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DEVELOPMENT OF LATERITE ORE PROCESSING AND ITS APPLICATIONS

PERKEMBANGAN PENGOLAHAN BIJIH LATERIT DAN APLIKASINYA

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ABSTRACT

Nickel ore is found in two types sulfide and laterite**.** The sulfide is a nickel ore that has high nickel content and low reserves of natural resources than of the zinc laterite. In contrast, the laterite is a rock mineral that contains the iron-nickel oxide compounds. There are two methods of processing nickel laterite, namely hydrometallurgy and pyrometallurgy. The former is a method that uses leaching by a chemical solution or solid such as acid, as a reducing agent. The alkaline leaching (ammonia) is the most optimal method to obtain a nickel grade with the highest recovery but it needs more modification. Pyrometallurgical method uses high heat up to 1800°C, so it requires a lot of energy and needs improvement to decrease the carbon usage. The rotary kiln-electric furnace method is the optimal method for developing the nickel laterite. These methods generate products that can be applied to various fields. For example, the pyrometallurgy method produces nickel pig iron and ferronickel as raw materials for stainless steel and steel alloys. The hydrometallurgy method produces nickel sulfate and nickel oxide with a purity of 99% by weight as raw materials for magnets, sensors, and batteries. Hence, the hydrometallurgy method still needs improvements for the environmentally friendly reagent. Therefore, bioleaching will be a nickel laterite leaching process in the future by using bacteria as the reducing agent.

Keywords: nickel, bioleaching, nickel laterite ore, hydrometallurgy, pyrometallurgy.

ABSTRAK

Bijih nikel terdapat pada dua jenis bijih, yaitu sulfida dan laterit. Bijih sulfida merupakan bijih nikel berkadar tinggi dengan cadangan sumber daya alam yang rendah dibandingkan dengan laterit seng sedangkan bijih laterit merupakan batuan mineral yang mengandung senyawa oksida besi-nikel. Secara umum, terdapat dua teknologi pengolahan nikel laterit, yaitu hidrometalurgi dan pirometalurgi. Hidrometalurgi merupakan metode yang menggunakan larutan kimia seperti asam sebagai pereduksi nikel laterit. Metode dengan pelindian basa (amoniak) adalah metode yang paling optimal untuk mendapatkan nikel dengan derajat dan perolehan tertinggi, namun masih perlu dilakukan beberapa modifikasi. Metode pirometalurgi menggunakan panas tinggi sampai 1800°C, sehingga membutuhkan banyak energi dan perlu pengembangan teknologi untuk menurunkan penggunaan karbon. Metode rotary kiln-electric furnace *merupakan metode optimal dalam pengembangan nikel laterit. Proses-proses pengolahan dengan berbagai metode tersebut menghasilkan produk yang dapat diaplikasikan ke berbagai bidang, seperti pirometalurgi menghasilkan nikel pig iron dan feronikel sebagai bahan baku stainless steel dan paduan baja. Proses hidrometalurgi menghasilkan nikel sulfat dan nikel oksida dengan kemurnian 99% berat sebagai bahan baku magnet, sensor maupun baterai. Akan tetapi, metode hidrometalurgi masih perlu pengembangan dalam penggunaan reagen yang lebih ramah lingkungan. Untuk itu,* bioleaching *akan menjadi proses pelindian nikel laterit di masa depan menggunakan bakteri sebagai agen pereduksi.*

Kata kunci: nikel, bioleaching*, bijih nikel laterit, hidrometalurgi, pirometalurgi.*

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INTRODUCTION

Two types of nickel ore are found on earth: nickel sulfide and laterite, representing roughly 30% and 70% of the world's nickel resource, respectively. Over 60% of nickel creation comes from sulfide (Lv *et al.*, 2010; Wang *et al.*, 2017). As the nickel sulfide reserves decrease the laterite nickel minerals with low nickel grades are desired for mineral extraction (Kim *et al.*, 2010; Pickles *et al.*, 2013; Pickles, Forster and Elliott, 2014; Pournaderi *et al.*, 2014; Wang *et al.*, 2017). Nickel laterite has low nickel content and is partitioned into three layers: limonitic, saprolitic, and garnieritic (Zevgolis *et al.*, 2010; Agacayak, Zedef and Aras, 2016; Wang *et al.*, 2017). Consequently, good handling processes for the productive usage of laterite nickel mineral should be exceptionally thought out and studied (Bunjaku *et al.*, 2012; Al-Khirbash, 2015; Elliott *et al.*, 2015; Pickles and Elliott, 2015; Ma, Cui and Zhao, 2016; Rice, 2016; Wang *et al.*, 2017; Bahfie, Manaf, Astuti and Nurjaman, 2021; Bahfie, Manaf, Astuti, Nurjaman and Prasetyo, 2022; Bahfie, Shofi, *et al.*, 2022). A survey by Rice (2016) controls the process for pre-convergence of nickel laterite metals, for example, the expulsion of coarse divisions from feed, sink-float partition, gravity detachment, attractive partition, electrostatic partition, and buoyancy before hydrometallurgical and pyrometallurgical processes existed. There are few improvements to nickel laterite metal handling processes to gain more advantages and fulfill the need for expanding nickel grade (Wang *et al.*, 2017; Nurjaman, Astuti, *et al.*, 2021; Nurjaman, Saekhan, *et al.*, 2021; Bahfie, Manaf, Astuti, Nurjaman, Prasetyo, *et al.*, 2022; Bahfie, Murti, Nuryaman, Astuti, Nurjaman, *et al.*, 2022). This paper aims to survey current investigations on the improvement history of laterite handling processes and their applications.

Nickel Applications

Nickel can be used in various applications related to the type of process carried out in nickel extraction. Pyrometallurgical process that use high heat produces the nickel pig iron and the ferronickel. Those products are beneficial in manufacturing stainless steel and steel alloys (Bunjaku *et al.*, 2012). In contrast, hydrometallurgical process that use chemical solutions and low heat can produce nickel sulfate and nickel oxide with a purity of 99% by weight. These products can be used as raw materials for sensors, magnets and batteries (Bunjaku *et al.*, 2012).

HISTORY OF LATERITE PROCESSING

Nickel laterite and sulfide have been studied in several processes (Chen *et al.*, 2010; Elliott *et al.*, 2015; Quast *et al.*, 2015). Descriptions of individual operations and processes have been provided in various symposia and proceedings (Zevgolis *et al.*, 2010; Bunjaku *et al.*, 2012; Pickles, Forster and Elliott, 2014; Al-Khirbash, 2015; Pickles and Elliott, 2015; Agacayak, Zedef and Aras, 2016; Ma, Cui and Zhao, 2016; Rice, 2016; Nurjaman, Sari, *et al.*, 2021). Most pyrometallurgical processes (ferronickel and matte smelting) use conventional flowsheets involving drying, calcining/reduction and electric furnace smelting. The hydrometallurgical processes that are commonly carried out by the Caron and the HPAL processes as well as future technologies will be the reference for laterite processing which will be discussed. All the history of laterite development can be seen in Figure 1 and 2.

PYROMETALLURGY OVERVIEW

The pyrometallurgical process is suitable for ores containing mostly saprolite with lower cobalt and iron than that of limonite ore. These ores are smelted to produce ferronickel or matte. In conventional pyrometallurgical process, the ore is dried, calcined, and sometimes reduced in a rotary kiln than smelted in an electric furnace in the presence of carbon. If matte is the desired product, then the sulfur is added to the kiln. The raw/matte metal is further processed/refined to produce the final product. The pyrometallurgical process is energy intensive as all free moisture, and combined water must be removed in the process, and all materials must first be calcined and then smelted to form the slag at a temperature of about 1600 °C (Nurjaman *et al.*, 2015; Bahfie, Manaf, Astuti, Nurjaman, *et al.*, 2021). The pyrometallurgy requires hydrocarbon fuels (coal, oil or naphtha) and electric power (Rhamdhani *et al.*, 2009). This technology is a well-known, robust and widely practiced process for the production of ferronickel or nickel matte. This is the preferred process for processing saprolite ores with high nickel (>2%) and magnesium (10-15%) and low iron (13-20%). Ferronickel smelting is the most widely applied technology (Stober *et al.*, 2008). In this process (Rotary Kiln - Electric Furnace or RKEF process), the laterite ore is mixed with coal or coke then dried and calcined in a rotary kiln at temperature of 900–1000°C. Reduction is a smelting process with the addition of coal or coke in an electric furnace at 1550°C which reduces all nickel and about 60–70% iron to form ferronickel as in reactions (1) and (2) in which the iron, magnesium, and silica become slag.

