
Unlocking Disseminated Nickel Sulphides Using the CESL Nickel Process

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1 Abstract

Economic nickel deposits occur as sulphides or laterites, with sulphide deposits accounting for the majority of the world's primary nickel supply. As global nickel supply from world class massive sulphide deposits become progressively depleted it has largely been anticipated that a greater portion of nickel will come from lateritic deposits in order to meet future demand. Historically, laterite projects have struggled technically and financially with few reaching nameplate capacity. This presents an opportunity for the development of alternative resources such as low-grade disseminated nickel sulphide ores to meet future nickel demand. To date these resources have remained relatively untapped as they can pose serious challenges for conventional processing methods. However, with the advancement of new processing methods and extractive technologies the development and role of disseminated sulphide deposits will become increasingly important.

Teck's CESL Nickel Process offers a hydrometallurgical solution for unlocking the nickel from disseminated nickel ore deposits. It is capable of treating lower grade nickel concentrates; including those with a high content of magnesia. The process can also efficiently treat bulk nickel-copper-cobalt concentrates with no need for metal separation at the milling stage.

This paper begins with an overview of the nickel industry which in turn draws attention to the importance and opportunity that exists to exploit disseminated nickel sulphide resources. Later the focal point of the paper shifts to the successful development of the CESL Nickel Process as an extractive technology for processing disseminated nickel sulphide concentrates. In closing, two case studies are presented (section 5) which highlight the potential economic benefit achieved through the application of the CESL Nickel Process to disseminated sulphide concentrates.

2 CESL Introduction

CESL Limited ('CESL') is a subsidiary Teck Resources Limited ('Teck') that operates within and forms part of Teck's Technology Group. The Technology Group undertakes research and development projects for Teck's core business areas together with external work. Composed of three main areas, the division's mandate is three-fold; to advance growth opportunities, including those generated by the application of our proprietary CESL hydrometallurgical technology, to transfer technology for operational improvement, and to deliver sustainable solutions to enhance environmental performance and metal use.

CESL hydrometallurgical technology can be applied to a wide variety of copper and nickel sulphide concentrates, and has the flexibility to treat bulk, lower grade, or impurity-challenged material. In doing so, it recovers a high percentage of all payable metals, including gold and silver by-products. The Technology Group is actively seeking opportunities to participate in existing operations and new ventures through the application of the CESL process. Work at CESL will be focused on advancing projects which have the best potential to deliver internal and external growth opportunities to Teck.

3 Nickel Resources and Supply

Nickel resources are typically classified as sulphides or laterites.^[1,2] Currently, some 60% of the world's nickel supply is derived from sulphide resources and almost all of the sulphides utilized now are massive sulphide ores, as opposed to disseminated sulphides.^[1] The balance of nickel supply comes from limonitic and saprolitic laterite deposits which represent an abundant nickel resource.^[1,15] Approximately 60-70% of the world's nickel resources are estimated to be contained in laterites while 30-40% are as classified as sulphide.^[1,2,15] These statistics are not likely to change unless a significant rise in metal prices and/or the development of new extractive technologies supports the development of resources that were previously considered uneconomic or metallurgically challenged.^[15]

Despite the discrepancy between laterite and sulphide resources, global nickel supply from massive sulphide resources will continue to be an integral source of primary nickel supply going forward.^[12] This is largely due to fact that laterite projects have generally been exploited at a loss, historically. Compared to massive sulphide ores, laterite ores exhibit a greater mineralogical and chemical complexity which makes them more challenging to process economically.^[13,14] Laterite ores which

have grades in the range of 0.9-3% are not well suited for upgrading, resulting in plant sizes and waste volumes which are significant compared to metal output.^[2,13] Unlike massive sulphide ores which are largely processed by proven efficient conventional pyrometallurgical routes, less than 40% of laterite resources (saprolite ores) are amenable by pyrometallurgical routes such as ferronickel technology.^[5,15] The remainder of laterite resources (limonite ores) are amenable to hydrometallurgically processing like high pressure acid leach (HPAL) technology.^[5,15]

Historically HPAL projects have struggled facing numerous cost over-runs, delays and failed start-ups.^[13,14] These difficulties can be attributed to the metallurgical complexity of the flowsheets as well as the energy intensive operating conditions required to leach nickel from laterite ores.^[14] Generally speaking the high operating pressures (33-35atm), temperatures (245-275°C), and acid consumptions (200-500 kg/t) required for HPAL give way to high capital, operating, and sustaining costs.^[13] Comparable to the previous generation of HPAL projects, several of today's HPAL projects continue to encounter delays and ongoing technical problems and may struggle to reach their nameplate capacity. In short, many of these projects continue to over promise and under-deliver. The dependence on laterites to successfully meet nickel supply demands going forward will evidently depend on improvements in current processing methods. In the meantime world nickel supply will remain heavily reliant on the processing of massive sulphides.

