Teck's CESL Nickel Process: Advancing Towards a Commercial Ready Hydromet Solution for Low Grade Disseminated Nickel Sulphides

By

Keith Mayhew, **Tannice McCoy**, **Rob Mean and Adam Miller**

Teck Resources Limited

Presented by

Adam Miller

adam.miller@teck.com

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1   Abstract

Disseminated nickel ore bodies are widely distributed around the world and are found in most of the known nickel sulphide districts. Teck has developed a novel hydrometallurgical process for treating low grade nickel concentrates and polymetallic concentrates with high magnesia content without the need for separation at the milling stage. This paper will focus on the metallurgical components of the CESL hydrometallurgical process and then examine a business case which utilizes data compiled by a third party engineering company.

2   CESL Introduction

Teck Resources Limited ('Teck') has developed CESL hydrometallurgical technology over the past 20 years. The technology is within Teck's Corporate Development group, focusing on growth 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, silver and PGM by-products. The Division is actively seeking opportunities to participate in existing operations and new ventures through the application of the CESL process. Work at CESL is focused on advancing projects which have the best potential to deliver internal and external growth opportunities for Teck.

3   Nickel Sulphide Resources[1]

Nickel resources are typically classified as sulphides or laterites. Approximately 73% of the world's nickel resources are estimated to be contained in laterites while 27% are as classified as sulphide. Currently, some 37% 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. The balance of nickel supply comes from limonitic and saprolitic laterite deposits which represent an abundant nickel resource.[1,15] 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.

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. This is largely due to laterite ores exhibiting a greater mineralogical and chemical complexity which makes them more challenging to process economically.

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. Concentrate smelting produces a high grade nickel matte which is then refined hydrometallurgically. With the majority of the world's nickel supply coming via pyrometallurgical processes, the technology has proven to be quite robust over the years. 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 world's largest deposits are often reasonable (0.6 to 0.9%).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 magnesium-rich serpentine type minerals which generate slimes during comminution. In most cases, treatment of such ores results in low nickel recovery and

produces a concentrate unacceptably high in magnesia. Nickel smelters typically cannot handle such concentrates without blending, due to inescapable problems with slag metallurgy. As a result, nickel grade and the Fe:MgO ratio in concentrate are key parameters in order to control smelting temperatures and slag viscosity.

Komatiite-hosted nickel-copper deposits contain some of the world's most economically significant disseminated ore deposits. These sulphide-poor, magnesium rich deposits are mainly found in Australia, Canada, Brazil, Zimbabwe, Finland and Russia. 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. 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. In doing so, significant improvements to overall nickel recovery could be achieved.

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   Nickel Economic Study Results

4.1   Nickel Economic Study Background

In 1997, a hydrometallurgical flowsheet processing nickel sulphide concentrates to metal was developed and a pilot plant successfully operated. In 2002, there was renewed interest by Teck in the nickel flowsheet for processing the polymetallic Mesaba concentrate. A successful pilot campaign was operated, producing copper cathode and a nickel intermediate product. Further flowsheet development ensued and in 2008 the Mesaba concentrate was processed to produce a higher grade nickel intermediate. After the successful completion of these campaigns, further flowsheet and bench testing was implemented for the recovery of nickel to metal. Piloting from a nickel intermediate product to metal was again undertaken in 2010 with consistent production of LME grade cathode.

Examining disseminated nickel projects from in-house capital and operating cost data showed a positive outlook for the technology from an economic perspective, including the increased cash flow of an onsite CESL refinery. Further verification of these costs using updated third party engineering was needed to support the financials.

An economic study was commissioned by Teck with the objective of validating the capital and operating costs that would be associated with constructing and operating a fully integrated CESL nickel refinery. The economic study was completed to a +/- 30% accuracy based on quotes provided for all major pieces of equipment.

The economic study assessed a conceptual commercial CESL plant to treat nickel concentrate and produce LME grade nickel cathode. The assessment was based on a concentrate with an average grade of 11% nickel and designed to treat a nominal concentrate throughput of 300,000 t/a.

It is important to note that CESL has completed extensive metallurgical testwork on concentrates generated from over 20 different nickel deposits, including those similar to the concentrate used in the study. The conceptual concentrate mineralogy, process flowsheets, operating conditions and expected metallurgical results are well known by CESL and served as the basis for the study.