$NiO + CO \leftrightarrow Ni + CO_2$...............................(1)

$Fe_2O_3 + 3CO \leftrightarrow 2Fe + 3CO_2$ ....(2)

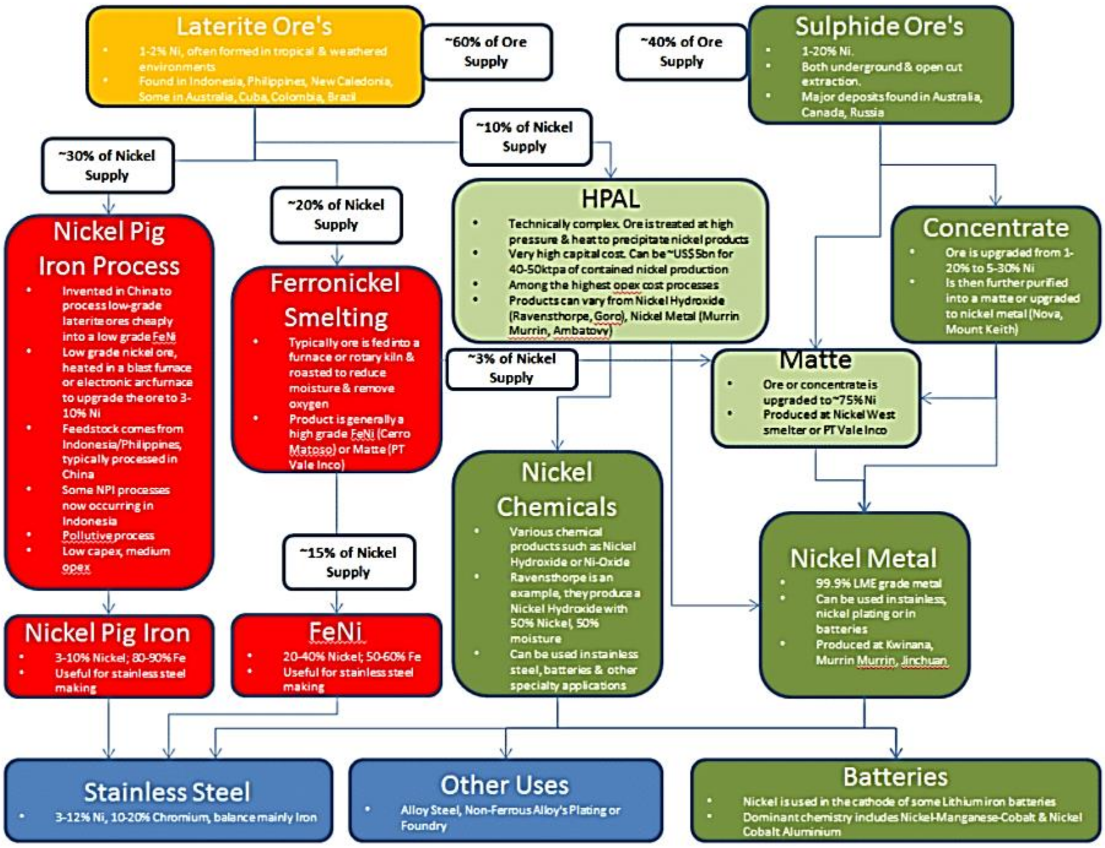

Figure 1. Nickel processing processes (Handayani and Suratman, 2016)

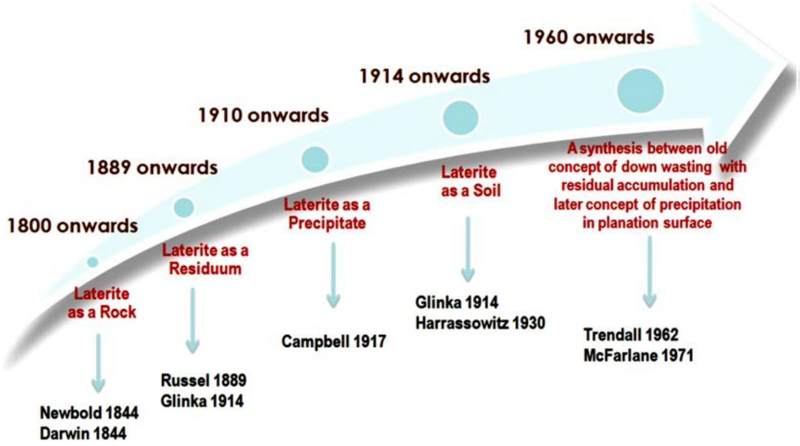

Figure 2. Laterite development history (Handayani and Suratman, 2016)

Ferronickel is purged by eliminating unused elements like sulfur, carbon, silicon, chromium, and phosphorus. The desulfurized ferronickel purifying interaction is treated in a converter with silica and lime to eliminate debasements and produce ferronickel item contains roughly 25% nickel. The nickel matte can be created by adding the sulfur in terms of diminishing the ore in a rotating oven. Nickel matte can also be produced by adding the sulfur to reduce the ore calcined in the rotary kiln. The electric furnace is used after the rotary kiln process into a final product containing 77-78% nickel and 22-23% iron (Stober *et al.*, 2008; Kyle, 2010). The most suitable ores for producing matte are ores with relatively high Fe/Ni ratios and SiO_2/MgO ratios of 1.8-2.2 (Stober *et al.*, 2008; Kyle, 2010).

The advantages of pyrometallurgical nickel extraction are the process is simple and proven, it can be applied to laterite ores with high magnesium (which generally contain high nickel concentrations), high nickel recovery (90%), and granular residues that are easy to dispose of. The disadvantages of such nickel extraction are high capital costs, high energy consumption, only applied to high magnesium laterite ores, the mixture of additives is required to maintain the SiO_2/MgO ratio, and the cobalt is not recovered as a product (Stober *et al.*, 2008; Kyle, 2010).

SELECTIVE REDUCTION

Selective reduction is a pyrometallurgical process using a lower temperature (<1000 °C), a combustion process with the addition of additives and magnetic separation for the recovery of ferronickel particles (Bahfie, Manaf, Astuti, Nurjaman, *et al.*, 2021). Based on the coal-based reduction process and melt separation at high temperatures, the results showed that when CaF_2 and lime were added together, they could produce metal separated from the slag (Li, Wang and Wei, 2011). With the C/O mole ratio increasing from 1.0 to 1.2 and the Ni content in metal particles increasing from 1.37% to 1.42%, the Ni recovery yield increased from 88.74% to 92.12% (Li, Wang and Wei, 2011; Bahfie, Manaf, Astuti, Nurjaman, *et al.*, 2021). In addition, the low C/O mole ratio inhibits the reduction of iron oxide and increases the Ni content in the metal, while the rate of Ni recovery decreases. Consequently, the selection of additives and the C/O mole ratio should be optimized (Bahfie, Manaf, Astuti, Nurjaman, *et al.*, 2021). The nickel extraction from low grade nickel laterite ore (1.09% Ni and 9.12% Fe) uses solid state deoxidation method. The percentage of total nickel conversion to metallic nickel increases rapidly with increasing the CO at maximum of 96% Ni and the phases is taenite with forsterite in the result of reduction as shown in Figure 3 (Li, Wang and Wei, 2011; Bahfie, Manaf, Astuti, Nurjaman, *et al.*, 2021).

Selective reduction of limonitic ore with nickel content of 1.38% and iron content of 45.7%. A two-stage reduction and thermal growth process was used to produce ferronickel products, an initial reduction of ore with 6% coal and addition of 4% sulfur at 600°C for 1 hour, followed by particle growth for 1 hour at 1000°C (Elliott *et al.*, 2015). A ferronickel concentrate with 4% nickel content and 93.2% nickel recovery was achieved. In addition, the particle size increases with increasing temperature and processing time. Laterite reduction process with additive variations at a dose of 10% produced phases such as F-kamacite ([Fe,Ni]), G-taenite ([Fe,Ni]), H-wustite (FeO), M-forsterite ($(Mg,Fe)_2SiO_4$), P-spinel ($MgFe_2O_4$), Q-troilite (FeS), K-nepheline ($Na3MgAl(SiO_4)_2$ as seen in Figure 4 (Jiang *et al.*, 2013; Bahfie, Manaf, Astuti, Nurjaman, *et al.*, 2021).

According to Nurjaman, Sa'adah and Suharno (2019), the effect of additives in nickel and iron separation is optimal when compared to the calcination process. Iron-nickel is formed optimally at 60 minutes at a temperature of 1150 °C and additives of 10 % by weight Na_2SO_4 with A, B, and C indicated the ferronickel (FeNi), troilite (FeS), and impurities dominated bySi and O elements as shown in Figure 5.

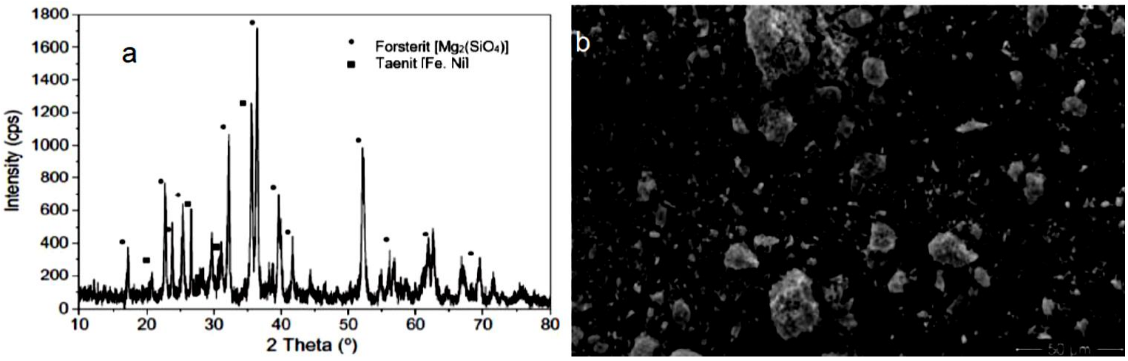

Figure 3. XRD (a) and SEM (b) results of the reduction of the laterite process (Li, Wang and Wei, 2011; Bahfie, Manaf, Astuti, Nurjaman, *et al.*, 2021)