Smelting and refining of massive sulphides begins with the flotation of ore, typically in the range of 0.2-2% nickel, to an acceptable concentrate grade of 10 to 20% nickel.^[2,11] Concentrate smelting produces a high grade nickel matte which is then refined hydrometallurgically.^[2,12] With the majority of the world's nickel supply coming via pyrometallurgical processes, the technology has proven to be quite robust over the years.^[12,14] Unlike massive sulphide ores, the processing of disseminated sulphide ores has proven to be more challenging even though the ore grades of some of the worlds largest most economic deposits are often reasonable (0.6 to 0.9%).^[7] The problem has been related to processing; the conventional flotation process on low-grade disseminated sulphide ores tends to be difficult due in large part to fines containing large amounts of magnesium rich serpentine type minerals which generate slimes during comminution.^[4,11,16] In most cases treatment of such ores results in a low nickel recovery and produces a concentrate unacceptably high in magnesia.^[17,18] Nickel smelters typically cannot handle such concentrates without blending, due to inescapable problems with slag metallurgy.^[15] As a result nickel grade and the Fe:MgO ratio in concentrate are key parameters in order to control smelting temperatures and slag viscosity and minimize operating costs.^[12,16]

Disseminated nickel and nickel-copper ores are widely distributed around the world and can be found in most of the world's nickel sulphide deposits.^[1,7,8] Komatiite-hosted nickel-copper deposits contain some of the world's most economically significant disseminated ore deposits.^[7,8] These sulphide-poor, magnesium rich deposits are mainly found in Australia, Canada, Brazil, Zimbabwe, Finland, and Russia.^[7,8] Various flowsheet considerations and adjustments to flotation conditions (i.e. particle size, pH and pulp density, etc.) have been developed to manage the well documented problems caused by slime-coating^[4,17]. However, these flowsheets may prove to be complex, costly and difficult to efficiently produce high-grade, low magnesia concentrates for conventional pyrometallurgical treatment. An alternative for consideration would be the production of a low-grade nickel concentrate for hydrometallurgical treatment.^[16] In doing so, significant improvements to overall nickel recovery could be achieved.

Several new hydrometallurgical leaching technologies have been developed and tested that merit consideration for application to sulphide-poor magnesium rich disseminated nickel-copper ores. Teck's CESL Nickel Process is a well developed hydrometallurgical technology which can unlock the nickel from disseminated sulphides and provide a reliable means of nickel production for future projects.

4 CESL Nickel Process

The CESL Nickel Process offers a method of unlocking the nickel from disseminated nickel sulphide ore bodies. It is capable of treating lower grade nickel concentrates and those with a high content of magnesia. The process can also treat bulk nickel-copper-cobalt concentrates with no need for metal separation at the milling stage.

Several nickel concentrates from various deposits have been tested by CESL at the bench scale level. Previous pilot plant testing on the CESL Nickel Process has included the production of mixed nickel/cobalt hydroxide and sulphide intermediate products, nickel hydroxide, as well as the production of nickel and cobalt cathode.



Figure 1 – CESL MHP 2009



Figure 2 – CESL Nickel Cathode 2010

CESL continues to advance the development of its nickel process technology. Current work has primarily focused on the production of separate nickel and cobalt intermediate products using a novel solvent extraction process. For projects with a high nickel nameplate capacity, it is economically advantageous to produce nickel metal, rather than an intermediate where the full payable metal value is not realized. Flowsheet enhancement work is underway to evaluate different processing methods for production of nickel metal from various intermediates.

4.1 Process Features

The CESL Nickel Process uses similar pressure oxidation (PO) conditions to the CESL Copper Process. [6] The process is characterized as a medium temperature leach which yields a low sulphur oxidation resulting in reduced capital and operating costs. Less oxidation in the autoclave results in a smaller vessel and lower oxygen and neutralization costs. The sulphur oxidation is controlled and the leaching rate is improved through the addition of chloride. Nickel sulphide minerals all oxidize very efficiently under these conditions, but nickel behaves differently to copper in that it quantitatively leaches into solution in PO.

Other notable attributes of the CESL Nickel Process include:

- Well developed hydrometallurgical process
- Ultra-fine grinding not required
- Flowsheet uses of known commercial technologies
- Effectively treats bulk concentrates
- High metal recoveries for nickel, copper, and cobalt
- Effective impurity control and purification (e.g. magnesium, manganese)
- Produces marketable intermediate products
- Minimal energy requirements outside of electrowinning for metal production
- Capable of operating with the use of seawater
- No exotic reagents required
- Closed circuit; virtually no effluent

4.2 Process Description

A conceptual flowsheet for the recovery of nickel to a nickel hydroxide product is given in Figure 3 below.

