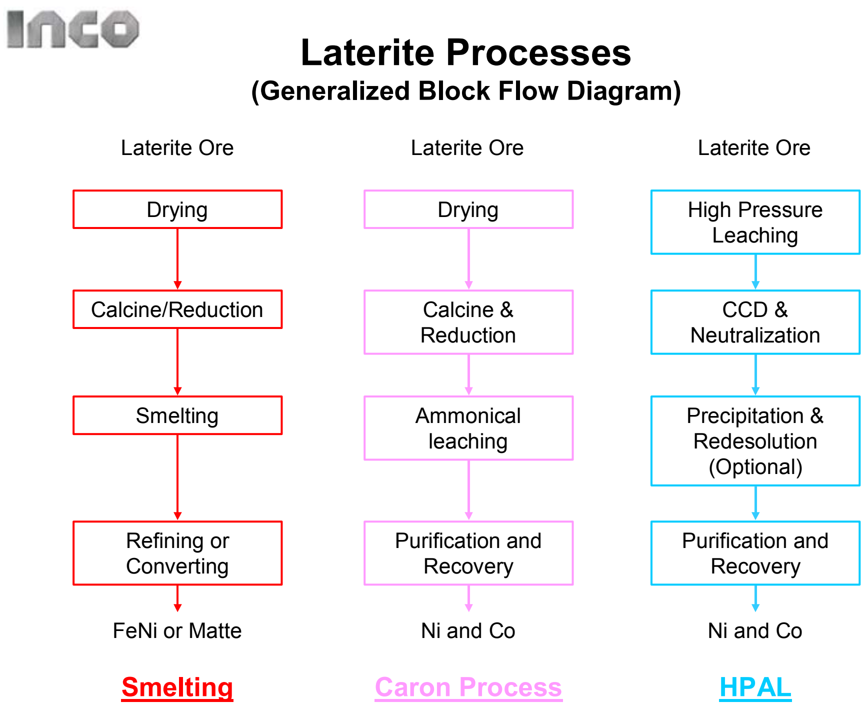
A majority of pyrometallurgical processes (ferronickel and matte smelting) use conventional flowsheet involving drying, calcining/reduction and electric furnace smelting. The two principal hydrometallurgical processes currently practiced are: Caron process and HPAL process. Generalized block flow diagrams for these processes are shown in Figure 7.

Typical feed compositions for various types of operations are provided in Table 1.

Table 1: Typical feed compositions for various operations

Analysis, wt. %	Moa Bay	Murrrin Murrin	SLN	Cerro Matoso	P.T. Inco
Ni	1.3	1.3	2.7	2.9	1.8
Co	0.15	0.09	0.07	0.07	0.07
Fe	48	22	14	14	18
Al	4.5	2.5			
Mg	1.0	4	15	9	10
SiO2	3.7	42	37	46	34
Mn	0.75	0.4			

Figure 7



Pyrometallurigical Processes

A review of pyrometallurgical processes for laterite ores has been done by Bergman [17]. Other reviews include those by Simons [15], Taylor [16], Diaz et.al. [18] and Ozberk et. al [19].

Pyrometallrugical processes are suited for ores containing predominantly saprolite (+/- supergene enrichment garnierite). These ores contain proportionately lower cobalt and iron compared to the limonitic ores. The Ni/Co ratio in the smelter feed is generally ~ 40. These ores are smelted to produce either ferro-nickel or matte.

In conventional pyrometallurgical processing the ore is dried, calcined (and sometimes reduced) in a rotary kiln and smelted in an electric furnace in the presence of carbon. If matte is the desired product, then sulfur is added to the kiln. The crude metal/matte is further processed/refined to produce the final product.

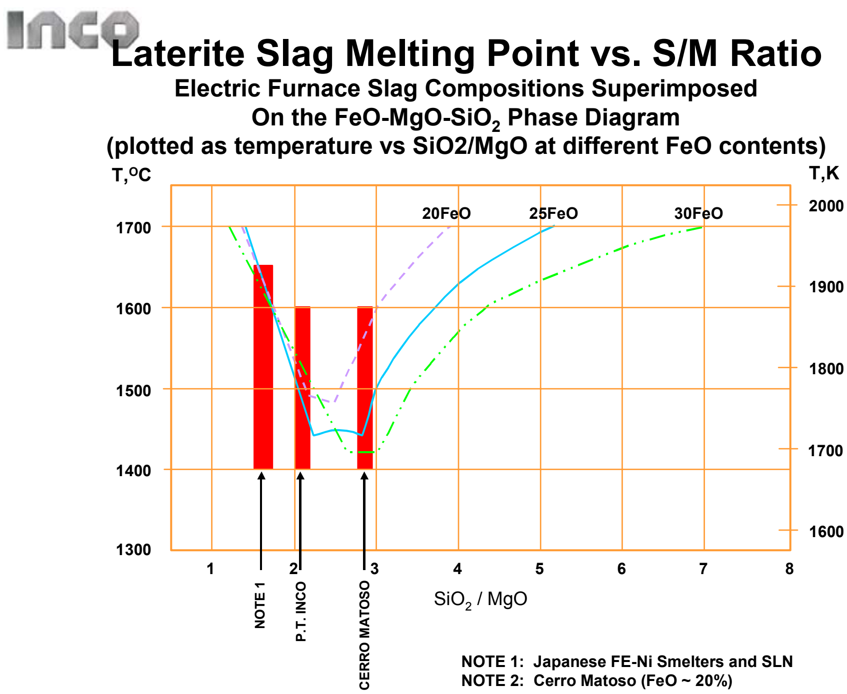
Pyrometallurgical processes are energy intensive since all of the free moisture and combined water has to be removed in the process and all of the material has to be first calcined and then melted to form a slag at about 1600°C. This requires both hydrocarbon fuels (coal, oil or naphtha) and electric power.

Figure 8 shows slag melting point as a function of SiO_2/MgO ratio and different FeO content. In an electric furnace the temperature difference between the metal or matte and slag is within a certain range, generally between 100 to 200°C at the metal-slag interface, depending on the electrical conditions in the furnace and slag characteristics. For an ore with a low melting point slag (those with the slag composition in the low-melting trough in the range 1.8 to 2.2 SiO_2/MgO ratio) the nickel-containing phase has to be low melting. Therefore production of mattes is better suited for such ores. Ores that produce high melting slags (either to the left or to the right of the eutectic trough, i.e.