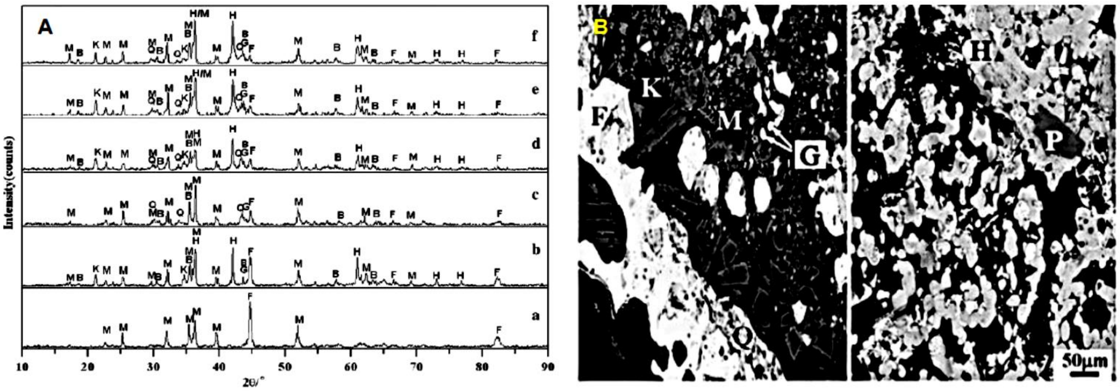

Figure 4. XRD of laterite reduction with additive variation (a-f) at a dose of 10% (A) and SEM as a description of phase forms (B) with information F-kamacite ([Fe,Ni]), G-taenite ([Fe,Ni]), H-wustite (FeO), M-forsterite ($(Mg,Fe)_2SiO_4$), P-spinel ($MgFe_2O_4$), Q-troilite (FeS), K-nephelin ($Na_3MgAl(SiO_4)_2$) (Jiang *et al.*, 2013; Bahfie, Manaf, Astuti, Nurjaman, *et al.*, 2021).

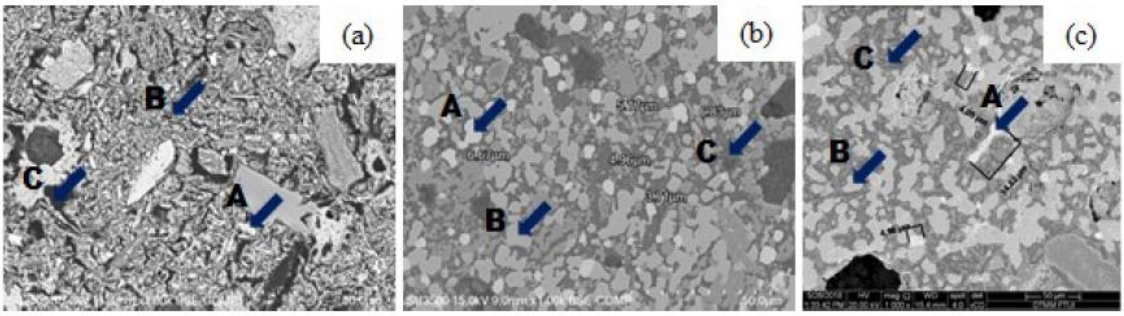

Figure 5. SEM samples at a temperature of 1150 °C and the addition of 10 wt% Na_2SO_4 with various reduction times (a) 60 minutes, (b) 90 minutes, and (c) 120 minutes (Nurjaman, Sa'adah and Suharno, 2019)

ROASTING

Roasting is a burning interaction with a low temperature under 1000°C with the utilization of carbon. Laterite is diminished to metal during the decrease interaction and afterward the ferronickel item is isolated from the slag by refining. Calcination characteristics of laterite ore (1.26% Ni, 32.6% Fe) by calcination process, removal of chemically bound water during guttite-hematite transformation at intervals of 350-700 °C

(Keskinkilic *et al.*, 2012). As a result, a temperature of 700 °C must be selected as the calcination temperature to effectively remove chemically bound water. According to Pournaderi *et al.* (2014) the effect of temperature, amount of coal, and reduction time on the pre-reduction of laterite ore (Ni 1.26 %, Fe 32.6 %) and it was found that Fe metallization is optimal up to 900 °C and increases rapidly at higher temperatures. Nickel metallization increased as the temperature from 700 to 800 °C, slightly to 900 °C and then to 1100 °C. The content of nickel and iron increases with the mounting in the percent concentration of coal and temperature as shown in Figure 6 (Pournaderi *et al.*, 2014; Bahfie, Manaf, Astuti, Nurjaman, *et al.*, 2021).

In addition, the nickel initiation is formed at 900^{o}C and the nickel products on the surface form a dense low-permeability layer that is covering the unreduced NiO as shown in Figure 7 (Rhamdhani, Jak and Hayes, 2008; Rhamdhani *et al.*, 2009).

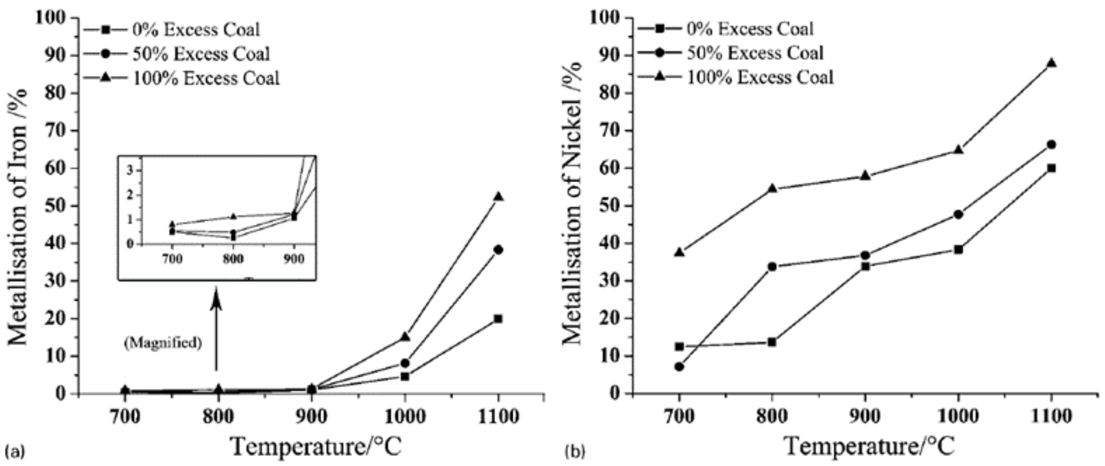

Figure 6. Effect of temperature and coal percent on metallization of (a) iron and (b) nickel (Pournaderi *et al.*, 2014; Bahfie, Manaf, Astuti, Nurjaman, *et al.*, 2021)

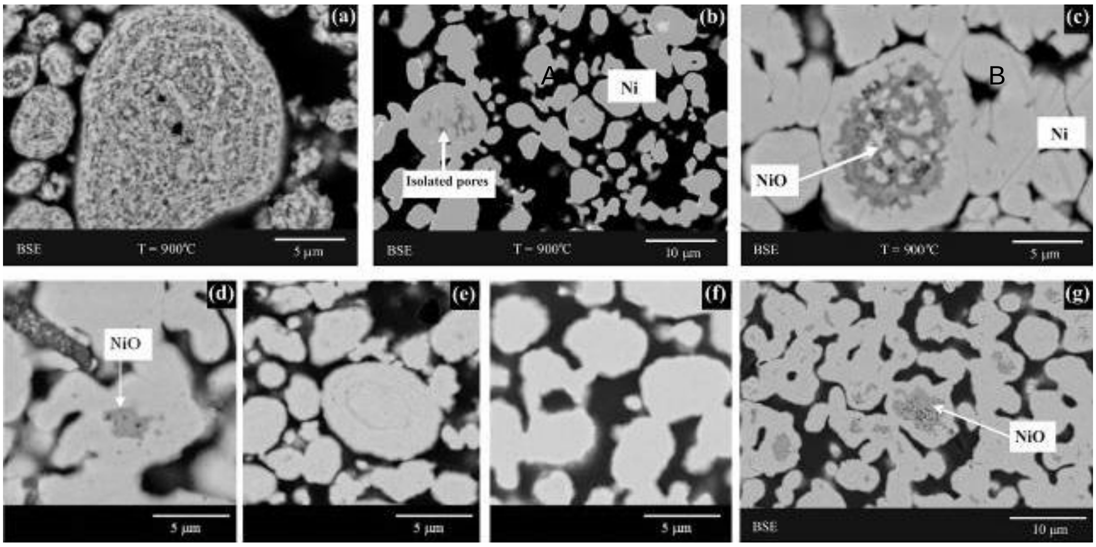

Figure 7. BSE on the part of BNC particles: (a) calcined in air at 900 °C and (b) reduced in 15 % H2-N2 at 900 °C; pre-calcined in air at (c) and (d) 900 °C, (e) 700 °C, (f) 500 °C then reduced in 15 % H2-N2 at 900 ^{o}C; and (g) reduced in 1.5 % H2-N2 at 900 ^{o}C. All used a heating rate of 10 °C/min and a holding time of 30 minutes (Rhamdhani, Jak and Hayes, 2008; Rhamdhani *et al.*, 2009)

CARON PROCESS

This process was first developed by Caron in the Netherlands in the 1920s and can be used for limonite ores with some tolerance to saprolite. It is based on the selective reduction of nickel and cobalt to metal, followed by dissolution in an ammonia/ ammonium carbonate solution. Iron is reduced at 850 °C to form alloys with nickel and cobalt, as well as magnetite (Kyle, 2010). Reaction (3) roasting (850°C) can be written as:

$NiO + 2Fe_2O_3 + 3H_2 \leftrightarrow FeNi + Fe_3O_4 + 3H_2O$ ....(3)

The ore is cooled at a temperature of 150-200 ^oC and cooled in an ammonia/ammonium carbonate solution. Nickel and cobalt are dissolved as ammonia complexes and iron is oxidized and precipitated as iron hydroxide as in reaction (4) (Kyle, 2010).