4.2   Nickel Economic Study Design Basis

The design basis for the study was selected by Teck and was intended to represent a nickel concentrate that would be difficult to sell to a smelter due to a high MgO:Fe ratio. The location of the nickel economic study was chosen to a greenfield site in central Canada. The study assumed a 20 year mine life operating 24 hours a day with 300,000 t/a of concentrate as the nominal feed. For equipment sizing, a plant availability of 93% was used with most circuits containing a design factor of 120%. Table 1 gives the design basis summary.

Table 1: Economic Study Design Basis

Overall Plant Criteria		Design Value
Operating		
Annual	d/a	365
Daily	h/d	24
Concentrate Feed (Nominal)	t/a	300,000
Nickel Production		
Nickel in Concentrate (Nominal)	t/a	32,816
Nickel Cathode (Nominal)	t/a	31,700
Nickel Recovery (from concentrate)	%	96.6
Cobalt Production		
Cobalt in Concentrate (Nominal)	t/a	1198
Cobalt in Hydroxide Product (Nominal)	t/a	1132
Cobalt Hydroxide Grade	%	61
Cobalt Recovery (from concentrate)	%	94.5

Concentrate mineralogy has considerable impact on equipment sizes, impurity loads and flowsheet design. Table 2 and Table 3 show the mineralogy and elemental assays of the concentrate used in the conceptual study. The major nickel bearing mineral is pentlandite with a smaller portion of nickel associated with violarite. Cobalt is found in co-pentlandite. The other major sulphide bearing minerals are pyrrhotite, chalcopyrite and pyrite.

Table 2: Concentrate Mineralogy

Mineral	Composition	Wt %
Pentlandite	$(Fe,Ni)_9S_8$	24.5
Violarite	$FeNi_2S_4$	1.7
Co-Pentlandite	$Fe_4Co_5S_8$	1.1
Pyrrhotite	Fe_7S_8	16.9
Pyrite	FeS_2	1.0
Chalcopyrite	$CuFeS_2$	1.6
Serpentine	$Mg_2Si_2O_5(OH)_4$	22.6
Dolomite	$CaMg(CO_3)_2$	0.4
Other Gangue	-	30.2

Table 3: Concentrate Elemental Assay

Al	Ca	Co	Cu	Fe	Mg	Mn	Ni	S	Zn
%	%	ppm	ppm	%	%	ppm	%	%	ppm
2.0	1.8	3994	5540	20.7	6.0	2841	10.9	17.5	523

Major impurity elements in the concentrate include magnesium, manganese and zinc. A ratio of MgO:Fe of 0.48 indicates that this concentrate would be penalized if sold to a smelter.

4.3   Process Description

A conceptual flowsheet for the recovery of nickel to a cathode product is graphically depicted in Figure 1 below.
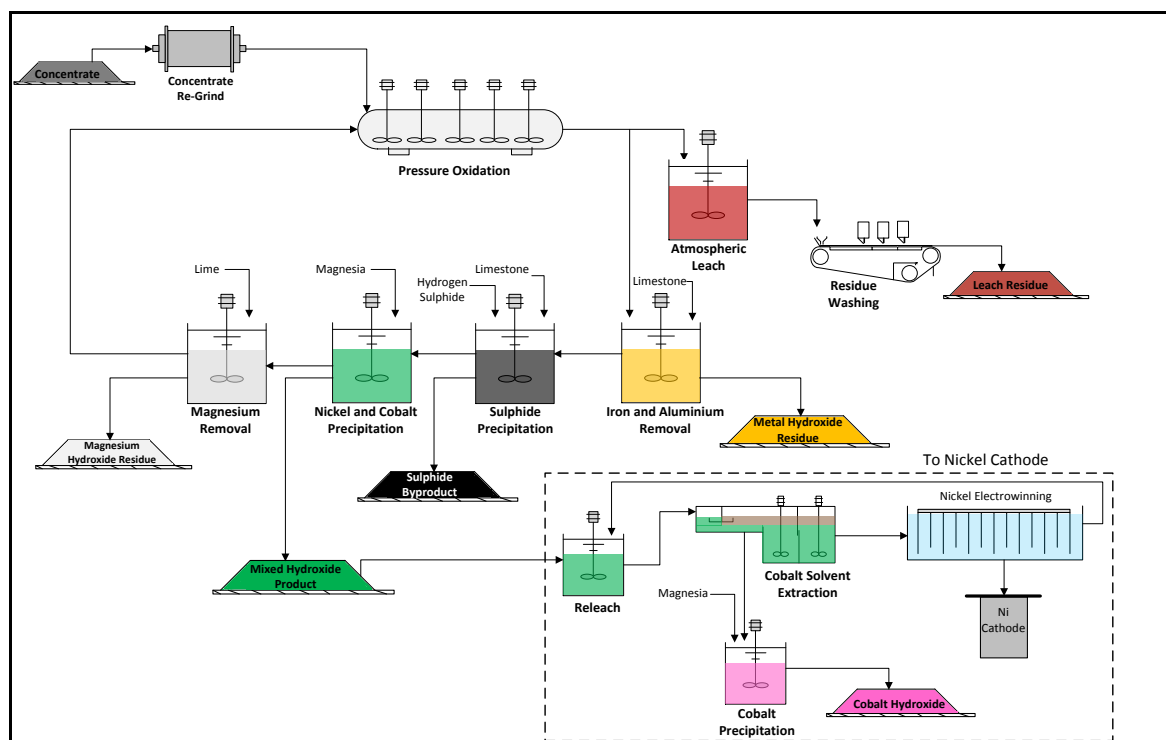