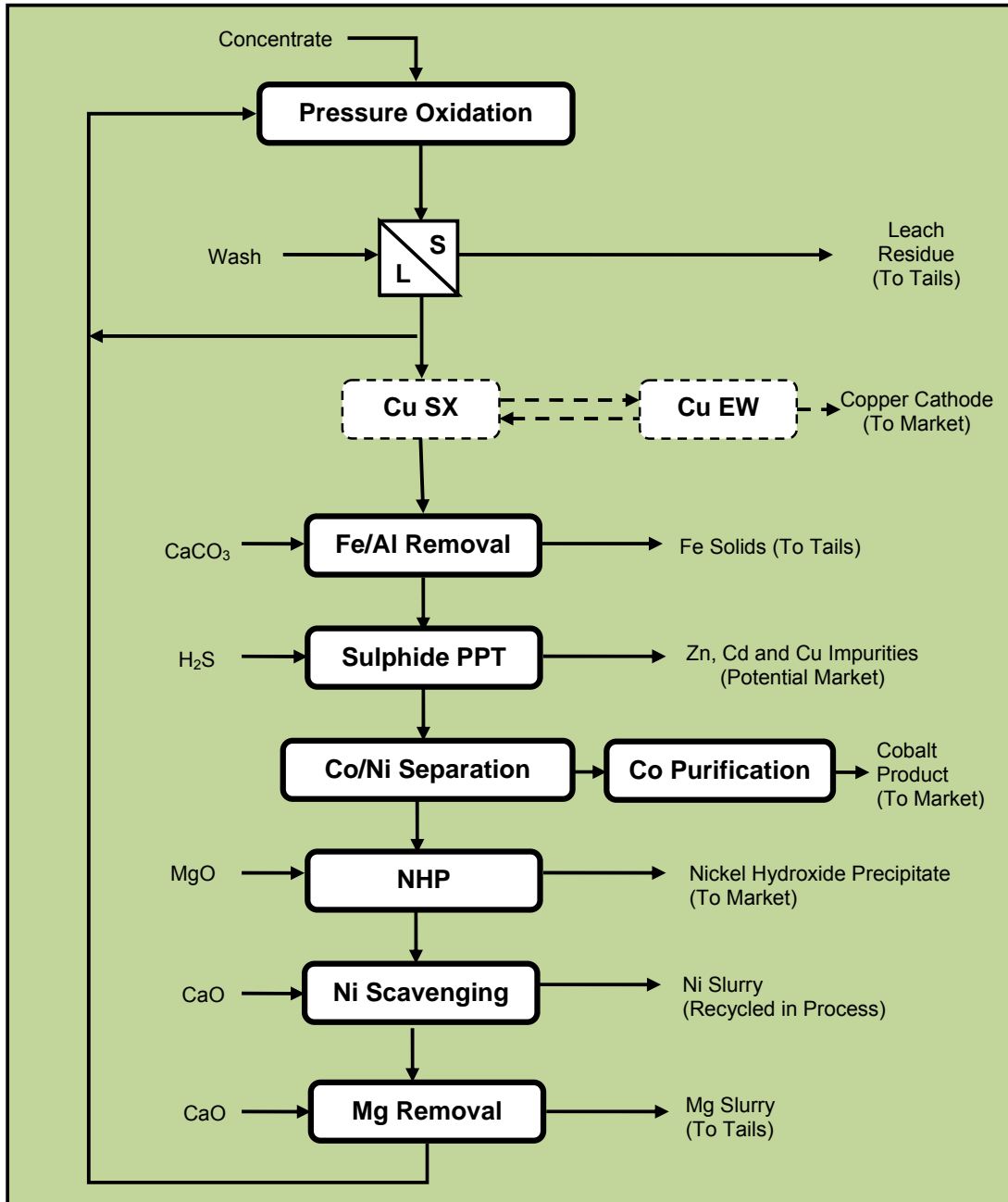


Figure 3 – CESL Nickel Process Flowsheet for Disseminated Concentrates

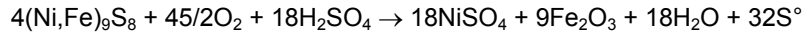
A process description of each unit operation is provided in the following section.

4.2.1 Pressure Oxidation

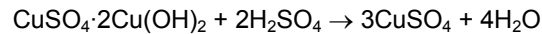
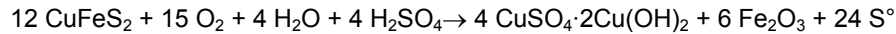
The purpose of pressure oxidation is to fully oxidize all the nickel, cobalt and copper in the concentrate to an acid soluble form. This occurs in the autoclave which operates at 150°C and 200psi. Concentrate-specific process conditions are adjusted to optimize metal extraction while minimizing sulphur oxidation.

Prior to being fed to the autoclave, the concentrate may undergo a light regrind to a p80 at 25-45µm in a closed loop ball mill circuit.

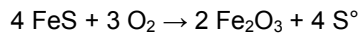
The oxidation reaction for pentlandite [(Ni,Fe)₉S₈] is given below. A similar reaction can be written for other nickel and cobalt sulphides.



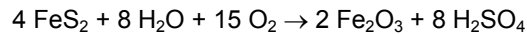
Similarly, the copper sulphide species present in the concentrate are also oxidized in the autoclave. For example, chalcopyrite (CuFeS₂) is first converted into basic copper sulphate [CuSO₄·2Cu(OH)₂] an acid-leachable solid. The amount of excess acid in the autoclave controls the degree of dissolution of the basic copper sulphate.



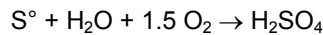
Pyrrhotite (FeS) in the concentrate is oxidized almost quantitatively to hematite and elemental sulphur, without significant sulphate formation.