$FeNi + 1.25O_2 + 2.5\ H_2O + 4\ NH_3 + (NH_4)_2CO_3 \leftrightarrow Ni(NH_3)_6CO_3 + Fe(OH)$ ....(4)

After separation, the cobalt is recovered as cobalt sulfide while nickel is recovered as nickel carbonate as in reaction (5). Nickel carbonate can be calcined to produce nickel oxide as the final product (Kyle, 2010).

$2\ Ni(NH_3)_6CO_3 + H_2O \leftrightarrow Ni_2(OH)_2CO_3 + 12\ NH_3 + CO_2$ ....(5)

The advantage of Caron process is that this technology is proven and can be applied to low nickel grade ores and can be applied to mixtures of limonite and saprolite.Separate nickel and cobalt products are obtained, although the cobalt recovery is still low. The ammonia leaching step in the process is highly selective for the nickel and the cobalt. The ammonia can be recycled and the standard materials can be used as leachate containers and are less susceptible to corrosion, and use relatively easy operating conditions (Kyle, 2010). The disadvantages of Caron process are energy-consuming pre-drying and calcination of the ore, extraction of nickel and cobalt is generally low at less than 90% Ni and 80% Co compared to pressurized acid leaching and acid leaching, and limited to limonite ores low in magnesium (Kyle, 2010).

HIGH PRESURE ACID LEACHING

This process is particularly suitable for limonite ore because the aluminum and magnesium content should not be too high. to avoid the increase of-the acid consumption (Kyle, 2010). The ore is dissolved in an autoclave with sulfuric acid at 240-270 ^oC and a holding time of 60-90 minutes. It results in the deposition of mostly dissolved iron as hematite or jarosite and aluminum as alunite (West and Connolly, 2007; Kyle, 2010). Due to the rapid leaching conditions, more than 95 % of nickel and cobalt and more than 90 % of magnesium and manganese are dissolved into the solution during the high pressure acid leaching process (Kyle, 2010). Most of the iron, aluminum, silica, and chromium are solids/residue, although small amounts remain in solution and contaminate the leaching product (Neudorf, 2006; Zhang *et al.*, 2009; Kyle, 2010). Precipitation of iron as hematite and jarosite is one of the main advantages of the high pressure leaching process as it reduces acid consumption and precipitates iron in a precipitated form so that it is easily separated from nickel-rich solutions. As shown later, the control of iron in other acid leaching processes such as atmospheric leaching is not as easy to perform as it is in high pressure leaching processes (Kyle, 2010).

The slurry contains about 5-7 g/L nickel and 45-60 g/L sulfuric acid in solution. This acid is neutralized with limestone and the remaining iron is precipitated as iron hydroxide prior to being filtered (Kyle, 2010). purifying the solution, the nickel and cobalt are then extracted from the clarified leachate by various methods such as solvent extraction to produce products in the form of sulfides or hydroxides or into finer products such as metals or oxides (Kyle, 2010). Some nickel and cobalt reduction occurs during this solvent extraction process to reduce the overall nickel recovery to about 90-92 % (Marshall and Buarzaiga, 2004; Kyle, 2010). Using the citric acid as a leaching solution under atmospheric pressure for the extraction of Indonesian saprolytic nickel ore with a nickel content of 1.76 % has been done (Marshall and Buarzaiga, 2004; Kyle, 2010). The highest Ni recovery 95.6 % was achieved at leaching conditions with ore particle size 212-355 µm, citric acid concentration 1 mol/L, leaching time 15 days, pulp density 20 % w/v, leaching temperature 40 °C and rotation speed 200 rpm (Astuti *et al.*, 2016). Comparison of leaching kinetics of atmospheric pressure citric acid from different saprolitic ores with nickel content of 1.76 % saprolite sulfide (SS) and 1.28 % saprolite hydroxide (SH) ore, respectively. The maximum leaching efficiency of nickel was achieved from SS ore and SH ore of 96 % and 73 %, respectively, as shown in Figures 7A and B as shown in Figure 8 (Astuti *et al.*, 2016; Bahfie, Manaf, Astuti, Nurjaman, *et al.*, 2021).

The advantage of this process is that it can be applied to relatively low grade laterites (1.5 % Ni). This process relies on dissolving very high solids in the slurry and consequently has great flexibility with respect to the ore type and requires a lot of acid. Leaching extracted nickel and cobalt were overall better than other processes (with recovery > 95 %), and without drying and calcination (Kyle, 2010). Its disadvantages are that this process cannot be economically applied to saprolite ores which contain higher impurities such as magnesium and aluminum, high pressure acid leaching is very corrosive and requires corrosive resistant materials, high levels of impurities in solution leach products require relatively heavy separation, acid consumption sulfate, although lower than competing acid leaching processes, is still high (generally 350-500 kg per tonne of ore), residual sulfuric acid at the end of the leaching process must be neutralized with limestone, and the process produces large quantities of liquid magnesium sulfate which must be disposed of, recycled, or turned into by-products (Kyle, 2010).

ATMOSPHERIC ACID LEACHING

This process is carried out just below the boiling point at atmospheric pressure (usually around 100 °C) for up to 12 hours. During this process, sulfur dioxide or other suitable reducing agent may be added to the leach slurry to aid the cobalt dissolution (Steyl, Peiser and Smit, 2008; Tan, 2008; Willis, 2008; Steemson and Smith, 2009). The long leaching time is not only to dissolve the nickel into the solution but also to encourage the precipitation of the iron from the solution. At Ravensthorpe, seawater is used to aid this process. After this reaction, the excess sulfuric acid is neutralized by the addition of saprolite ore to the leach slurry that is dissolving more nickel into the solution. The leaching solution is then separated from the solid so that nickel and cobalt are recovered from the leaching liquid (Liu *et al.*, 2004; Wen and Ruan, 2006; McDonald and Whittington, 2008; Wedderburn, 2009). Under optimal conditions, the extraction yields nickel and cobalt around 89.4 % and 97.3 % respectively. For the initial stage of leaching, the iron will dissolve in the leaching solution by Reaction (6), which is followed by precipitation of goethite by Reaction (7). Furthermore, the water content is reduced from the goethite through the Reaction (8). However, $NiCl_2$ does not precipitate as the oxide, because the precipitation of $FeCl^{4-}$ in the form of Fe_2O_3 is more thermodynamically possible than the precipitation of Ni^{2+} as the NiO. Thus, pressurized hydrochloric acid leaching has also achieved selective pressure leaching.

$FeOOH + 4HCl \rightarrow FeCl^{4-} + 2H_2O + H^+$......(6)
$FeCl^{4-} + 2H_2O \rightarrow FeOOH + 3H^+ + 4Cl^-$.....(7)
$2FeOOH \rightarrow Fe_2O_3 + H_2O$..........................(8)

As in the high-pressure leaching process, the most frequently used acid during atmospheric pressure leaching is sulfuric acid with an optimal yield of nickel, cobalt and iron of 90% as shown in Figure 9 (MacCarthy *et al.*, 2016; Bahfie, Manaf, Astuti, Nurjaman, *et al.*, 2021).

The advantage of the atmosphere pressure leaching process is it can be applied to laterite at lower content of 1.5 % Ni and using limonite and saprolite ore, extraction of high nickel and cobalt compared to 80 % point with > 90 % health, and the excess of free sulphuric acid neutralized with saprolite ore (Kyle, 2010). The main disadvantages of the atmosphere pressure leaching compared to high pressure acid leaching are longer leaging time and lower metal recovery, higher sulfuric acid consumption (generally from 500 to 700 kg per ton of ore), less filltration process, less effilution of manufactured water.

IMPLEMENTATION OF EXTRACTION PROCESS IN THE FUTURE

Under the Paris Agreement, zero-emission was declared by countries around the world. For this reason, further steps are needed in the extraction process for nickel laterite, which is safer and more environmentally friendly. The extraction process can be carried out through two methods, namely sulphate leaching and bioleaching.

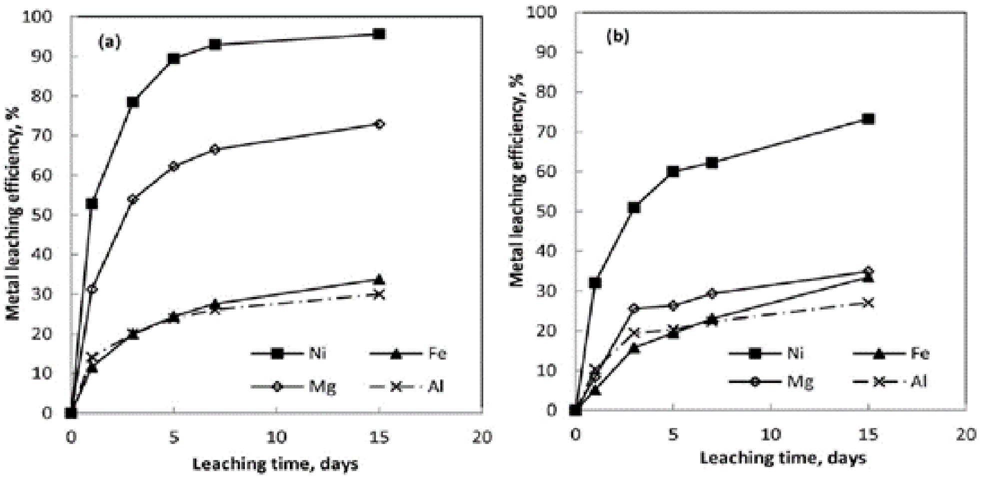

Figure 8. Comparison of the leaching efficiency of nickel sulfide (A) and laterite or hydroxide (B) ores (Astuti *et al.*, 2016; Bahfie, Manaf, Astuti, Nurjaman, *et al.*, 2021).