Figure 1: CESL Nickel Process Flowsheet for Disseminated Concentrates

A process description of each unit operation is provided in the following section coupled with typical pilot plant metallurgical results.

4.3.1   Pressure Oxidation

One of the key unit operations in the CESL Process is Pressure Oxidation (PO) in an autoclave, where the Ni and Co minerals are oxidized to an acid soluble form. Autoclave operating conditions are maintained at 60 minute retention time at a total pressure of 1,380 kPag and a temperature of 150°C. Concentrate-specific process conditions are adjusted to optimize metal extraction while minimizing sulphur oxidation.

The oxidation reaction for pentlandite $[(Ni,Fe)_9S_8]$ is given below. A similar reaction can be written for other nickel and cobalt sulphides.

$$4\ (Ni,Fe)_9S_8 + 22.5\ O_2 + 18\ H_2SO_4 \rightarrow 18\ NiSO_4 + 9\ Fe_2O_3 + 18\ H_2O + 32\ S°$$
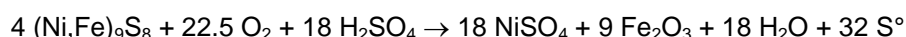
Pyrrhotite $[Fe_{1-x}S, (x = 0\ to\ 0.2)]$ in the concentrate is oxidized almost quantitatively to hematite and elemental sulphur, without significant sulphur oxidation.

$$4\ FeS + 3\ O_2 \rightarrow 2\ Fe_2O_3 + 4\ S°$$
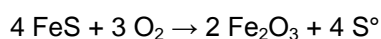
A portion (50-75%) of the pyrite $[FeS_2]$ in the concentrate oxidizes directly to sulphuric acid and hematite.

$$4\ FeS_2 + 8\ H_2O + 15\ O_2 \rightarrow 2\ Fe_2O_3 + 8\ H_2SO_4$$
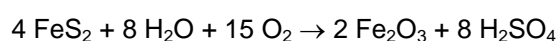
In addition to pyrite, a small amount (1-5%) of elemental sulphur produced oxidizes to create acid.

$$S° + H_2O + 1.5\ O_2 \rightarrow H_2SO_4$$
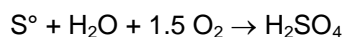
Chloride increases reaction kinetics in the autoclave and works as a catalyst to ensure complete oxidation of the sulphide minerals to form elemental sulphur whilst minimizing sulphate formation. Therefore, the entire plant process liquor inventory contains a chloride concentration of approximately 8-12 g/L.

Table 4 presents a summary of the major metallurgical operating values used for the study. Overall metal extractions were in line with results achieved during previous pilot plant campaigns.

Table 4: Major Metallurgical Operating Values

Parameter	Value	Parameter	Value
Ni Extraction (%)	97.3	Mass Loss (%)	2.5
Ni in Residue (%)	0.3	O_2 Ratio (t O_2 / t con)	0.15
Co Extraction (%)	97.0	Sulphur Oxidation (%)	9
Co in Residue (%)	0.01	Mg Extraction (%)	15

The autoclave heat balance showed a vessel solids density of 220 g/L would be targeted to achieve the 150°C operating temperature. Sulphur oxidation and magnesium leaching were modeled based on previous bench testwork on similar concentrates. These values are significantly less than what would be achieved through total oxidative leaching.

4.3.2   Iron and Aluminum Removal

Iron and aluminum are removed from solution to less than 5 mg/L in a two-stage precipitation circuit. The impurities are precipitated to minimize contamination of the Mixed Hydroxide Precipitation (MHP) product and to reduce magnesia consumption. Each stage operates at 40°C, 1-hour residence time, and pH is controlled using limestone to a pH of 3.7 in Stage 1 and 5.0 in Stage 2.