SiO_2/MgO ratio either <2 or >2.5) are better suited to produce ferronickel. Ores in the SiO_2/MgO ratio in the intermediate range (2.3-2.5) are very corrosive to the furnace lining and require alteration to feed chemistry (by blending or fluxing) before they can be smelted

Recovery of nickel is in the range 90-95 % and that of cobalt is around 50%.

Figure 8



Ores suited to produce <u>high carbon ferro-nickel</u> are those with:

- High nickel grade (>2.2 % Ni)
- Low Fe/Ni ratio (5-6)
- High MgO

Examples of these operations are:

SLN Doniambo; Japanese Fe-Ni Smelters; Aneka Tambang smelter in Pomalaa (See Figure 8)

Low carbon ferronickel can be produced from saprolitic ores with generally >1.5% Ni and,

- Relatively high Fe/Ni ratio (6-12)
- High melting point slag (either high MgO (Example: Falcondo) or high SiO_2 (Example: Cerro Matoso) (See Figure 8)

Matte Smelting –

- Relatively high Fe/Ni ratio (>6)
- Lower melting point slag (<1600 deg C); SiO_2/MgO ratio between 1.8 and 2.2

Example: P.T. Inco

Hydrometallurgical Processes

A review of hydrometallurgical processes for laterites has been done by Reid and Barnett [20]. A general description is provided by Simons [15]. Other reviews include those by Taylor [16], Berezowsky et. al. [21-23], Urbain et. al [24] and O'Kane [25].

Caron Process

The Caron process could be used for limonitic ores or a mixture of limonite and saprolite. The ore is dried and nickel is selectively reduced (together with cobalt and some iron) to metallic nickel at ~ 700°C. The metallics are extracted by leaching in an ammoniacal solution. Recovery of nickel and cobalt decreases with increasing amount of saprolite since nickel and cobalt are locked in a silicate matrix and are difficult to reduce at this temperature.

However, the process can tolerate higher amount of Mg than the PAL processes

Examples: Nicaro, Punta-Gorda, Yabulu, Nonoc (now closed)

The Caron process suffers from several disadvantages: The front-end of the Caron process is pyrometallurgical involving drying, calcining and reduction. These steps are energy intensive. The back-end is hydrometallurgical requiring various reagents. The nickel and cobalt recoveries are lower than for the smelting processes or the HPAL process.

HPAL Process

HPAL processes require ores that are predominantly limonitic; in the case of the dry laterites they contain nontronite and/or smectite. In general the ores:

- contain some saprolite
- have lower Mg- usually limited to <4 % (At higher Mg acid consumption is higher)
- require lower Al content (clays are high acid consumers; therefore the Al content should not be too high)

The pressure leaching is carried out either in pachuka tanks (Moa Bay) or titanium lined autoclaves (all modern plants). Leach temperatures vary in the range 245 to 270°C. Solid-liquid separation is carried out by Counter-Current Decantation (CCD). There are various ways of purifying the nickel-containing solution and separating nickel and cobalt. In modern plants such separation is carried out by solvent extraction (SX). Final products produced are electro-nickel, nickel oxide or nickel briquettes. Some plants produce intermediate materials (mixed sulfides or mixed hydroxides) that are refined elsewhere.

Other Hydrometallurgical Processes

There are several newer processes that are currently being piloted and evaluated. These include:

EPAL Process: This includes an additional leaching step for saprolite using residual acid from the HPAL step (+ added acid). Saprolite is leached at atmospheric pressure and is a high acid consumer (believed to be up to 1 t acid/t ore). This process can consume more saprolite than the conventional HPAL process. This is currently being piloted by BHP-B for Ravensthorpe.

The following processes are at various stages of piloting but none has been commercialized.

AL: Atmospheric Leaching- Similar to the leaching step described for saprolite above
Acid Heap Leaching (for saprolitic ores)
Chloride Leaching (for mixed limonitic and saprolitic ores)

History of Laterite Production

Production of nickel from laterites preceded that of sulfide nickel production. The history of nickel production from laterites dates back more than a century. Table 2 provides a summary of various laterite operations (past and present) dating back to the 1940's.

Early Production

New Caledonian Production

Nickel metallurgy has accompanied mining since its inception, with the remoteness of European markets justifying the smelting of the ore within New Caledonia. The first nickel smelter began operating at Pointe Chaleix, Nouméa in 1879, and two other processing plants were subsequently established, one by the Société des Hauts-Fourneaux de Nouméa at Doniambo in 1910, the other by SLN at Thio in 1913. The latter closed in 1931, when the nickel smelting plant at Doniambo passed into the control of SLN (now a part of Eramet). The Doniambo smelter was expanded in 1958 [2].

Doniambo's annual production has risen threefold from about 20 kt in 1960 to about 60 kt in 2002. In 2001 a $180 million program to increase the production capacity of the smelter to 75 kt Ni/yr was launched. The expansion includes replacement of one of three furnaces and improvement of the Tiebaghi mine. The planned target date for completion is 2006.

The Doniambo smelter uses a conventional flowsheet consisting of ore dryers, rotary kilns and electric furnaces to produce crude ferronickel. A major part of the ferronickel is refined to produce refined ferronickel. The remaining ferronickel is converted to matte, which is further processed at a refinery at Le Havre in France to produce nickel cathode and salts. A part of its electric power used by the Doniambo smelter is thermally generated. This, as well as the cost of ore transportation and relatively high cost of processing in New Caledonia, results in a relatively high unit cost (but lower than that for the Japanese Fe-Ni producers) of around US $ 2.20/lb Ni in Fe-Ni.

Mines from New Caledonia have supplied saprolite ore feed not only to Doniambo but also to Japanese ferro-nickel smelters and limonite ore to QNI's Yabulu Operation. Total ore production in New Caledonia has increased several-fold from <1 Mt in 1950 to 8.1 Mt in 1997, declining to 6.5 Mt/yr since 2001.