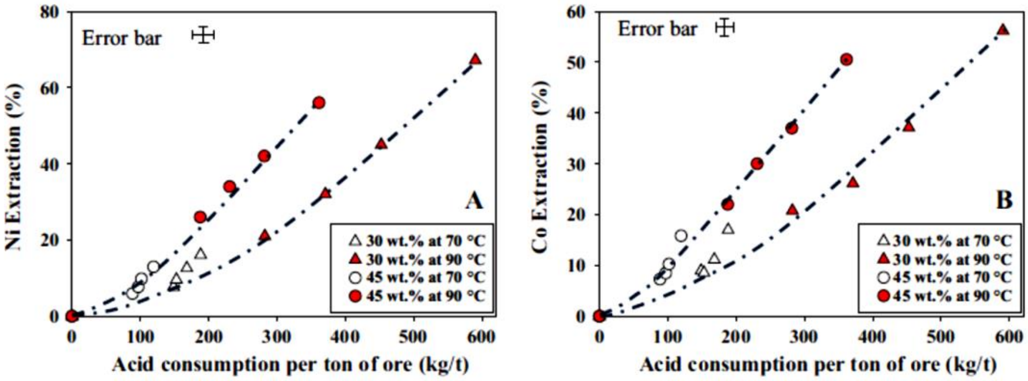

Figure 9. Acid consumption vs. (A) Ni and (B) Co extraction of 30 and 45 wt.% SG slurries for 4 h leaching at pH 1 and temperatures of 70 and 90 °C (MacCarthy *et al.*, 2016; Bahfie, Manaf, Astuti, Nurjaman, *et al.*, 2021)

SULPHATION ACID LEACHING

The novelty of this process is in the ore preparation stage where concentrated sulfuric acid is added directly to the limonite ore. The combined effect of high acidity and heat of reaction leads to good the sulfation of nickel and cobalt (Kyle, 2010). After sulfation, the limonite sulfate ore is mixed with the crushed saprolite and water and soil to produce a leaching slurry that is leached at 90-100 °C and atmospheric pressure. Sulfur dioxide can be added to the leachate to increase the dissolution of the cobalt (Gibson and Rice, 1977; Harris, Magee and Lakshman, 2004; Kyle, 2010). After removal the iron as goethite, counter current decantation (CCD) and purification of the solution, mixed hydroxide precipitates for sale to nickel/cobalt refiners are produced (Gibson and Rice, 1977; Harris, Magee and Lakshman, 2004; Harris *et al.*, 2006; Harris, White and Demopoulos, 2006; Harris and White, 2008; Königsberger, May and Harris, 2008; Kyle, 2010). As Figure 10, the iron dissolution ratio increased slowly from 0.2 % to 2.2 % with increasing a/o ratio from 0.1 to 0.3. Increasing the amount of sulfuric acid in the leach solution increases the amount of iron dissolved, i.e., 14.7 % Fe dissolved at an a/o ratio of 0.6. Since the amount of Fe in the leach solution is one of the most important parameters affecting the downstream process, the dissolved Fe/Ni ratio was also calculated (Ucyldiz and Girgin, 2017). Whereas in Figure 9B, the dissolution ratios of Mg, Ca, Mn, Al and Cr were also determined despite having different dissolution values, Mg (mainly from smectite and dolomite) and Mn (mainly from asbolane or $Mn_4+(O,OH)_2·(Co,Ni,Mg,Ca)x(OH)_2x·nH_2O$.) had similar leaching behavior, increasing up to a ratio of a /o 0.3, and has a nearly constant value above the a/o value 0.3 (Ucyldiz and Girgin, 2017).

BIOLEACHING

Bioleaching offers a new "green method" innovation for removing nickel from laterite at lower expenses and lower energy requests than previous processes (Kyle, 2010). It has been claimed to offer the potential for a step change in technology to treat these ores by using more selective leaching agents that target nickel and cobalt, rather than the acid used which can dissolve most elements (Valix, Tang and Cheung, 2001; Kyle, 2010). This solubility can occur with various organic acids such as citric acid, oxalic acid, and others. The organic acids are capable to dissolve the iron oxide minerals, including hematite and goethite (Bosecker, 1986; Kyle, 2010) Therefore, it can selectively dissolve the nickel iron oxide within the ores.

Bosecker (1986) initially tested fifteen different commercial organic acids (including oxalic, acetic, formic, citric, ascorbic, succinic, fumaric, and tartaric acids) for their ability to solubilize nickel from limonitic and silicate laterite ores. Surprisingly, in this chemical leaching experiment, very little nickel mobilization occurs from the limonite ore, but up to 90% of the nickel is extracted from the silicate ore with 0.5 M citric acid. In the bioleaching experiment, using microorganisms rather than organic acid chemicals, *Penicillium* bacteria were more effective than that of the *Aspergillus* in extracting nickel within the solution (Bosecker, 1986; Kyle, 2010). As in chemical leaching experiments, silicate minerals are more soluble than limonite, with nickel dissolving up to 70%. However, the dissolution of magnesium is also above 50% (Bosecker, 1986; Kyle, 2010). In bioleaching experiments, bacteria capability to produce the organic acids are mixed with the suitable nutrients (generally pure sugar derivatives) and ores (Verbaan *et al.*, 2007; Kyle, 2010). In the experiments of nickel ore, namely hematite and garnierite (Kyle, 1999), it was also found that the citric acid was the most effective organic acid for leaching and was more selective for dissolving nickel in iron and magnesium than that of the sulfuric acid. Oxalic acid is highly selective for dissolving iron against nickel, leaching up to 46% iron but only 1.6% nickel in one ore sample. This is probably caused by the formation of nickel oxalate deposits which have low solubility. However, more recent data by Tang and Valix (2006) suggest that metal leaching from low grade limonite and nontronite ores from New Caledonia is more dependent on acidity than the type of organic acid used. Citric, malic, and lactic acids provide similar metal dissolution after a fixed leaching period when the metal extraction rate is conditioned to the initial acidity of the organic acids. According to Figure 11, the nickel extraction profile for 20 days is direct leaching at 5% pulp density. Nickel extraction by *Aspergillus sp* until the 4th day of leaching was not much due to the formation of less organic acid which was seen from the pH value of around 5 (Kyle, 2010; Handayani and Suratman, 2016). It seems that the rapid nickel leaching occurs after 7 days. The final nickel extraction by Aspergillus sp was 57% for 16 leaching days at pH 2.2. For Penicillium sp, this trend was similar but suggested a more delay of about 7 days before nickel was leached more rapidly, and the final nickel recovery was only 48% at pH 2.6 after 18 days of leaching (Kyle, 2010; Handayani and Suratman, 2016).

For limonite, the leaching selectivity is Co > Mn > Mg > Ni > Cr > Al > Fe and for nontronite Co > Mn > Mg > Al > Ni > Fe. These data confirm the greater acceptability of the serpentine phase for bioleaching compared to the goethite and illite phases. Very little work has been done on the recovery of nickel and cobalt from solution. Chelating resins have been used to obtain nickel and cobalt recovery, but the resin selectivity is low, and the adsorption capacity is poor (Kyle, 1999, 2010; Taylor, 2000). In another way, Burgstaller and Schinner (1993) demonstrated recovery of nickel with an insoluble oxalate salt. One of the main problems that must be addressed is to obtain a cheap source of organic carbon for the bacteria, which will be specific. Although laboratory studies have used sugars such as sucrose and glucose, other suitable and cheaper organic carbon sources require further research. Such as molasses, sugar, pears, and milk waste (Moyes *et al.*, 2005; Deepatana, Tang and Valix, 2006; Tang and Valix, 2006; Kyle, 2010; Bahfie, Supriadi, Oediyani, Nurjaman, Astuti *et al.*, 2022).