A portion (50-75%) of the pyrite (FeS₂) in the concentrate oxidizes directly to sulphuric acid and hematite.



In addition to the pyrite, a small amount (1-5%) of the elemental sulphur produced oxidizes to create acid.



A chloride concentration of 12g/L is maintained in the autoclave through recycling acidic solution from the autoclave and by the addition of HCl to make up for soluble losses from the process. The chloride acts as a catalyst to increase reaction kinetics, ensuring complete oxidation of the sulphide minerals.

Sulphuric acid may be added to the autoclave feed (depending on the sulphate balance). A cryogenic oxygen plant will supply oxygen to oxidize the desired minerals.

The autoclave slurry is discharged into a one-stage flash vessel. The flashed slurry is pumped to the pressure oxidation thickener for solid-liquid separation. The thickener overflow is pumped on to copper solvent extraction (or to Fe/Al Removal if sufficient copper is not present). The thickener underflow is washed and filtered before being sent to tails.

4.2.2 Copper Solvent Extraction and Electrowinning

Copper is recovered via solvent extraction and electrowinning if a sufficient amount of copper is present to make this economic. The copper cathode produced using SX/EW will meet LME Grade A standards. The resulting raffinate solution is fed to the Fe/Al Removal circuit. If economic quantities of copper are not present, the copper will be removed from solution in the sulphide precipitation circuit.

4.2.3 Iron and Aluminum Removal

The iron and aluminum removal circuits are the first of the impurity removal circuits required to make a salable Nickel Hydroxide Precipitate (NHP) product. The circuit is fed with raffinate from copper solvent extraction (or the PO thickener overflow if solvent extraction is not used).

The iron and aluminum removal circuit is a two-stage counter-current process that uses limestone to adjust the pH of the feed to selectively precipitate iron and aluminum from solution. As well as removing iron and aluminum, the limestone neutralizes the majority of the sulphuric acid thereby creating gypsum.

Both stages of the circuit consist of three cascading reactors and a thickener. The residues from the first stage is washed and filtered for disposal.

4.2.4 Sulphide Precipitation

The sulphide precipitation circuit used hydrogen sulphide gas to selectively precipitate zinc, copper, and residual cadmium from solution to a final concentration of <1ppm. The solids are a potentially marketable product, depending on the purity of the sulphide product and the degree of impurities in the leach solution.

4.2.5 Nickel-Cobalt Separation

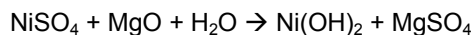
Cobalt is separated from nickel using Synergistic Solvent Extraction (SSX), a novel technology developed by CSIRO and CESL. The SSX circuit effectively separates cobalt from nickel thereby producing a nickel raffinate with $\geq 700:1$ nickel to cobalt ratio. Details of the process can be found in the ALTA 2010 paper "A New Process for Co-Ni Separation".^[9]

The cobalt-rich stream is further processed through a cobalt purification circuit using Cyanex 272. Subsequently, a pure cobalt carbonate product is precipitated using Na_2CO_3 .

The nickel-rich stream from SSX is sent to the nickel hydroxide precipitation (NHP) circuit.

4.2.6 Nickel Hydroxide Precipitation

The purified nickel solution is finally reacted with magnesia to precipitate the nickel from solution as a nickel hydroxide precipitate (NHP) product.



The NHP circuit consists of five cascading reactors, a thickener and a belt filter. The spent solution is sent through the nickel scavenging and magnesium removal circuits before being recycled to the autoclave. The expected nickel concentration would be ~45% (at ~40% moisture).

4.2.7 Nickel Scavenging

The spent solution from the NHP circuit still contains a small amount of nickel in solution (< 1g/L Ni). This nickel remains in solution to limit the amount of magnesium which deports to the NHP product. In the Nickel Scavenging circuit, lime is used to precipitate nickel which can then be recycled to the pressure oxidation discharge slurry. The remaining solution is sent through the magnesium removal circuit before it can be recycled to the autoclave.

4.2.8 Magnesium Removal

The magnesium removal circuit provides a bleed for the magnesium leached from the concentrate during pressure oxidation and the magnesium added via MgO during nickel hydroxide precipitation. The residue from the magnesium removal circuit is filtered for disposal. The solution is recycled to the pressure oxidation circuit.

4.3 Metallurgical Results

CESL has examined several nickel and bulk nickel and copper concentrates at the bench scale. This work has demonstrated the capability of the CESL Nickel Process to process a wide range of concentrates with diverse mineralogical characteristics and metallurgical complexity.