Table 2: Past and Present Laterite Operations

Operation	Company (Original O'pn)	Country	Capacity kt Ni/yr	Product	Start Date	Shut Down	Process
Doniambo	SLN/Eramet	N. Caledonia	49	Fe-Ni	1879/1958		Smelting
			11	Matte			
Hyuga	SMM/Nippon Steel/Mitsui	Japan	22	Fe-Ni	1956		Smelting
Oheyama	Nippon Yakin Kogyo	Japan	13	Fe-Ni	1939		Krupp-Renn
Hachinohe	Pacific Metal Co.	Japan	48	Fe-Ni	1966		Smelting
Saganosaki	Nippon Mining Co	Japan	6.5	Fe-Ni	1952	1987	Smelting
Ufaley		Russia	14	Fe-Ni	1934		Smelting
Yuzuralnickel		Russia	6	Fe-Ni	?		Smelting
Riddle	Hanna Mining Co/Cominco	USA	12	Fe-Ni	1954	1998	Smelting
Morro Do Niquel	Morro Do Niquel S.A.	Brazil	2.5	Fe-Ni	1962	1998	Smelting
Larymna	Larco	Greece	19.5	Fe-Ni	1966		Smelting
Nicaro	Freeport	Cuba	23	NiO	1952		Caron
Moa Bay	Freeport Sulfur	Cuba	25	Mixed Sulfide	1959		HPAL
Debottlenecked	General Nickel/Sherritt JV		6		2000		
Bonao	Falconbridge Dominicana/ Falconbridge	Dominican Republic	30	Fe-Ni	1971		Smelting
Exmibal	Inco	Guatemala	11	Matte	1977	1981	Smelting
Pomalaa	P. T. Aneka Tambang	Indonesia	5	Fe-Ni	1975		Smelting
Expansion			6	Fe-Ni	1995		
Sorowako	P. T. Inco/Inco	Indonesia	45	Matte	1977		Smelting
Expansion			23	Matte	2000		
Surigao	Marinduque/Freeport	Philippines	35	Briquettes	1974	1986	Caron
Greenvale/Yabulu	Freeport/Metals Expl	Australia	18	Briquettes	1974		Caron
Debottlencked	QNI/BHP-Billiton		10	Briquettes			
Codemin	Anglo American	Brazil	7	Fe-Ni	1982		Smelting
Niquelandia/Sao Paulo	Votorantim/Tocantins	Brazil	17.5	Electronickel	1981		Caron
Cerro Matoso	(Hanna/Billiton)	Colombia	23	Fe-Ni	1982		Smelting
Expansion	QNI/BHP-Billiton		27	Fe-Ni	2001		
Kosovo	SAP-Kosova	Yugoslavia	12	Fe-Ni	1984	2000	Smelting
Fenimac	Fenimac	Macedonia	6.5	Fe-Ni	?		Smelting
Punta Gorda	Union del Niquel	Cuba	31.5	Ni Oxide	1986		Caron
Murrin Murrin	Anaconda Nickel	Australia	40	Ni Briquettes	1999		HPAL
Cawse	Centaur	Australia	9	Electro Ni	1998		HPAL
Bulong	Resolute/Preston Resources	Australia	7	Electro Ni	1999	2003	HPAL
Loma de Niquel	Anglo American	Venezuela	17	Fe-Ni	2000		Smelting

Japanese Production

The other early producers of nickel from laterite were the Japanese, starting from the Second World War, but more consistently from about 1952. The start-up of the current three Japanese operating plants (Hyuga Nickel Co., Pacific Metal Co and Nippon Yakin Kogyo Co) was in the time period between 1952 (Nippon Yakin) and 1968 (Pacific Metal). [1-3; 26-30] Japanese ferronickel operations import saprolite ore from New Caledonia, Indonesia and Philippines.

Most of the laterite smelters produced ferronickel. The Japanese ferronickel operations (similar to the Doniambo smelter in New Caledonia) processed high-grade nickel (>2.5 % Ni) saprolite ores to produce high carbon crude ferronickel.

The existing Japanese smelters (except Nippon Yakin) use a conventional flowsheet (similar to Doniambo) consisting of rotary dryers, rotary kilns and electric furnaces to produce crude ferronickel. In the case of Hyuga, this is refined further (desulfurisation, de-phosphorization and deoxidation) to produce ferronickel market product (pigs or shots). Pamco uses the crude Fe-Ni directly to produce stainless steel. Nippon Yakin applies a modified version of the Krupp-Renn process to produce crude ferronickel (high carbon and low carbon) in rotary kilns. These are directly used in stainless steel production.

In addition to the three Japanese smelters mentioned above, Nippon Nickel Co. operated a nickel smelter at Saganosaki employing blast furnace technology for a number of years. This smelter closed in 1987.

The current major equipment and capacities of the Japanese Fe-Ni operations are as follows:

Operation	Equipment	Current Capacity kt Ni/yr
Hyuga	1 rotary dryer 2 rotary kilns (120 wet t/h each) 2 EF (60 MW, 40 MW)	22
Pamco	1 rotary dryer 3 rotary kilns 3 EF (60 MW each) 80 MW diesel power plant	48
Nippon Yakin	2 rotary kilns	13

While the total installed capacity is 83 kt Ni/yr the actual production of these operations between 1990 and 2003 has been in the range 50 kt (1994) and 75 kt (2000, 02, 03). The future of Japanese ferronickel operations is constrained by the availability of high nickel low iron garnieritic saprolite ores and high power costs causing production to be predominantly in off-peak power periods.

All of these smelters are high cost producers. The Japanese smelters have to import ore at an average cost in the range US$ 1.00 to 1.25/lb Ni (including transportation). The cost of ore increases with the price of nickel (> $ 2/lb at $7/lb Ni LME). In addition the cost of power in Japan is very high (variable between 6 and 13 cents per kWh). The unit cash cost of nickel production is ~ US $ 2.75/lb Ni.

Russian Fe-Ni Producers

Fe-Ni in Russia (formerly the USSR) was produced in three plants: Orsk, Rezh and Ufaley in southern Urals, from low-grade lateritic ores. Start of production was as follows: Ufaley: 1934; Rezh: 1936; Orsk: 1939. Two of these operations (Ufaley and Yuzural) currently produce a total of ~20 kt Ni/yr.