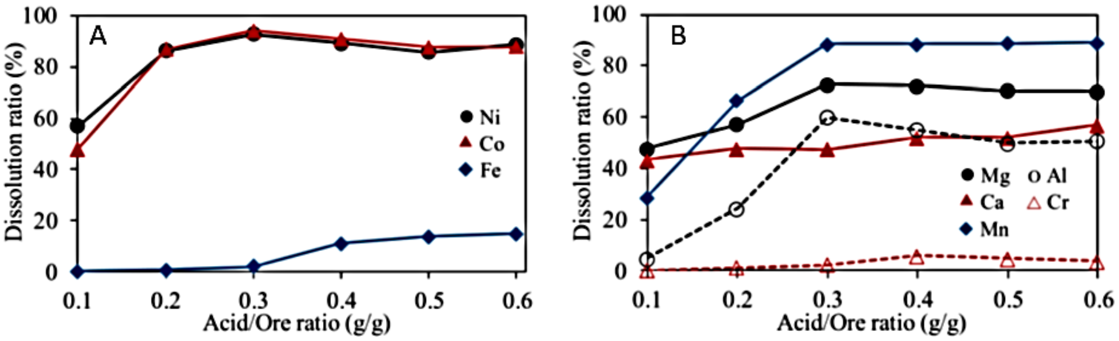

Figure 10. Dissolution ratio of acid and ore in (A) Ni, Co, and Fe, (B) Mg, Ca, Al, Cr, and Mn (Ucyldiz and Girgin, 2017)

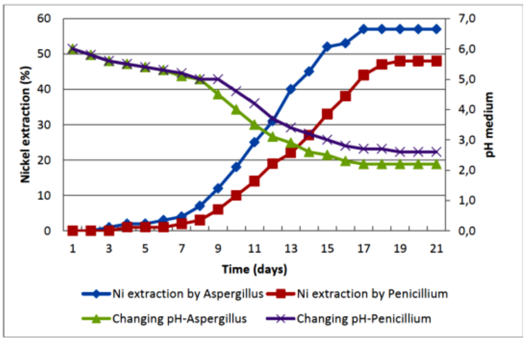

Figure 11. Nickel extraction by direct leaching at a pulp density of 5% (Handayani and Suratman, 2016)

APPLICATION OF LATERITE PROCESSING TECHNOLOGY IN INDUSTRY

The application of processing technology can be known depending on the material characteristics and needs. The smelting process remains for most of the nickel produced from laterite, and further projects are being developed in Figure 12. Examples of current smelting operations using pyrometallurgical processes are Cerro Matoso (Hanna, BHP Billiton, Columbia), Doniambo (Eramet, New Caledonia), Pomalaa (Aneka Tambang), and Soroako (PT Inco) in Indonesia and Onca Puma in Brazil (Elias, Donaldson and Giorgetta, 1981; BPH Minerals International, 1996; Arroyo and Neudorf, 2001; Duyvesteyn and Liu, 2002; Dalvi, Bacon and Osborne, 2004; Kyle, 2010). In Cilegon, Banten; PT INDOFERRO is the first NPI factory outside China. PT INDOFERRO has been processing low-grade laterite using a blast furnace (BF) to produce NPI since 2012 (Prasetyo, 2016; Bahfie, Manaf, Astuti, Nurjaman, *et al.*, 2021). Laterite processing has a significant opportunity to be developed in Indonesia. Therefore, research on laterite processing will continue to find results that can be used as alloys in stainless steel smelting in Indonesia. Namely, as many as 30 new nickel processing and refining facilities (smelters) are currently under construction. Nickel ore smelters and other derivative factories, such as stainless steel to battery components, are also being built based on the "The Future of Indonesian Nickel"- a Webinar on June 25, 2020 (Zulhan, 2020; Bahfie, Manaf, Astuti, Nurjaman, *et al.*, 2021). In addition, several Japanese smelters process imported ore from the Philippines, Indonesia, and New Caledonia. The Caron process is also applied in Nonoc in the Philippines (1986) and welding Camariocas in Cuba. High-pressure acid leaching is found in Ramu in Papua New Guinea (Metallurgical Construction Corp.) and Ambatovy in Madagascar (Sherrill) (Burger, 1996; King, 2005). The most in-demand industry is the manufacture of smelters, but this still produces NPI (nickel pig iron) products with a nickel content of 5 wt.% (Dalvi, Bacon and Osborne, 2004; Kyle, 2010; Bahfie, Manaf, Astuti, Nurjaman, *et al.*, 2021).

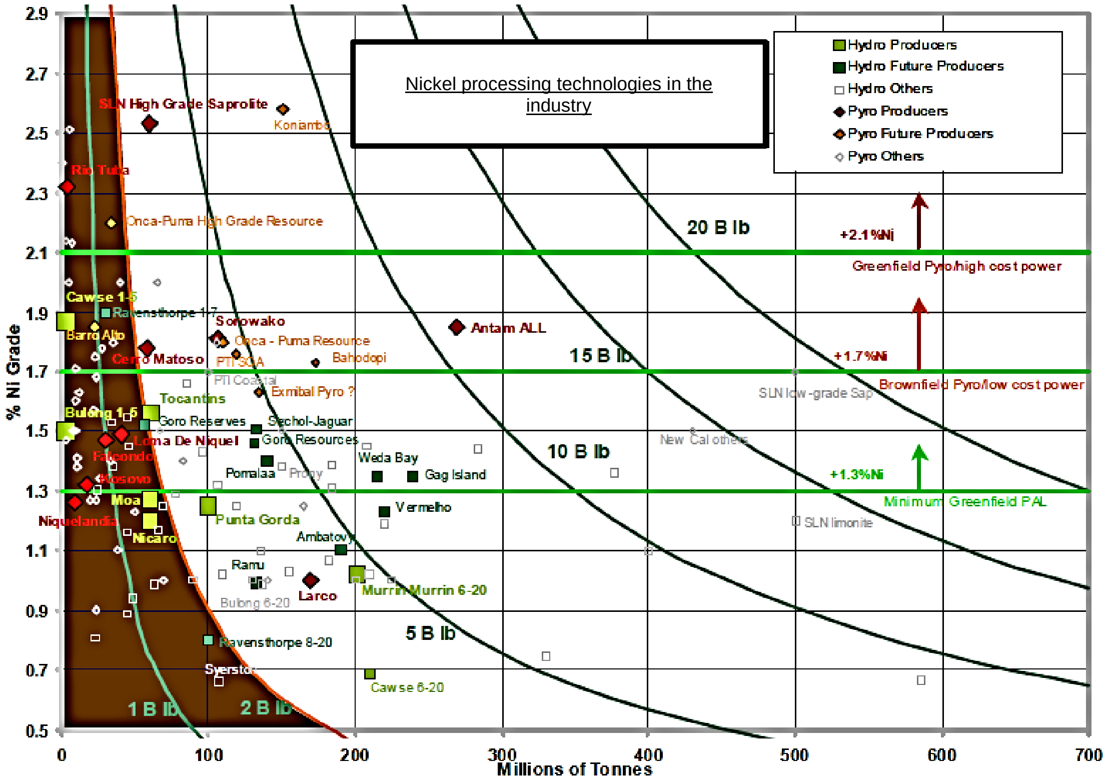

Figure 12. Nickel processing technologies in the industry (Dalvi, Bacon and Osborne, 2004)

SUMMARY

There are two nickel ore sources, namely laterite and sulfide. The laterite is different from the sulfides because it has an OH structure and is more complex. The laterite is also preferred in the processing because of its abundant resources compared to the sulfides. Laterite processing can be done by hydrometallurgical and pyrometallurgical processes. Hydrometallurgy produces powder, such as MHP product (Mn-Ni-Co) for batteries, while pyrometallurgy produces metal alloys with low Ni content. Nickel can be applied for raw materials of stainless steel, steel alloys, and batteries, depending on the process and product results. Bioleaching is more prospective for the future because it uses safe reagents, bacteria, and green technology during the process.

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REFERENCE

Agacayak, T., Zedef, V. and Aras, A. (2016) ‘Kinetic study on leaching of nickel from Turkish lateritic ore in nitric acid solution’, *Journal of Central South University*, 23(1), pp. 39–43. doi: 10.1007/s11771-016-3046-8.

Al-Khirbash, S. (2015) ‘Genesis and mineralogical classification of Ni-laterites, Oman Mountains’, *Ore Geology Reviews*, 65, pp. 199–212. doi: 10.1016/j.oregeorev.2014.09.022.

Arroyo, J. C. and Neudorf, D. A. (2001) ‘Atmospheric leach process for the recovery of nickel and cobalt from limonite and saprolite ores’. United State.

Astuti, W., Hirajima, T., Sasaki, K. and Okibe, N. (2016) ‘Comparison of atmospheric citric acid leaching kinetics of nickel from different Indonesian saprolitic ores’, *Hydrometallurgy*, 161, pp. 138–151. doi: 10.1016/j.hydromet.2015.12.015.

Bahfie, F., Manaf, A., Astuti, W. and Nurjaman, F. (2021) 'Studies on reduction characteristics of limonite and effect of sodium sulphate on the selective reduction to nickel', *Journal of The Institution of Engineers (India): Series D*, 102(1), pp. 149–157. doi: 10.1007/s40033-020-00240-3.

Bahfie, F., Manaf, A., Astuti, W., Nurjaman, F. and Herlina, U. (2021) 'Tinjauan teknologi proses ekstraksi bijih nikel laterit', *Jurnal Teknologi Mineral dan Batubara*, 17(3), pp. 135–152. doi: 10.30556/jtmb.Vol17.No3.2021.1156.

Bahfie, F., Murti, D. U., Nuryaman, A., Astuti, W., Nurjaman, F., Prasetyo, E., S. Sudibyo and Susanti, D. (2022) 'Kinetic Properties of Nickel Leaching by ANOVA Method', *Progress in Physics of Metals*, 23(3), pp. 476–488. doi: 10.15407/ufm.23.03.476.

Bahfie, F., Manaf, A., Astuti, W., Nurjaman, F. and Prasetyo, E. (2022) 'Studies of carbon percentage variation and mixing Saprolite-Limonite in selective reduction', *Materials Today: Proceedings*, 62, pp. 4156–4160. doi: 10.1016/j.matpr.2022.04.679.