Solids from the first stage contain the bulk of the Fe and Al, with minimal Ni and Co values, and are a residue stream produced by the process. The second stage of Fe/Al Removal can tolerate some Ni loss to improve MHP product quality as the residue solids are recycled to the front end of the first stage.

Table 5 shows the recirculating load of nickel and cobalt from the second stage thickener underflow to Stage 1.

Table 5: Recirculating Load of Metals

Metal Deportment	Metal Precipitated
Ni	4.1%
Co	6.3%

4.3.3   Sulphide Precipitation

Copper and zinc are selectively precipitated with hydrogen sulphide to a final concentration of <0.1 mg/L prior to MHP. Production of the copper sulphide product should enable the disposal of this by-product to Cu smelters. Losses of nickel and cobalt to the sulphide solids were 0.24% and 1.0% respectively. Acid generated by the sulphide precipitation process is neutralized using limestone. Composition of the solids is presented in Table 6.

Table 6: Sulphide Precipitation Solid Composition

Cu (%)	Co (%)	Ni (%)	S (%)	Zn (%)
21.0	0.28	1.7	23.3	2.1

4.3.4   Nickel and Cobalt Hydroxide Precipitation

Nickel and cobalt are recovered from solution through the addition of calcined MgO.

$$NiSO_4 + MgO + H_2O \rightarrow Ni(OH)_2 + MgSO_4$$
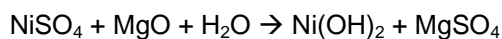
The MHP circuit consists of five cascading reactors, a thickener and a belt filter. The spent solution is sent through the nickel scavenging and magnesium removal circuits before being recycled to the autoclave.

Production of a high quality MHP product could be sold to a third party refinery based on previous testing at CESL which was utilized for the study as presented in Table 7.

Table 7: MHP Product Composition

Ni (%)	Co (%)	Al (%)	Cl (%)	Fe (%)	Mg (%)	Mn (%)	S (%)	Zn (%)
46.4	1.65	<0.01	0.11	<0.01	0.50	0.24	4.30	<0.01

4.3.5   Nickel Scavenging

In order to maintain a quality MHP product (i.e. low Mg), a small fraction of the Ni (0.5-1 g/L) is deliberately left behind in the MHP product solution. The Ni Scavenging stage precipitates the remainder with lime and recycles it back to Fe Removal.

4.3.6   Magnesium Removal

Magnesium is both leached from the concentrate in Pressure Oxidation and added via magnesia in the MHP circuit. The purpose of the Mg Removal circuit is to bleed magnesium from the process yet leave enough magnesium to support the chlorides to minimize the formation of calcium chloride. Residue produced is filtered and disposed of while the resulting solution is recycled to PO.

4.3.7   Releach

The MHP product is releached using anolyte from the Nickel Electrowinning circuit. Limestone is added to adjust the final pH to 3.5, and in doing so, removing ferric from solution. The residual solids, which are principally gypsum, are thickened and pumped back to the Fe Removal circuit. Pilot results consistently showed greater than 99.9% of the nickel was releached into solution.

4.3.8   Cobalt Solvent Extraction

Cobalt Solvent Extraction utilizes Cyanex 272 organic extractant to effectively separate cobalt and impurities from nickel. Three extract cells, one wash cell and two strip cells make up the majority of the equipment in the circuit. Caustic is added to each extract cell to maintain constant pH targets. Stripping of the organic is done by the use of diluted sulphuric acid solution. The stripped solution is high in cobalt (> 50 g/L) and is pumped to the cobalt precipitation circuit. The raffinate from the extraction cells goes through organic removal and then on to Nickel Electrowinning.

4.3.9   Cobalt Precipitation

Cobalt is recovered from the strip solution via the addition of calcined MgO to precipitate cobalt to a high purity cobalt hydroxide intermediate product.

4.3.10 Nickel Electrowinning

Electrowinning is utilized for the recovery of nickel in the form of cathodes. Catholyte is fed into the cellhouse where a portion of the nickel is removed from solution before the resulting solution (anolyte) is returned to the releach stage. The acidic anolyte is kept separate from the catholyte via diaphragm bags. Due to the chloride content of the catholyte, DSA anodes and titanium cathodes were chosen for the study. This configuration was tested during pilot plant operations which showed the voltage in EW could be reduced by 0.8V and chlorine evolution was not detected.