Other Laterite Smelters of 1950's and 60's

Hanna Nickel Company's Riddle (Oregon) smelter has been the only primary nickel producer in the United States. It started operation in 1954 and used a unique process consisting of melting the ore followed by reduction of nickel to Fe-Ni using Fe-Si by ladle mixing. The ore was low grade (1.65 % Ni) and it was a high cost operation. The plant capacity was ~12 kt Ni/yr. It was taken over by Cominco in 1993 and operated using purchased higher-grade (2.35% Ni) ore from New Caledonia until 1998. The operation was shut down in 1998 due to high cost of production and low nickel prices.

Moro Do Niquel smelter at Pratapolis in Minas Gerais in Brazil started in 1966 smelting low-grade (1.3 % Ni) ore, with an original capacity of 1 kt Ni/yr. It closed down in 1998 (capacity ~ 2.5 kt Ni/yr) due to high cost of production and low nickel prices.

Larymna operation of Larco (owned by various government and quasi- governmental organizations in Greece) started in 1966. Nickel is produced using kiln and electric furnace and concentrated using oxygen in an L-D converter. The current capacity of the plant (with an ore grade of ~ 1.15 % Ni) is 20 kt Ni/yr. The plant is one of the highest cost nickel producers in the world with cash operating cost of about US $ 2.80/lb Ni (low grade ore, thermal power, low productivity, low capacity). It had its own share of financial difficulties and is sustained by government assistance.

Early Hydrometallurgical Operations in Cuba

The two principal processes for treatment of nickel laterite ores are the Caron process and the Pressure Acid Leach (PAL or HPAL) process. Both of these processes were originally used in plants that were started in Cuba by Freeport Sulfur Company.

Of these, the Caron process using atmospheric ammonia leaching of reduced nickel ore predates the HPAL process. The original patent was granted in 1924. The first plant was operated by Nicaro Nickel Co. between 1944 and 1947 for the US Government. It was reopened in 1952 with an ultimate capacity of 23 kt Ni/yr. The plant was taken over by the Castro Government after the Cuban Revolution. Its current capacity is ~15 kt Ni/yr, with an estimated operating cost of US $ 3.00/lb Ni. It produces nickel in the form of nickel oxide sinter from limonitic ore grading 1.3 % Ni and 0.12 % Co. Cobalt is extracted into a mixed nickel-cobalt sulfide (cobalt recovery is ~ 30 %).

This process was subsequently used (with modifications) at Punta Gorda (Cuba), Greenvale/Yabulu (Australia), and at Marindoque/Nonoc (Philippines).

The other Cuban hydrometallurgical nickel operation at Moa Bay is the precursor of all of the modern day HPAL operations utilizing the pressure acid leach technology. It was also started in 1959 by the Freeport Sulfur Company as a means of providing market for its sulfur and at the same time to produce nickel at relatively low cost and ~90% recovery (higher than the Caron process). The process was carried out in two separate plants – the front end process was carried out in Cuba to produce a mixed nickel-cobalt sulfide and the back-end of the process was carried out at Port Nickel (near New Orleans) in Louisiana where nickel and cobalt were refined electrolytically.

The Moa Bay plant was taken over by the Castro Government after the Cuban Revolution and recommissioned in 1961. The Port Nickel refinery was closed. The intermediate material was processed in the USSR (at Yuzuralnickel) during the Cold War years. In 1994 Sherritt formed a 50:50 Joint Venture with General Nickel Co of Cuba. After this the refining of the mixed sulfide was carried out at Sherritt's Fort Saskatchewan refinery (Corefco) in Alberta, Canada.

Because of change of personnel and lack of parts and materials the Cuban/Russia refinery personnel took 7 years to ramp up to about 50 % of the design capacity. After Sherritt's involvement it took two years to ramp up to the original capacity (25 kt Ni/yr). Subsequently it was debottlenecked to the current capacity of ~ 31 kt Ni/yr with an estimated cash operating cost of US $ 2.00/lb Ni to final product.

1970's and 80's Operations

The producer price of nickel was US$ 0.93/lb Ni by late 1960's. This increased to US $ 1.33/lb as a result of a strike at Inco in 1968/69. (US$5.90/lb in today's dollars). The price of nickel actually rose to $7/lb (US $ 31/lb in today's dollar!) during the strike. This was prior to the "Oil Shock". The Western economies were booming and the cost of oil was US$1/bbl. There was perceived continuing increase in nickel demand, and the demand was constrained by supply.

Many new laterite operations came into existence between 1971 and 1986 as a result of these events and perceptions. These included both smelters and hydrometallurgical operations using the Caron process. These operations included:

1. Falconbridge Dominicana by Falconbridge in Dominical Republic: Smelter
   capacity of 30 kt Ni/yr as Fe-Ni
   Started in 1971
2. Surigao Nickel Refinery of Marinduque Mining and Industrial Corp in Philippines:
   Hydrometallurgical Operation (Caron Process)
   capacity of 35 kt Ni/yr as nickel briquettes
   Started in 1974
3. Greenvale nickel operation of Freeport Minerals Co and Metals Exploration Pty Ltd. in Australia: Hydrometallurgical operation (Caron Process)
   capacity of 18 kt Ni/yr as nickel briquettes
   Started in 1974
4. Pomalaa Operation of P. T. Aneka Tambang in Indonesia: Smelter
   capacity of 5 kt Ni/yr as Fe-Ni
   Started in 1975
5. Exmibal Operation of Inco in Guatemala: Smelter
   capacity of 11.3 kt Ni/yr as matte|
   Started in 1977
6. Sorowako Operation of P.T. Inco/Inco in Indonesia: Smelter
   capacity of 45 kt Ni/yr as matte
   Started in 1977
7. Cerro Matoso operation of Hanna Mining Co./Billiton in Columbia: Smelter
   capacity of 23 kt Ni/yr as Fe-Ni
   Started in 1982
8. Las Camariocas project in Cuba – never completed

9. Kosovo Fe-Ni operation in former Yugoslavia: Smelter capacity of 12 kt Ni/yr as Fe-Ni
   Started in 1984.
10. Punta Gorda operation of Union del Niquel in Cuba
    Hydrometallurgical Operation (Caron Process)
    capacity of 31.5 kt Ni/yr as nickel oxide
    Started in 1986

A total of 211 kt of nickel capacity was thus added or about 42 % of Western World production in 1970! Of this, 60 % was smelter capacity and the remaining 40 % was hydrometallurgical capacity. Of the 211 kt Ni/yr installed capacity only about 150 kt Ni/yr or 71 % was ultimately realized. Most of these operations were high consumers of energy. As a result of the "oil shock" of the 1970's there was a double impact on these operations. The direct impact of rapid increase in oil price to greater than US $ 30/bbl (in 1970's dollars!) meant the cost of production soared. Additionally, the world economies went into recession as a result of the oil shock resulting in low nickel prices during the 1980's. As a result of this, most of these operations had financial problems. The Exmibal operation of Inco and the Nonoc/Surigao operation of Freeport eventually closed. Greenvale operation went into receivership and was financially restructured; it was eventually purchased by Billiton (together with the Cerro Matoso operation). The Falconbridge operation in the Dominican Republic had been a marginal producer with frequent shutdowns or slowdowns during low nickel prices. The P. T. Inco operation has several years of losses. The Las Camariocas plant was never completed. The Kosovo operation after producing up to 10 kt Ni/yr closed down in 2000 due to political problems and war in Yugoslavia.