Table 1 presents metallurgical results from eight different concentrate samples, labeled concentrate A through H. The concentrate denoted 'A' in Table 1 represents recent results achieved while processing a low grade, bulk copper-nickel-cobalt concentrate from Teck's Mesaba project in the Duluth Complex in Minnesota, USA. The details of using the CESL technology for Mesaba have been previously published.^[10]

Table 1 – CESL Nickel Process Metallurgical Results

	Concentrate Grade				Metallurgical Results			
	% Ni	% Cu	% Co	% Mg	Ni Ext.	Mg Ext.	Net O2 Ratio (t O2/t Conc.)	Acid Consumption (kg H ₂ SO ₄ /t Conc)
A	2.1	18.6	0.1	1.9	95.2%	34%	0.23	0
B	3.7	8.0	0.1	3.7	98.7%	43%	0.22	226
C	4.0	1.1	0.2	11.7	98.5%	7%	0.12	88
D	10.9	0.6	0.2	6.4	99.2%	11%	0.16	200
E	12.9	0.1	0.4	5.2	99.0%	44%	0.22	110
F	5.7	0.3	0.2	14.0	95.4%	22%	0.16	79
G	3.6	1.1	0.3	1.5	94.7%	13%	0.22	131
H	6.3	0.3	0.3	7.2	98.2%	65%	0.16	250

Despite the wide variation in nickel grades between these concentrates, high metal extractions were realized for all samples. Although not displayed in Table 1, cobalt extractions are typically equal to or greater than nickel extraction. It is worth noting that for all of the concentrates tested, no fine grinding was required. Concentrates are typically tested at a p80 of 20-40µm. For the most part the pressure oxidation leaching times were maintained for 60 minutes but in some cases optimal nickel extraction was achieved in only 30 minutes. In each case the optimal nickel recovery will ultimately need to be evaluated against the cost of major consumables (i.e. oxygen and acid).

Magnesium extraction tends to be a function of the leach acid concentration. Magnesium leaching also increases with longer retention times, where additional acid is supplied by elevated sulphur oxidation levels. It is expected that batch testing yields magnesium leaching results greater than would be expected from continuous autoclave operations. In the batch process, the concentrate and the acid feed liquor are premixed and heated to 150°C without oxygen which allows time for the acid to leach the magnesia. In continuous operations, the feed liquor and concentrate are mixed in the first compartment of the autoclave and therefore a higher portion of the acid in the feed liquor is consumed for leaching nickel versus magnesium extraction.

For the majority of the concentrates tested above, sulphur oxidation results were generally moderate to low. The corresponding oxygen ratios were quite reasonable for the full suite of results presented. The gross oxygen ratios, a key design parameter for pressure oxidative leaching, are typically 15% greater than the net values presented. The amount of sulphur oxidized affects numerous aspects of the flowsheet, and low sulphur oxidization is usually desirable, if not essential for an economic process.

The key metallurgical results (i.e. metal extractions, oxygen ratios, and acid consumptions) from the historical data presented in Table 1 were used in each of the case studies presented in section 5. Metallurgical results were selected based on the specific assumptions made regarding the type of concentrate that is being evaluated.

5 Disseminated Nickel Case Studies

The purpose of this section is to demonstrate the potential economic benefit that can be achieved through the application of the CESL Nickel Process to concentrates produced from disseminated nickel and/or nickel-copper deposits. Two hypothetical projects are presented in which the deposits for each of the cases are representative of low-grade, magnesium rich, komatiite-hosted ore deposits which are widely distributed around the world.^[6] In both cases, complex mineralogy and downstream metallurgical challenges attributed to the ore deposit warrants the evaluation of a hydrometallurgical alternative to traditional concentrate sales.

The first case study (section 5.1) compares the hydrometallurgical treatment of a low-grade bulk nickel-copper concentrate versus the sale of separate nickel and copper concentrates. Although two separate smelter-grade nickel and copper concentrates can be produced from a finely disseminated sulphide ore, recoveries to a low-grade single bulk nickel-copper concentrate are significantly better. Due to high magnesia content, the low-grade single bulk concentrate is not overly attractive to a smelter and therefore requires a hydrometallurgical processing option.

The second case study (section 5.2) compares the hydrometallurgical treatment of a low-grade nickel concentrate high in magnesia versus the sale of a nickel concentrate. For this case it is assumed that concentrate production for conventional pyrometallurgical treatment is difficult due to the high content of serpentine minerals which generate slimes during comminution, negatively impacting metal recovery to final concentrate. To significantly improve metal recovery, the production of a low-grade nickel concentrate high in magnesia is considered for on-site hydrometallurgical treatment.

In each of the above cases, the revenue stream achieved from traditional concentrate sales is compared against the potential revenue stream generated from the sale of refined products from on-site hydrometallurgical treatment of concentrate using the CESL Nickel Process. In order to do so effectively, net revenue calculations were derived for each option. They are presented in the table below.

Table 2 – Net Revenue Calculation

Concentrate Sales Option	On-site CESL Refinery Option
Gross Metal Value in concentrate(s) for sale <i>x percent payable</i>	Gross Metal Value in refined products for sale <i>x percent payable</i>
= Payable Metal Value in concentrate(s) for sale - <i>treatment charges, refining charges and price participation (TC/RC/PP)</i> - <i>concentrate freight</i>	= Payable Metal Value in refined products for sale + <i>refined product premiums</i> - <i>refined product freight</i>
= Net Revenue from sale of concentrate(s)	= Net Revenue from sale of refined products

To calculate the net revenue from concentrate sales, first the gross metal value is multiplied by the percent payable term, giving the payable metal value. The net revenue is the payable metal value of the concentrate(s) for sale less associated downstream costs (i.e. treatment and refining charges, and freight).