LME Grade Ni cathodes were produced with the composition presented in Table 8.

Table 8: Nickel Cathode Purity

Ni (%)	Co (%)	Cu (%)	Fe (%)	Mn (%)	Pb (%)	Zn (%)	S (%)	C(t) (%)
99.95	0.041	0.001	0.008	<0.001	<0.001	0.001	<0.005	<0.005

The simplistic Ni refining process uses commercially proven, cost-effective technologies to recover cathode with minimal technical risk.

4.4 Nickel Economic Study CAPEX/OPEX

Capital and operating costs for the study were compiled by a third party engineering company. Results of the capital costs for the nickel economic study are displayed in Table 9[2]. As described in the process description, the flowsheet processes concentrate and produces nickel cathode and cobalt hydroxide as the final products.

Table 9: Capital Cost Estimates[2]

Area	Nickel Metal (US$M)
Leach Plant	120
Solution Purification and Precipitation	96
Co SX and Ni EW	196
Services, Utilities, and Reagents	156
Total Direct Costs	568
Indirects (including camp)	269
Owner's Costs	57
Total Indirect and Owner's Costs	326
Total Direct and Indirect Costs and Owner's Cost	894
Contingency (23.5% of Directs + Indirects)	197
Total Project Cost	1091

Results from the nickel economic study indicate an estimated capital cost of ~1.09 billion US$ for producing 31,700 t/a of nickel.

Operating cost estimates are displayed in Table 10 below.

Table 10: Operating Cost Estimates[2]

Operating Cost Summary	Nickel Metal US$M/a	Nickel Metal US$/t Ni
Labour	19.0	600
Power	12.3	388
Reagents	53.9	1,701
Consumables	13.2	416
Totals:	98.4	3,105

Refinery operating costs were calculated to be 3,105 US$/tonne Ni (1.41 US$/lb Ni) for producing nickel metal. Operating costs were broken into labour, power, reagents and consumables. Reagent costs were calculated from sourcing each reagent in the proposed study area, and Canadian rates were used to calculate labour costs.

Reagent addition to the refinery represents the single highest contribution to the operating costs. A review of the major reagent costs are summarized below in Table 11.

Table 11: Major Reagent Costs

Reagent	Annual Consumption (t/a)	Cost (inc. transport) (US$)	Total Cost	Percent (of total cost)
Hydrochloric Acid	6,168	300	1.9	3%
Sulphuric Acid	72,618	200	14.5	27%
Lime	33,460	306	10.2	19%
Hydrogen Sulfide	876	2,400	2.1	4%
Magnesium Oxide (Magnesia)	21,900	950	20.8	39%
Other			4.4	8%
Total for all Reagents			**53.9**	**US$M/annum**

Magnesia represents the highest total reagent cost at 39%, partially because the reagent specified was transported from Australia. Shipping costs were estimated at 400 US$/t for the magnesia to reach site, almost doubling the unit cost. Sulphuric acid and lime addition round up the other major reagent costs. Both sulphuric acid and lime were sourced and priced for the site chosen, and together with the magnesia, represent 85% of the total reagent costs.

4.5   Nickel Economic Study Opportunities

In assessing the outcome from the Economic Study, several opportunities were identified to reduce costs outlined in Section 4.4.

- MHP product is saleable, which presents the opportunity to market MHP directly, and to defer more than $200M associated with building the Ni cell house. Operating costs of over $40M/year would also be eliminated.
- MgO represents ~12% of total operating costs. If onsite metal production is performed, the use of CaO should be evaluated as an alternative as this would save over $0.15/lb Ni in operating costs.
- In a remote location, building a small acid plant should be considered to minimize sulphuric acid costs. The elemental sulphur, contained in the final residue, required for the acid plant would be recovered through flotation and recycled.
- The design basis for the plant was constructed after several technical reviews of the process were completed, with the aim of the external consultants being to minimize technical risk. One such example is the use of Ti and DSA electrodes in Ni Electrowinning. A review and further testing is required to assess this recommendation versus the use of stainless steel and lead electrodes as it adds additional capital to the project.
- The greenfield central Canada site location added cost to the project:
    a. Capital: elevated construction costs, winterization of equipment, large boilers, construction camp and catering costs, etc.
    b. Operating: heating costs (process and buildings), zero effluent necessitating a large evaporator, reagent shipping costs, etc.