Only two operations eventually emerged as low cost operators out of this group: P. T. Inco's Sorowako operation due to its captive hydroelectric power source, and Cerro Matoso operation of BHP-Billiton due to its high grade ore and low cost natural gas.

The result of the addition of this large capacity was low nickel prices for a long period of time. This was compounded by the collapse of the Berlin Wall and the East Block economy during the 1990's. This collapse resulted in net addition of about 200 kt Ni/yr to the Western World supply and additional nickel in the form of stainless steel scrap that poured into Western Europe during the 1990's. As a result of this very little new capacity was added until the late 1990's.

The 1990's Operations and Expansions

By mid-1990's the additional Russian capacity was being absorbed. While the growth in nickel consumption during the late 1980's was 2.5 % p.a., it rose by an average of greater than 8% p.a. during the early 90's followed by a growth rate of 3.5 % later that decade. No significant new greenfield capacity was added since 1986. A new crop of laterite projects and expansions emerged with the Australian PAL projects in the lead, as a result of this. The following greenfield operations were commissioned:

1. Murrin Murrin operation of Anaconda Nickel in Australia (HPAL)
   with a capacity of 45 kt Ni/yr as briquettes
   Started in 1999
2. Cawse Operation of Centaur in Australia (HPAL)
   with a capacity of 9 kt/yr as electronickel (cathode)
   Started in 1999

3. Bulong operation of Resolute (later by Preston Resources) in Australia (HPAL) with a capacity of 7 kt Ni/yr as electronickel (cathode)
   Started in 1999
4. Loma de Niquel operation of Anglo American in Venezuela: Smelter with a capacity of 17 kt Ni/yr as Fe-Ni
   Started in 2000

Expansions:

1. P. T. Inco: Fourth Line Expansion Project increased capacity in 2000 by 23 kt Ni/yr as matte
2. Cerro Matoso: Twinning of the production line increased capacity in 2001 by 27 kt Ni/yr as Fe-Ni
3. P.T. Aneka Tambang: Twinning of the original production line increased capacity in 1995 by 6 kt Ni/yr as Fe-Ni

This added a total capacity of 134 kt Ni/yr or about 12 % or total world production at that time. Of this 55 % was smelter capacity and the remaining 45 % was hydrometallurgical capacity. The trend towards increasing hydrometallurgical capacity seen in the 1970's projects thus continued. Much of this capacity did not immediately materialize due to ramp up problems experienced by the Australian PAL projects. The expansion projects required more than one year to ramp-up. Of the original 61 kt Ni/yr capacity of the Australian projects, currently only 37 kt Ni/yr capacity (or 61% of the installed capacity) is realized. Murrin Murrin has produced up to 30 kt/yr rate on a sustained basis and Cawse has produced about 7 kt Ni/yr on a sustained basis. The Bulong project has been shut down as a result of slow ramp up and financial difficulties. The Loma de Niquel project reached design capacity within 2 years. The expansion projects have all realized their stated capacity.

Economics of Laterite Projects

Economics of laterite projects has been discussed by the authors in previous papers and presentations by Bacon, Dalvi et. al. [31-34]. We have noted that an economic project would have at least 40 kt nickel per year capacity requiring 800 kt (~2 billion pounds) of nickel deposit for a mine life of 20 years.

A major difference between laterite and sulfide processing is that the sulfides ores are amenable to beneficiation producing high-grade concentrates (10 to 26 % Ni). This reduces both the size of the processing facilities (especially the front-end processing facilities) and overall processing costs for the sulfides. Only a limited upgrading (by a factor of <3, but mostly <2) can be carried out with laterite ores. This means a large tonnage of feed material is processed and a large tonnage of tailings or slag is disposed. Laterite projects have generally high capital costs and laterite smelters have high energy costs.

Economics of the laterite projects are very sensitive to feed grade to the plant (after upgrading).

The authors do not believe that the Caron Process is economic at lower nickel prices and is not competitive with smelting and HPAL operations due to lower feed grade compared to smelters and low nickel and especially lower cobalt recoveries and high energy and reagent costs. While existing plants utilizing the Caron process would continue to operate (since the capital is sunk) and they are expected to carry out debottlenecking to increase process efficiencies and reduce costs, no new greenfield projects utilizing Caron process are currently contemplated to process laterite nickel ores.

Economics of laterite smelters

Economics of laterite smelters is summarized in Table 4. Projects are categorized as attractive, marginal and unattractive based on nickel grade and power costs ($/kWh).

Capital costs for greenfield laterite smelters vary in the range US$ 12 to 15/lb Ni annual capacity. This benchmark applies to project with an annual capacity of ~ 40 kt Ni/yr with a feed grade ~ 2 % Ni.