Bahfie, F., Shofi, A., Herlina, U., Handoko, A. S., Septiana, N. A., Syafriadi, Suharto, Sudibyo, Suhartono and Nurjaman, F. (2022) 'The effect of sulfur, temperature, the duration of the process and reductant on the selective reduction of limonite ore', *Gospodarka Surowcami Mineralnymi – Mineral Resources Management*, 38(1), pp. 123–135. doi: 10.24425/gsm.2022.140606.

Bahfie, F., Manaf, A., Astuti, W., Nurjaman, F., Prasetyo, E. and Sumardi, S. (2022) 'Thermal upgrading of nickel from limonite by means of selective reduction', *Izvestiya. Ferrous Metallurgy*, 65(7), pp. 471–478. doi: 10.17073/0368-0797-2022-7-471-478.

Bahfie, F., Supriadi, M. R., Oediyani, S., Nurjaman, F., Astuti, W., Prasetyo, E. and Susanti, D. (2022) 'Use of monosodium glutamate (MSG) for green leaching process: An overview', *Periodico di Mineralogia*, 91(2), pp. 155–162. doi: 10.13133/2239-1002/17756.

Bosecker, K. (1986) 'Leaching of lateritic nickel ores with heterotrophic microorganisms', in Lawrence, R. W., Branion, R. M. R., and Ebner, H. G. (eds) *Fundamental and Applied Biohydrometallurgy*. Canada: Elsevier.

BPH Minerals International (1996) 'Process for recovering nickel from high-magnesium containing Ni-Fe-Mg lateritic ore'. United State.

Bunjaku, A., Kekkonen, M., Pietilä, K. and Taskinen, P. (2012) 'Effect of mineralogy and reducing agent on reduction of saprolitic nickel ores', *Mineral Processing and Extractive Metallurgy*, 121(3), pp. 156–165. doi: 10.1179/1743285512Y.0000000010.

Burger, P. A. (1996) 'Origins and characteristics of lateritic nickel deposits', in Grimsey, E. J. and Neuss, I. (eds) *Nickel '96, Mineral to Market*. Carlton: Australasian Institute of Mining and Metallurgy, pp. 179–184.

Burgstaller, W. and Schinner, F. (1993) 'Metaheaching with fungi', in Torma, A. E., Wey, J. E., and Lakshmanan, V. I. (eds) *International Symposium on Biohydrometallurgy*. Warrendale: TMS, pp. 325–333.

Chen, S., Guo, X., Shi, W. and Li, D. (2010) 'Extraction of valuable metals from low-grade nickeliferous laterite ore by reduction roasting-ammonia leaching method', *Journal of Central South University of Technology*, 17(4), pp. 765–769. doi: 10.1007/s11771-010-0554-9.

Dalvi, A. D., Bacon, W. G. and Osborne, R. C. (2004) 'The past and the future of nickel laterites', in *PDAC 2004 International Conference Trade Show and Investors Exchange*. Toronto: PDAC, pp. 1–27.

Deepatana, A., Tang, J. A. and Valix, M. (2006) 'Comparative study of chelating ion exchange resins for metal recovery from bioleaching of nickel laterite ores', *Minerals Engineering*, 19(12), pp. 1280–1289. doi: 10.1016/j.mineng.2006.04.015.

Duyvesteyn, W. P. C. and Liu, H. (2002) 'Process for organic acid bioleaching of ore'. United State.

Elias, M., Donaldson, M. J. and Giorgetta, N. E. (1981) 'Geology, mineralogy, and chemistry of lateritic nickel-cobalt deposits near Kalgoorlie, Western Australia', *Economic Geology*, 76(6), pp. 1775–1783. doi: 10.2113/gsecongeo.76.6.1775.

Elliott, R., Rodrigues, F., Pickles, C. A. and Peacey, J. (2015) 'A two-stage thermal upgrading process for nickeliferous limonitic laterite ores', *Canadian Metallurgical Quarterly*, 54(4), pp. 395–405. doi: 10.1179/1879139515Y.0000000009.

Gibson, R. W. and Rice, N. M. (1977) ‘A hydrochloric acid process for nickeliferous laterites’, in Cooper, W. C. and Mihaylov, I. (eds) *Hydrometallurgy and Refining of Nickel and Cobalt, Vol. 1*. Montreal: The Metallurgical Society of CIM, pp. 247–261.

Handayani, S. and Suratman, S. (2016) ‘Bioleaching of low grade nickel ore using indigenous fungi’, *Indonesian Mining Journal*, 19(3), pp. 143–152. doi: 10.30556/imj.Vol19.No3.2016.540.

Harris, B., White, C., Jansen, M. and Pursell, D. (2006) ‘A new approach to high concentration chloride leaching of nickel laterites’, in *ALTA Nickel/Cobalt/Copper Conference*. Melbourne: ALTA Metallurgical Services Publications, pp. 1–20.

Harris, B. and White, C. (2008) ‘Recent developments in the high-strength chloride leaching of base metal sulphide ores’, in *ALTA Nickel/Cobalt Conference 2008*. Melbourne: ALTA Metallurgical Services Publications, pp. 170–184.

Harris, G. B., Magee, T. J. and Lakshman, V. I. (2004) ‘The Jaguar Nickel Inc. sechol laterite project atmospheric chloride leach process’, in *Annual Meeting and International Laterite Nickel Symposium*. Warrendale: TMS, pp. 219–241.

Harris, G. B., White, C. W. and Demopoulos, G. P. (2006) ‘Iron control in high-concentration chloride leaching processes’, in *Third International Symposium on Iron Control in Hydrometallurgy*. Montreal: Canadian Institute of Mining, Metallurgy and Petroleum, pp. 445–464.

Jiang, M., Sun, T., Liu, Z., Kou, J., Liu, N. and Zhang, S. (2013) ‘Mechanism of sodium sulfate in promoting selective reduction of nickel laterite ore during reduction roasting process’, *International Journal of Mineral Processing*, 123, pp. 32–38. doi: 10.1016/j.minpro.2013.04.005.

Keskinkilic, E., Pournaderi, S., Geveci, A. and Topkaya, Y. (2012) ‘Calcination characteristics of laterite ores from the central region of Anatolia’, *Journal- South African Institute of Mining and Metallurgy*, 112, pp. 877–882.

Kim, J., Dodbiba, G., Tanno, H., Okaya, K., Matsuo, S. and Fujita, T. (2010) ‘Calcination of low-grade laterite for concentration of Ni by magnetic separation’, *Minerals Engineering*, 23(4), pp. 282–288. doi: 10.1016/j.mineng.2010.01.005.

King, M. G. (2005) ‘Nickel laterite technology—Finally a new dawn?’, *JOM*, 57(7), pp. 35–39. doi: 10.1007/s11837-005-0250-7.

Königsberger, E., May, P. and Harris, B. (2008) ‘Properties of electrolyte solutions relevant to high concentration chloride leaching I. Mixed aqueous solutions of hydrochloric acid and magnesium chloride’, *Hydrometallurgy*, 90(2–4), pp. 177–191. doi: 10.1016/j.hydromet.2007.10.009.

Kyle, J. (2010) ‘Nickel laterite processing technologies – where to next?’, in *ALTA 2010 Nickel/Cobalt/Copper Conference*. Melbourne: ALTA Metallurgical Services Publications, pp. 30–66.

Kyle, J. H. (1999) ‘Water quality in nickel laterite processing’, in *Water Management in Metallurgical Operations conference*. Perth: Australian Mineral Foundation Inc.

Li, B., Wang, H. and Wei, Y. (2011) ‘The reduction of nickel from low-grade nickel laterite ore using a solid-state deoxidisation method’, *Minerals Engineering*, 24(14), pp. 1556–1562. doi: 10.1016/j.mineng.2011.08.006.

Liu, H., Gillaspie, J., Lewis, C., Neudorf, D. and Barnett, S. (2004) ‘Atmospheric leaching of laterites with iron precipitation as goethite’, in Imrie, P. W. and Lane, D. M. (eds) *International Laterite Nickel Symposium 2004*. Charlotte: TMS, pp. 347–368.

Lv, X., Bai, C., He, S. and Huang, Q. (2010) ‘Mineral change of philippine and Indonesia nickel lateritic ore during sintering and mineralogy of their sinter’, *ISIJ International*, 50(3), pp. 380–385. doi: 10.2355/isijinternational.50.380.

Ma, X., Cui, Z. and Zhao, B. (2016) ‘Efficient utilization of nickel laterite to produce master alloy’, *JOM*, 68(12), pp. 3006–3014. doi: 10.1007/s11837-016-2028-5.

MacCarthy, J., Nosrati, A., Skinner, W. and Addai-Mensah, J. (2016) ‘Atmospheric acid leaching mechanisms and kinetics and rheological studies of a low grade saprolitic nickel laterite ore’, *Hydrometallurgy*, 160, pp. 26–37. doi: 10.1016/j.hydromet.2015.11.004.

Marshall, D. and Buarzaiga, M. (2004) ‘Effect of process water on high pressure acid leaching of laterite ores’, in Imrie, P. W. and Lane, D. M. (eds) *International Laterite Nickel Symposium 2004*. Charlotte: TMS, pp. 263–271.

McDonald, R. G. and Whittington, B. I. (2008) ‘Atmospheric acid leaching of nickel laterites review. Part II. Chloride and bio-technologies’, *Hydrometallurgy*, 91(1–4), pp. 56–69. doi: 10.1016/j.hydromet.2007.11.010.