Similarly, the net revenue from the sale of refined products is determined by first calculating the payable metal value as the gross metal value multiplied by the percent payable term for each refined product (e.g. nickel intermediate) The net revenue is equal to the payable metal value plus any refined metal premiums (e.g. cathode) less the freight for the refined product.

A basic financial evaluation is used to assess the potential economic benefit of an on-site CESL refinery for each of the two case studies. To do so the cash flows generated from each option are compared. Mining and milling costs are assumed equal for both options hence they are not factored into the comparison for either of the two case studies. For the concentrate sales option, cash flows are simply equal to the calculated net revenues. However, for the on-site CESL refinery option, the operating costs must be deducted from the net revenues to determine the project cash flows.

If the on-site CESL refinery option yields higher project cash flows than the traditional concentrate sales option, then the economics of an on-site refinery can be evaluated further. The net gain in project cash flow attributed to the on-site refinery is used to calculate a simple payback on the refinery capital along with standard project IRR and NPV calculations.

The results for each of the case studies introduced above are detailed in sub-sections 5.1 and 5.2.

5.1 Case 1: Bulk Disseminated Nickel-Copper Concentrate

The CESL Nickel Process is capable of treating bulk concentrates with no need for metal separation at the milling stage thus potentially improving overall metal recovery. As a result, on-site processing of a bulk nickel-copper concentrate could improve project economics significantly compared to the sale of separate nickel and copper concentrates.

The following case study evaluates the option of producing separate nickel and copper concentrates for sale versus the on-site CESL refinery option treating a single bulk nickel-copper concentrate. The hypothetical mine/mill operation will process 31k tpd of disseminated nickel-copper ore containing 0.30% nickel and 0.42% copper. The assumptions used in this case study are summarized in Table 3.

Table 3 – Case 1 Assumptions

<i>Mining and Milling</i>			<i>Economic Assumptions</i>	
Mining Rate	11	M tpa	Nickel	8.00 US\$/lb
Milling Rate	31	k tpd	Copper	2.75 US\$/lb
Reserves	0.30%	Ni	Cobalt	15.00 US\$/lb
	0.42%	Cu	Freight	90 US\$/wmt
	0.01%	Co		

The first option considered is to produce separate nickel and copper concentrates for traditional pyrometallurgical treatment. A high grade copper concentrate containing 30% copper is produced with a copper recovery of 80%. A low-magnesia bearing nickel concentrate containing 12% nickel is produced with a nickel recovery of 65%. As detailed in Table 4, this option realizes total net revenues of 454M US\$/yr. Producing two separate concentrates offers the benefit of minimizing the project's capital and operating costs. However, due to lower realized metal recoveries and associated downstream costs, only 50% of the contained metal value in the ore contributes to the net revenue.

Table 4 - Revenue from Separate Nickel and Copper Concentrates

	<i>Recovery from Ore to Concentrate</i>		<i>Concentrate Grade</i>		<i>Concentrate Production (tpa)</i>	<i>Percent Payable</i>	<i>Net Revenue (M US\$/yr)</i>
Cu Concentrate	80%	Cu	30.0%	Cu	123,000	78%	188
Ni Concentrate	65%	Ni	12.0%	Ni	176,000	60%	266
	65%	Co	0.6%	Co			
	12%	Cu	3.1%	Cu			

¹ 96.7% smelter payment term less \$75/t TC, 7.5¢/lb RC and \$90/wmt freight

² 80% smelter payment term less \$150/t TC and 6.5¢/lb RC_[3], \$90/wmt freight

The second treatment option involves on-site processing of 540,000tpa of a low-grade bulk nickel-copper concentrate using the CESL Nickel Process. The bulk concentrate grade is 5% nickel and 8% copper. The concentrate is also high in magnesia due to the high mass pull in flotation to generate improved metal recoveries. As shown in Table 5, this option yields total net revenues of 654M US\$/yr. This is equivalent to 72% of the contained metal value processed through the mill, a significant improvement over producing separate nickel and copper concentrates.

Table 5 - Revenue from On-site Processing

	Recovery from Ore to Product		Grade		Production (tpa)	Percent Payable	Net Revenue (M US\$/yr)
Copper Cathode	89%	Cu	>99%	Cu	41,060	100% ¹	249
NHP Product	82%	Ni	45%	Ni	68,489	78% ²	368
Co Product	82%	Co	46%	Co	3,134	89% ²	37

¹ 100% payment term plus LME cathode premium of 100 US\$/t Cu less \$90/wmt freight

² Estimated percent payables based on information gathered from internal marketing study

The improved revenue gained through on-site processing is due to increased metal recovery to a bulk concentrate and the production of value-added products. As highlighted in Figure , the gross metal value of the products produced from on-site processing is 80M US\$/yr higher than the gross metal value of separate nickel and copper concentrates. When payment terms are incorporated, the production of a bulk concentrate yields net revenues that are 200M US\$/yr higher than the production of separate nickel and copper concentrates.