Benchmarking of laterite smelters is possible with a reasonable degree of confidence since a relatively large number of smelters have been built since 1950. We have carried out benchmarking of laterite smelters based on the available data and find the following:

Table 3: Economics of Laterite Smelters (Greenfield Projects)

Scenario	Grade % Ni	Power Cost Cents/kWh	Capital $/lb Ni	Capex Charges $/lb Ni	Opex* $/lb Ni	Price req'd for justification $/lb Ni	Attractive-ness
High ore grade, or upgradable; large scale; low cost power; existing or low-cost infrastructure	2.5	3	10-12	2	1.5	3.5	Attractive
Average ore grade and infra-structure; relatively large scale; medium cost power	2	4	12-14	2.3	2	4.3	Marginal
Low ore grade; relatively small scale; infrastructure req'd; thermal power at lower fuel costs	1.7 or lower	5+	15	2.6	2.4	5	Unattractive

*Opex includes sustaining capex and cost of conversion of intermediate to a saleable product

- Capital cost of brownfield smelters is reduced by about US $ 4/lb Ni annual capacity due to the available infrastructure and synergies
- Installed power requirement for a laterite smelter is in the range 3-4 MW/kt Ni annual capacity (depending on the feed grade and the process). This translates into capital cost of power generation facility to about US$ 4.50 to 5.00/lb Ni. Smelters that do not have to build their own power plants thus have a capital cost advantage. However, the cost of power ($/kWh) for such smelters could be high since the power supplier has to recover his capital. This would add to the operating cost.
- Overall capital cost of a smelter (US$/lb Ni annual capacity) can be benchmarked at a median value of the feed grade (say 2% Ni) and prorated at other feed grades based on the actual grade, in inverse relationship to the grade.
- Overall capital cost is also subject to the economies of scale. Thus capital cost could be benchmarked at say 40 kt Ni/yr and prorated based on the engineering estimate formula (size ratio to the power of 0.65). Thus larger plants have lower capital costs per pound of nickel annual capacity.

- Based on the recent experience of hydromet (HPAL) projects, the authors believe that the laterite smelters have a capital cost advantage over HPAL plants. This is partly due to the fact that the smelter feed is saprolitic with relatively high nickel grade (typically >1.8% Ni), while the HPAL plant feed is typically in the range 1.0 to 1.5 % Ni for life of project.
- The operating costs of laterite smelters is highly sensitive to:
  - Nickel feed grade
  - Cost of power
  - Cost of fuel and reductants (heavy oil, naphtha, diesel, natural gas, coal, coke)
- Cost of purchased ore is very high ($/lb of contained nickel) and makes plants purchasing ore, high cost operations
- Most laterite smelters produce ferronickel and do not recover cobalt. Therefore they do not get by-product credit for cobalt.

Based on these facts and observations, the following conclusions can be drawn:

- Laterite smelter projects with low-grade ore and high-cost power are not economic. We believe that the lower limit for nickel grade for laterite smelter is 1.7 % Ni for plants with captive hydroelectric power (or those supplied with low cost power) and 2.1 % for plants with thermal power.
- Laterite smelters with purchased feed are high cost producers. Going forward such projects are uneconomic as greenfield projects
- New laterite smelting capacity with economic advantage include:
  - Brownfield projects/expansions/debottlenecking projects
  - Projects with access to low cost power that is already installed (from a utility)
  - Projects with captive hydroelectric power
  - Projects with above features with high grade feed.
  - Projects in the vicinity of existing infrastructure (reducing infrastructure costs)
  - Projects located at or near tidewater with one or more of above features
- However, high-grade laterite ore feeds are dwindling and there are very few places in the world where undeveloped hydroelectric power capacity exists in the vicinity of a laterite mine. Therefore going forward new laterite smelters will be few and far between.

Economics of PAL Projects

Economics of laterite PAL projects is summarized in Table 4. Projects are categorized as attractive, marginal and unattractive based on nickel grade, capex, opex and cobalt credits.

Capital costs for greenfield laterite PAL projects vary in the range of US$ 12 to 18/lb Ni annual capacity. This benchmark applies to project with an annual capacity of ~ 40 kt Ni/yr with a feed grade ~ 1.4 % Ni.

Benchmarking of laterite PAL projects is not possible with a reasonable degree of confidence since only a small number of modern PAL plants have been built. We have carried out benchmarking of laterite PAL plants based on <u>limited</u> data and find the following:

- Capital cost of brownfield PAL plants would also be reduced compared to greenfield but probably by an amount less than US $ 4/lb Ni annual capacity due to cost of auxiliary plants and tailing disposal.

- Installed power requirement for a PAL plant is in the range 0.6-1 MW/kt Ni annual capacity (depending on the feed grade and the process). This is considerably less than for a laterite smelter and translates into capital cost of power generation facility to about US $1 to 2/lb Ni annual capacity (The larger cost is with plants with electrolytic refinery and low grade feeds).
- Overall capital cost of a PAL plant (US$/lb Ni annual capacity) can be benchmarked at a median value of the feed grade (say 1.4 % Ni) and prorated at other feed grades based on the actual grade, in inverse relationship to the grade.
- Overall capital cost is also subject to the economies of scale. Thus capital cost could be benchmarked at say 40 kt Ni/yr and prorated based on the engineering estimate formula (size ratio to the power of 0.65). Thus larger plants have lower capital costs per pound of nickel annual capacity.

Table 4: Economics of PAL Projects (Greenfield Projects)

Scenario	Grade %Ni	Capex $/lb Ni	Capital Charges $/lb Ni	Opex* $/lb Ni	Cobalt Credit $/lb Ni	Price req'd for justification $/lb Ni	Attractive-ness
High ore grade, or upgradable ore; large scale; intermediate products with low conversion costs; low acid consumption	>1.5	12	2.10	2.00	1.00	3.10	Attractive
Average ore grade and infrastructure; relatively large Scale; finished products or high conversion costs for intermediate	1.4	14	2.45	2.20	0.70	4	Marginal
Low grade ore, low cobalt; relatively small scale; high infrastructure costs, or high conversion cost; high acid consumption	1.3 or lower	16+	2.80	2.50	0.40	5	Unattractive

*Opex includes sustaining capex and cost of conversion of intermediate to a saleable product

- Based on the recent experience of hydromet (HPAL) projects, the authors believe that such plants have relatively higher capital cost ($/lb Ni annual capacity). As more plants are built and experience is gained in design, material selection and construction of PAL plants, these costs may decrease in the long term.
- The operating costs of laterite PAL plants are highly sensitive to:
    - Nickel feed grade
    - Cost of reagents (sulfur, limestone, lime, SX reagents)
- Cost of purchased ore is very high ($/lb of contained nickel) and makes plants purchasing ore high cost operations
- Laterite PAL plants recover cobalt in relatively pure form. Therefore they get by-product credit for cobalt, thus reducing the cash cost after by-product credit.

Based on these rules and observations, the following conclusions can be drawn:

- Laterite PAL projects with low nickel grade (< 1.3% Ni fed to the autoclave(s)) are not economic (See Figure 6).