Moyes, J., Houllis, F., Tong, A. and Sammut, D. (2005) ‘The Intec nickel laterite process’, in *ALTA 2005 Nickel/Cobalt Conference*. Melbourne: ALTA Metallurgical Services Publications, pp. 136–155.

Neudorf, D. (2006) ‘Method for nickel and cobalt recovery from laterite ores by reaction with concentrated acid water leaching’. United State.

Nurjaman, F., Shofi, A., Bahfie, F. and Suharno, B. (2015) ‘Teknologi pembuatan spiegel pig iron menggunakan hot blast cupola furnace’, *Jurnal RISET Geologi dan Pertambangan*, 25(1), pp. 13–22. doi: 10.14203/risetgeotam2015.v25.138.

Nurjaman, F., Saekhan, K., Bahfie, F., Astuti, W. and Suharno, B. (2021) ‘Effect of binary basicity (CaO/SiO2) on selective reduction of lateritic nickel ore’, *Periodico di Mineralogia*, 90(2), pp. 91–97.

Nurjaman, F., Sari, Y., Manurung, P., Handoko, A. S., Bahfie, F., Astuti, W. and Suharno, B. (2021) ‘Study of binary, ternary, and quaternary basicity in reduction of saprolitic nickel ore’, *Transactions of the Indian Institute of Metals*, 74(12), pp. 3249–3263. doi: 10.1007/s12666-021-02391-7.

Nurjaman, F., Astuti, W., Bahfie, F. and Suharno, B. (2021) ‘Study of selective reduction in lateritic nickel ore: Saprolite versus limonite’, *Materials Today: Proceedings*, 44, pp. 1488–1494. doi: 10.1016/j.matpr.2020.11.687.

Nurjaman, F., Sa’adah, A. and Suharno, B. (2019) ‘Optimal conditions for selective reduction process of nickel laterite ore’, *IOP Conference Series: Materials Science and Engineering*, 523(1), p. 012068. doi: 10.1088/1757-899X/523/1/012068.

Pickles, C. A., Harris, C. T., Peacey, J. and Forster, J. (2013) ‘Thermodynamic analysis of the Fe–Ni–Co–Mg–Si–O–H–S–C–Cl system for selective sulphidation of a nickeliferous limonitic laterite ore’, *Minerals Engineering*, 54, pp. 52–62. doi: 10.1016/j.mineng.2013.03.029.

Pickles, C. A. and Elliott, R. (2015) ‘Thermodynamic analysis of selective reduction of nickeliferous limonitic laterite ore by carbon monoxide’, *Mineral Processing and Extractive Metallurgy*, 124(4), pp. 208–216. doi: 10.1179/1743285515Y.0000000009.

Pickles, C. A., Forster, J. and Elliott, R. (2014) ‘Thermodynamic analysis of the carbothermic reduction roasting of a nickeliferous limonitic laterite ore’, *Minerals Engineering*, 65, pp. 33–40. doi: 10.1016/j.mineng.2014.05.006.

Pournaderi, S., Keskinkılıç, E., Geveci, A. and Topkaya, Y. A. (2014) ‘Reducibility of nickeliferous limonitic laterite ore from Central Anatolia’, *Canadian Metallurgical Quarterly*, 53(1), pp. 26–37. doi: 10.1179/1879139513Y.0000000099.

Prasetyo, P. (2016) ‘Sumber daya mineral di Indonesia khususnya bijih nikel laterit and masalah pengolahannya sehubungan dengan UU Minerba 2019’, in *Seminar Nasional Sains dan Teknologi 2016*. Jakarta: Fakultas Teknik Universitas Muhammadiyah Jakarta, p. TM-008.

Quast, K., Connor, J. N., Skinner, W., Robinson, D. J. and Addai-Mensah, J. (2015) ‘Preconcentration strategies in the processing of nickel laterite ores Part 1: Literature review’, *Minerals Engineering*, 79, pp. 261–268. doi: 10.1016/j.mineng.2015.03.017.

Rhamdhani, M. A., Chen, J., Hidayat, T., Jak, E. and Hayes, P. (2009) ‘Advances in research on nickel production through the Caron process’, in *Proceedings of EMC 2009*. Melbourne: TMS, pp. 899–913.

Rhamdhani, M. A., Jak, E. and Hayes, P. C. (2008) ‘Basic nickel Carbonate: Part I. Microstructure and phase changes during oxidation and reduction processes’, *Metallurgical and Materials Transactions B*, 39(2), pp. 218–233. doi: 10.1007/s11663-007-9124-4.

Rice, N. M. (2016) ‘A hydrochloric acid process for nickeliferous laterites’, *Minerals Engineering*, 88, pp. 28–52. doi: 10.1016/j.mineng.2015.09.017.

Steemson, M. L. and Smith, M. E. (2009) ‘The development of nickel laterite heap leach projects’, in *ALTA 2009 Nickel/Cobalt Conference*. Melbourne: ALTA Metallurgical Services Publications, pp. 429–451.

Steyl, J. D. T., Peiser, M. and Smit, J. T. (2008) ‘Atmospheric leach process for nickel laterite ores’, in Courtney, A. Y. et al. (eds) *Proceedings 6th International Symposium*. Colorado: Society for Mining, Metallurgy, and Exploration, pp. 541–550.

Stober, F., Walker, C., Voermann, N., Solar, M. and Wasmund, B. (2008) ‘‘Evolution and future of Rotary Kiln - Electric Furnace (RKEF) plants for smelting of nickel laterites’, in *ALTA 2008 Nickel/Cobalt Conference*. Melbourne: ALTA Metallurgical Services Publications, pp. 7–28.

Tan, I. (2008) ‘Canegrass nickel-cobalt heap leaching project – An emerging nickel producer’, in *ALTA 2008 Nickel/Cobalt Conference*. Melbourne: ALTA Metallurgical Services Publications, pp. 59–122.

Tang, J. A. and Valix, M. (2006) ‘Leaching of low grade limonite and nontronite ores by fungi metabolic acids’, *Minerals Engineering*, 19(12), pp. 1274–1279. doi: 10.1016/j.mineng.2006.04.009.

Taylor, A. (2000) ‘Future trends in PAL plant design for Ni/Co laterites’, in *ALTA 2000 Nickel/Cobalt Conference*. Melbourne: ALTA Metallurgical Services Publications, pp. 417–431.

Ucyldiz, A. and Girgin, I. (2017) ‘High pressure sulphuric acid leaching of lateritic nickel ore’, *Physicochemical Problems of Mineral Processing*, 53(1), p. 475−488. doi: 10.5277/ppmp170137.

Valix, M., Tang, J. Y. and Cheung, W. H. (2001) ‘The effects of mineralogy on the biological leaching of nickel laterite ores’, *Minerals Engineering*, 14(12), pp. 1629–1635. doi: 10.1016/S0892-6875(01)00181-9.

Verbaan, N., Sist, F., Mackie, S. and Todd, I. (2007) ‘Development and piloting of Skye’s atmospheric limonite and saprolite leach process (SAL) at SGS minerals’, in *ALTA 2007 Nickel/Cobalt Conference*. Melbourne: ALTA Metallurgical Services Publications, pp. 464–486.

Wang, X., Sun, T., Chen, C. and Hu, T. (2017) ‘Current studies of treating processes for nickel laterite ores’, in *Proceedings of the 2nd International Conference on Mechatronics Engineering and Information Technology (ICMEIT 2017)*. Paris, France: Atlantis Press, pp. 139–152. doi: 10.2991/icmeit-17.2017.27.

Wedderburn, B. (2009) ‘Nickel laterite processing - A shift towards heap leaching’, in *ALTA 2009 Nickel/Cobalt Conference*. Melbourne: ALTA Metallurgical Services Publications, pp. 362–428.

Wen, J. and Ruan, R. (2006) ‘Heap leaching - An option of treating nickel laterite ore and sulphide’, in *ALTA 2006 Nickel/Cobalt Conference*. Melbourne: ALTA Metallurgical Services Publications, pp. 439–447.

West, J. and Connolly, D. (2007) ‘Comparative leaching strategies’, in *AusIMM Australian Nickel Conference*. Kalgoorlie: AusMM.

Willis, B. (2008) ‘Trends in PAL down stream recovery options’, in *ALTA 2008 Nickel/Cobalt Conference*. Melbourne: ALTA Metallurgical Services Publications, pp. 545–599.

Zevgolis, E. N., Zografidis, C., Perraki, T. and Devlin, E. (2010) ‘Phase transformations of nickeliferous laterites during preheating and reduction with carbon monoxide’, *Journal of Thermal Analysis and Calorimetry*, 100(1), pp. 133–139. doi: 10.1007/s10973-009-0198-x.

Zhang, W., Mason, P., Wang, W. and Zhu, Z. (2009) ‘Preliminary tests for manganese removal from nickel laterite mixed hydroxide precipitation circuit by oxidative precipitation with SO2/Air’, in *48th Annual Conference of Metallurgists: Hydrometallurgy of Nickel and Cobalt Symposium*. Sadbury: Canadian Institute of Mining, Metallurgy and Petroleum.

Zulhan, Z. (2020) ‘Hilirisasi komoditas nikel’, in *Webinar Keprofesian Teknik Metalurgi “Masa Depan Nikel Indonesia”*. Bandung: Ikatan Alumni Teknik Metalurgi ITB.