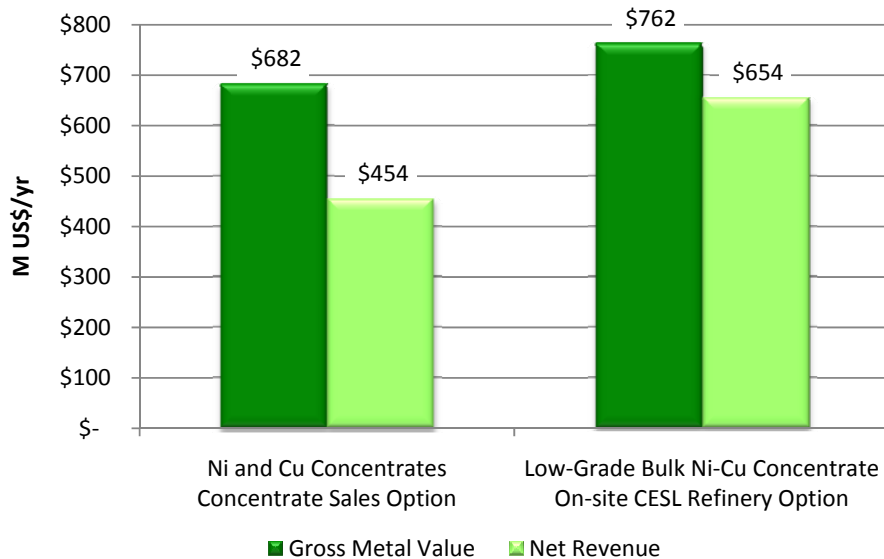


Figure 4 – Gross Value and Net Revenue for Two Options

As can be seen in Table 6, for an estimated 450M US\$ investment, the addition of a CESL hydrometallurgical refinery could realize a 144M US\$/yr (pretax) increase to project cash flow.

Table 6 - Financial Return on Refinery Capital

Net Revenue from sale of CESL Refinery Products	654 M	US\$/yr
Net Revenue from Combined Cu and Ni Concentrate Sales	454 M	US\$/yr
Net Gain in Revenue from On-site Processing	200 M	US\$/yr
Operating Cost of the CESL Refinery	56 M	US\$/yr
Net Gain in Project Cash Flow	144 M	US\$/yr
Estimated combined Cu and Ni CESL Refinery Capital	450 M	US\$
Simple Payback	3.1	years
IRR - 15 year	25%	
NPV - 15 year (10% Discount Rate)	393 M	US\$

Using the net gain in project cash flow achieved through the on-site CESL refinery option, a simple payback of 3.1 years was determined for the expenditure. The project IRR was 25% with a positive NPV value of 393M US\$. This preliminary economic assessment indicates that the on-site CESL refinery option offers a superior financial return to the project than the option of producing two separate nickel and copper concentrates for sale.

The conceptual capital and operating costs estimates used in this case study (section 5.1) and the preceding case study (section 5.2) were factored from recent external engineering studies.

5.2 Case 2: Disseminated Nickel Concentrate

The CESL Nickel Process is capable of treating low-grade nickel concentrates (as low as 3%) and those with magnesia concentrations significantly above the smelter cut-off grade of 7-9% MgO.^[3] Unlike smelters, high magnesia content in concentrate does not negatively impact metallurgical performance in the CESL Nickel Process. As a result, a mine/mill operation may be able to capitalize on significant improvements in recovery by producing a lower grade nickel concentrate (high in magnesia) that is not necessarily attractive to a smelter but can be efficiently treated by a hydrometallurgical process.

The following case study evaluates the option of producing nickel concentrates for sale versus the on-site CESL refinery option of treating a low-grade nickel concentrate high in magnesia. The hypothetical mine/mill operation will process 8.6M tpa of high magnesia disseminated nickel ore containing 0.55% nickel. Assumptions for this case study are given below in Table 7.

Table 7 – Case 2 Assumptions

<i>Mining and Milling</i>			<i>Economic Assumptions</i>	
Mining Rate	8.6	M tpa	Nickel	8.00 US\$/lb
Milling Rate	24	k tpd	Copper	2.75 US\$/lb
Reserves	0.55%	Ni	Cobalt	15.00 US\$/lb
	0.05%	Cu	Freight	90 US\$/t
	0.03%	Co		

The first option considered is the production of a salable nickel concentrate from the disseminated nickel ore which contains large amounts of serpentine minerals. A saleable concentrate containing 12% nickel and 6% magnesia was produced with a nickel recovery of 65%. As detailed in Table 4, this option realizes total net revenues of 365M US\$/yr. This is equivalent to only 37% of the contained metal value in the ore contributing to the net revenue.

Table 8 - Revenue from Salable Nickel Concentrate

	Recovery from Ore to Concentrate	Concentrate Grade	Concentrate Production (tpa)	Percent Payable	Net Revenue (M US\$/yr)
Ni Concentrate	65% Ni	12.0% Ni	271,000	58% ¹	365
	65% Co	0.6% Co			
	15% Cu	0.2% Cu			

¹ 80% smelter payment term less \$150/t TC, 6.5¢/lb RC_[3], and \$90/wmt freight

The second treatment option involves on-site processing of 800,000tpa of a low-grade nickel concentrate using the CESL Nickel Process. By producing a low-grade nickel concentrate that is not suitable to traditional smelting (5% nickel and 15% magnesia), nickel recoveries can be greatly improved. As shown in Table 9 on-site processing of a low-grade nickel concentrate yields total net revenues of 605M US\$/yr, which is equivalent to 61% of the contained metal value processed through the mill.