- Laterite hydrometallurgical plants with purchased feed are high cost producers. Going forward such projects are uneconomic as greenfield projects
- New laterite PAL capacity with economic advantage include:
    - Brownfield projects/expansions/debottlenecking projects
    - Projects with relatively high grade feed (>1.5% Ni)
    - Projects with feed that requires low acid consumption
    - Projects in the vicinity of existing infrastructure
    - Projects located at or near tidewater with one or more of above features

Project Risk and Attractiveness

Various factors (economic, political, environmental, social and mineral) affecting a base metal project have been discussed by Dalvi and Poetschke [35] who also refer to other studies in this field. These factors are country specific. Each of these factors has a risk associated with it. We have used Fraser Institute ranking (for example 2003/04 Survey of Mining Companies) to rank projects by country risk.

Project risk analysis should include analysis of the following factors:

- Political risk
- Technical risk related to mining and processing
- Environmental risk
- Financing risk
- Market and Economic risk including supply-demand and price risk
- Construction related risk

Technology can have positive impact on project economics. Counter-point to this is the risk a new technology entails. Terry McNutty [36] analysed 41 projects in mineral processing and chemical industries and showed that the project risk increased as the degree of innovation increased. The risk is reflected in two factors: (1) Time it takes to reach design capacity, and (2) Final production capacity reached as per cent of the design capacity. The recent example of the three laterite nickel projects in W. Australia utilizing the pressure acid leach technology illustrates this point. It is possible to mitigate the risk to a large degree by building a large-scale pilot plant or a demonstration point. The cost of building and operating such plants could be considered as insurance against the possible risk. Inco is taking this approach in developing its Goro nickel project in New Caledonia and hydrometallurgy for its Voisey's Bay Project in Newfoundland and Labrador in Canada. Even after mitigating the process risk there is residual risk associated with project engineering and implementation. These risks must be taken into account.

In reviewing future laterite projects listed in the previous section, we have used the Fraser institute ranking and also McNutty's classifications related to process innovation and the degree of risk mitigation related to this. We have also looked at whether major mining companies are involved with a project and financing probability of a project. We have also looked at realistic schedules for project execution. Some of the factors related to the ranking could be subjective. Going forward some or all of the parameters may change, affecting the future probability (and success) of a project.

Future Laterite Projects

New Capacity Additions between 2004 and 2007

Today the world nickel demand is increasing at a rate greater than 4 % p.a. mainly due to expansion of stainless steel capacity in China. China currently accounts for about 70 % of the increase in nickel demand. The demand is currently constrained due to supply. Expected laterite capacity expansion during this period could be divided into greenfield capacity and brownfield expansion/debottlenecking. There are only two greenfield laterite projects expected to be commissioned during this period:

1. Goro Nickel Project of Inco in New Caledonia (HPAL)
   with a capacity of 54 kt Ni/yr as nickel oxide
   to be refined in the Far East into Utility Nickel
   Expected to start in 2007
2. Coral Bay Project of Sumitomo/Mitsui in Philippines (HPAL)
   with a capacity of 10 kt/yr as mixed nickel-cobalt sulfide
   to be refined into electronickel at an expanded refinery in Niihama in Japan
   Starting in 2005

Expansions and Debottlenecking

1. P. T. Inco: Possible debottlenecking and installation of additional hydro-electric capacity to increase capacity by 2007 by 16 kt Ni/yr as matte
2. Doniambo: Increased capacity by 2006 by 15 kt Ni/yr as Fe-Ni
3. P.T. Aneka Tambang: Fe-Ni III line to increase capacity by 2006 by 15 kt Ni/yr as Fe-Ni
4. Murrin Murrin: Debottlenecking of the existing operation by 2004 with a capacity increase of 10 kt Ni/yr as briquettes

The Japanese Fe-Ni producers have the potential to increase production by up to 10 kt Ni/yr. However, their ability is constrained by availability of ore and manpower, and cost of electricity.

The projects listed above (excluding Japanese Fe-Ni producers) would add a total capacity of 120 kt Ni/yr or about 10 % or total world production at that time. Of this 38 % is smelter capacity and the remaining 62 % is hydrometallurgical capacity. The trend towards increasing hydrometallurgical capacity seen in the 1970's and 1990's projects is thus expected to continue.

New Capacity in 2008 and Beyond

We have put together "most-likely" scenario for 2008 and beyond. This list is to some extent subjective. Also, any of the risk factors can change within the next two years affecting which projects would be implemented in this period, or not. Therefore we have not named these projects but have identified them generically by type of technology, capacity and region.

These projects include greenfield PAL, PAL expansions, greenfield smelters and smelter expansions. We recognize that there may be surprise projects not in our list. Similarly one or more projects in our list may not materialize.

New Capacity Additions between 2008 and 2012

It is expected that the 2004-07 capacity addition together with new sulfide nickel capacity will not satisfy the growth in nickel demand due to additional stainless steel capacity, demand for aerospace alloys and for battery grade nickel. Of the projects that are "on the drawing board" today, those the authors expect are likely to go forward in this period are shown in Table 5.

This would add a total capacity of 292 kt Ni/yr or about 21 % or total world production at that time. Of this 45 % is smelter capacity and the remaining 55 % is hydrometallurgical capacity.

Table 5: Possible Laterite Projects: 2007-12

Project	Country	Process	Capacity kt Ni/yr
Project 1	Australasia	HPAL	45
Project 2	S. America	HPAL	45
Project 3	Africa	HPAL	40
Project 4	S. E. Asia	PAL Exp	15
Project 5	Caribbean	PAL Exp	10
Project 6	Australasia	Smelting	60
Project 7	S. America	Smelting	25
Project 8	S. America	Smelting	20
Project 9	S. E. Asia	Smelting Exp	12
Project 10	C. America	?	20
	Sub-Total		**292**

New Capacity Additions beyond 2012

A large number of greenfield laterite projects are currently in various stages of exploration, studies and process development. Some of these projects could materialize in the period beyond 2012 (Table 6)

Table 6: Possible Future Laterite Projects: 2012+

Project	Country	Process	Capacity kt Ni/yr
Project 1	Australasia	HPAL	54
Project 2	S. E. Asia	HPAL	40
Project 3	S. E. Asia	HPAL	45
Project 4	S. E. Asia	HPAL	45
Project 5	S. E. Asia	HPAL	32
Project 5	Caribbean	HPAL	40
Project 7	C. America	Hydro Other	20
Project 8	S. America	Smelting	25
Project 9	S. E. Asia	Smelting	45
	Sub-Total		**346**

This is about 19 % of expected world capacity in 2012. It is ~80 % hydrometallurgical.

Conclusion: The Future of Laterites

Since 1950 the demand for nickel has increased at an average rate of 4 % per year. For the next ten years growth in nickel demand is expected to exceed this, mainly due to the expansion of the Chinese economy and the consequent growth in stainless steel demand in China. Currently, China accounts for about 70 % of growth in nickel demand worldwide. Slowdown in China's economic activity therefore poses a risk to the future demand of nickel and therefore various laterite projects in the process of development.

In the past, most of the nickel production has come from sulfide ores. However, the replenishment rate of sulfide reserves has lagged significantly behind their depletion rate. During the next ten years nickel production from the sulfide ores is expected to grow only slightly, including additional production from Inco's Voisey's Bay project and any additional production from Russia. The growth in nickel production in the future is thus expected to come from laterite ores of nickel. The laterites account for almost 70 % of world land based nickel resources, and there are many undeveloped laterite deposits in the world allowing exploitation of laterites to satisfy the growing demand for nickel. To satisfy nickel demand we need one project the size of Inco's Goro project every year! This is a major challenge.

The existing laterite producers have an excellent opportunity to grow since brownfield projects and debottlenecking projects are most economical and have advantage over greenfield projects. Greenfield smelters will be few and far between due to requirement for high-grade ore and their large power requirements. The Caron process is not economical at lower nickel prices and not competitive with smelting and PAL processes. We believe, most of the future greenfield laterite projects will be PAL projects (HPAL or E-PAL). PAL processes have the following advantages:

- They treat limonitic, nontronitic and some saprolitic nickel laterites which are abundant (laterites suitable for hydrometallurgical processes are estimated to have more than twice the tonnage compared to saprolitic ores)
- They are not as energy intensive as smelters since drying, calcining and melting are not required
- Recovery of nickel and cobalt are high (~ 90 % for both). Smelters have low (or no economic) recovery of cobalt. Caron process has low recoveries for both nickel and cobalt compared to PAL and smelting. PAL processes thus get by-product credit for cobalt. Going forward, we believe the cobalt market is slightly more positive than in the immediate past due to the political situation is Africa and slow progress in implementation of laterite PAL technology.

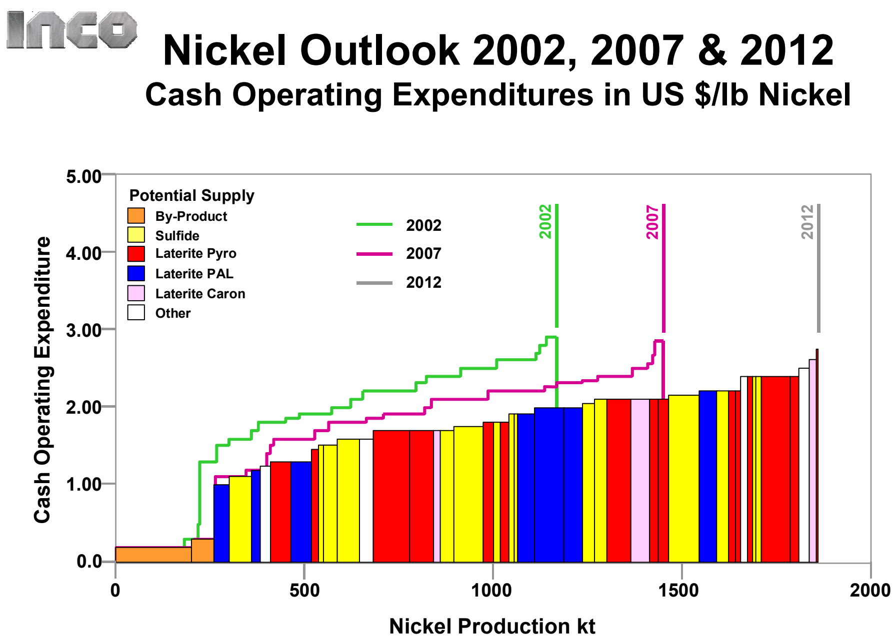
Although, PAL process has been practiced for more than 60 years, the modern technology is unproven and faces technical, engineering, project management and ramping-up challenges. We believe these will be eventually overcome. However, it will take more experience, therefore slowing down expansion in laterite nickel capacity.

Cash operating costs for laterite operations have been optimistically projected to be low. This has not come to pass. However, with new projects and more experience the operating costs (net of by-product credits) are expected to decline. Our projection for overall nickel production capacity in 2012 and the related operating costs (nickel cost curve) is shown in Figure 9. This shows laterite source nickel production would account for a majority (51 %) of world nickel production, with a significant expansion in hydrometallurgical capacity (PAL capacity). The capacity shown in Figure 9 for 2012 is nickel price dependent and assumes that the nickel price in the future would be adequate to provide a reasonable rate of return for the producers.

Several newer technologies are currently being developed. Their future will depend on their ability to reduce capital and operating costs and applicability for smaller projects where existing technologies are expensive. Past experience has shown that commercialization of new technologies is time consuming and expensive and has significant risk attached to it.

.

Figure 9: Nickel cost curves



The question is whether the nickel consumers (and the society in general) are willing to pay a higher price for nickel and stainless steel, its most important application, or face supply uncertainty in times of economic growth. The growth in nickel demand requires installation of significant greenfield capacity. The history of laterite projects as discussed earlier has not been encouraging. Many projects closed down, or were restructured, or had economic difficulties. Experience of the nickel industry (especially laterite nickel industry) has shown that greenfield capacity requires significantly higher price of nickel for the producers to obtain a reasonable return on equity (greater than the cost of borrowing). It also requires tolerance for risk. Laterite projects are generally in remote areas requiring high investment in infrastructure. Going forward, the social and environmental burdens on all mining projects are going to be significant. New laterite projects must provide reasonable return on investment while carrying commercial and social costs for nickel (and stainless steel, its major user) to guarantee stable supply while avoiding price spikes like this year.

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