Table 9 - Revenue from On-site Processing

	Recovery from Ore to Product		Grade		Production (tpa)	Percent Payable	Net Revenue (M US\$/yr)
NHP Product	77%	Ni	45%	Ni	86,742	78% ¹	532
Co Product	77%	Co	46%	Co	4,196	89% ¹	57
Cu Product	77%	Cu	60%	Cu	5,264	75%	16

¹ Estimated percent payables based on information gathered from internal marketing study

As can be seen in Figure , the gross metal value of the products is significantly greater (135M US\$/yr) when a low-grade nickel concentrate is processed through the CESL Nickel Process than when a saleable nickel concentrate is produced. The increased payables from the refined products further results in a net revenue which is 240M US\$/yr greater for the on-site processing option.

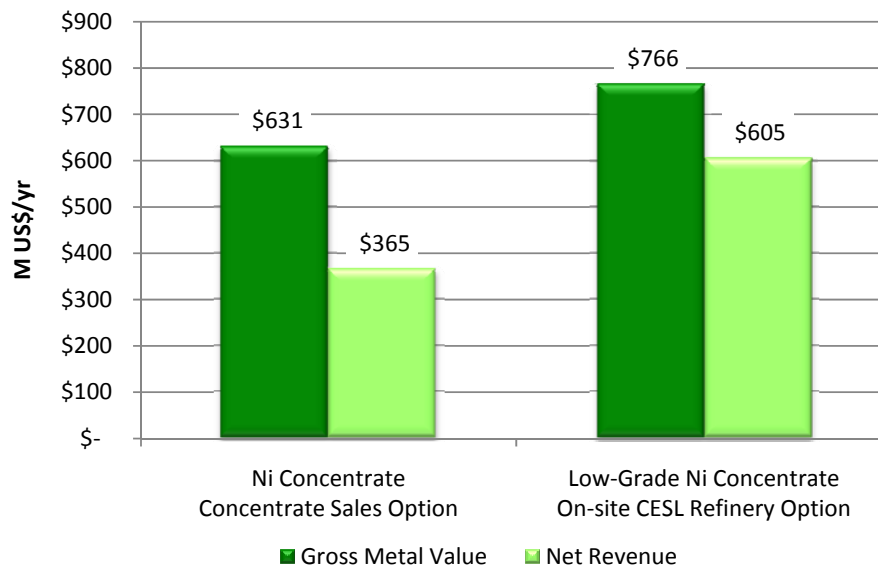


Figure 5 – Gross Value and Net Revenue for Two Options

As can be seen in Table 10, for an estimated 400M US\$ investment, the addition of a CESL hydrometallurgical refinery could realize a 157M US\$/yr (pretax) increase to project cash flow.

Table 10 - Financial Return on Refinery Capital

Net Revenue from sale of CESL Refinery Products	\$605 M	US\$/yr
Net Revenue from Ni Concentrate Sales	\$365 M	US\$/yr
Net Gain in Revenue from On-site Processing	\$240 M	US\$/yr
Operating Cost of the CESL Refinery	\$83 M	US\$/yr
Net Gain in Project Cash Flow	\$157 M	US\$/yr
Estimated Ni CESL Refinery Capital	\$400 M	US\$
Simple Payback	2.6	years
IRR - 15 year	29%	
NPV - 15 year (10% Discount Rate)	\$504 M	US\$

Using the net gain in project cash flow achieved through the on-site CESL refinery option, a simple payback of less than 3 years was determined for the expenditure. The project IRR was 29% with a positive NPV value of 504M US\$. This preliminary economic assessment indicates that the on-site

CESL refinery option treating a low-grade nickel concentrate high in magnesia offers a superior financial return than the option of producing a nickel concentrate for conventional pyrometallurgical treatment.

6 Conclusions

With the progressive depletion of world class massive sulphide deposits the development and role of alternative nickel resources such as laterites and disseminated sulphides will become progressively important in order to meet future nickel demand. These distinctly different resources represent large opportunities for future nickel supply but clearly require unique processing methods and extractive technologies.

Nickel laterites represent a significant portion of the world's nickel resources and are currently processed through pyrometallurgical and hydrometallurgical methods. However, historically laterite projects have struggled technically and financially with few reaching nameplate capacity.

Disseminated sulphides are widely distributed around the world, present at most nickel sulphide deposits. Despite their moderate grades the processing of disseminated nickel sulphides can be challenging due in large part to fines containing large amounts of magnesium rich serpentine type minerals which generate slimes during comminution. In most cases these problems result in low nickel recovery and produce a concentrate with unacceptably high magnesia. As a result many disseminated sulphide deposits remain undeveloped and available for exploitation.

Despite their unique metallurgical complexity and mineralogical diversity, Teck's CESL process offers a competitive and reliable technology that can unlock the value in disseminated nickel deposits.

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