5   CESL Refinery Economics

A financial evaluation of a conceptual disseminated nickel business case was done using inputs from the nickel economic study. The case compares the hydrometallugical treatment of a lower grade nickel concentrate high in magnesia versus concentrate sales. The case assumes that concentrate of suitable grade for conventional pyrometallurgical treatment comes with a mill nickel recovery of 60%. If the production of a low-grade nickel concentrate high in magnesia is considered for on-site hydrometallurgical treatment, a nickel recovery of 66% can be achieved. The following table summarizes the major assumptions used in the financial model.

Table 12: Major Assumptions Used in Financial Model

Parameter	Mine to Concentrate	Mine to Metal
Concentrate grade	15% Ni, 0.3% Co, 10% MgO	11% Ni, 0.17% Co, 15% MgO
Metal Prices		
Nickel	9.00 US$/lb	9.00 US$/lb
Cobalt	15.00 US$/lb	15.00 US$/lb
Recoveries:		
Mine/Mill (concentrator)	60% Ni and Co	66% Ni and Co
CESL refinery		96.6% Ni and 94.5% Co
Payables :		
Concentrate	90% Ni and 30% Co	100% Ni + *200 US$/t premium*
Refined products		75% Co
Operating Costs:		
Mine/Mill	3.90 US$/lb Ni	3.90 US$/lb Ni
CESL Refinery		1.41 US$/lb Ni
Treatment and Refining Charges:	1.58 US$/lb Ni	

The evaluation assumes metal prices of $9.00/lb nickel and $15.00/lb cobalt. The waterfall graph in Figure 2 highlights the increase in EBITDA as a result of constructing an onsite CESL nickel refinery.
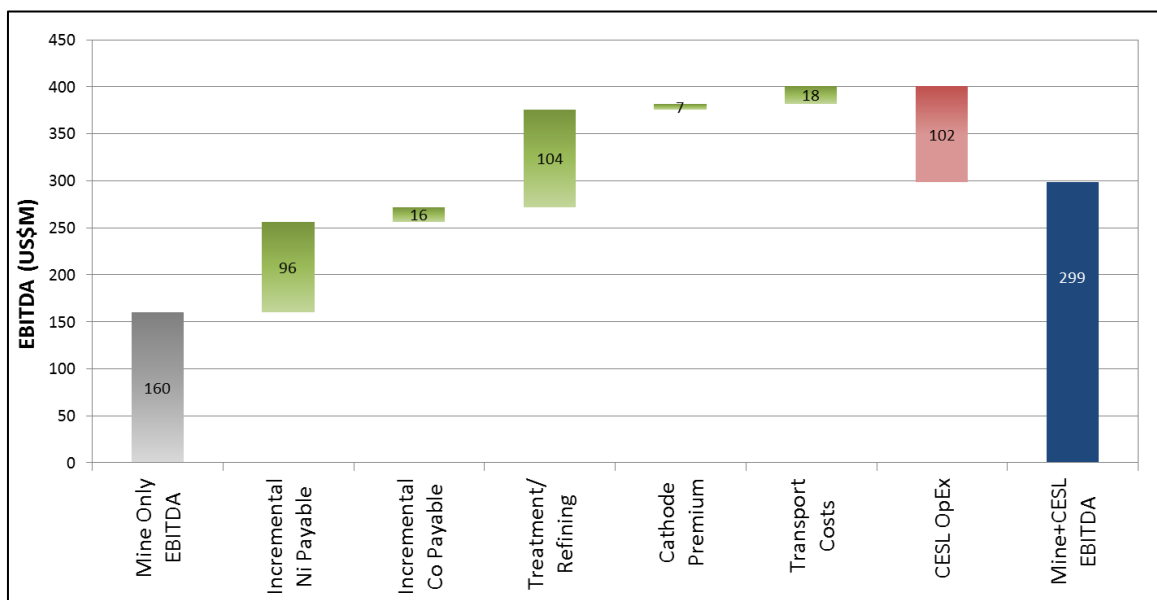
Figure 2: EBITDA Evaluation of Adding CESL Nickel Refinery

Driven by a 6% improvement in mill recoveries from producing a lower grade nickel concentrate, CESL refinery recoveries (96.6% nickel), reduced site realization costs (122 million US$/annum), and applicable payable terms for CESL products (nickel cathode and cobalt hydroxide) the increase in EBITDA each year from a CESL refinery would be ~140 million US$/annum.

The following table summarizes other economic metrics and highlights the positive impact of construction of the CESL refinery on the project economics:

Table 13: CESL Nickel Refinery Economic Evaluation

	Mine Only	Mine + CESL	CESL Benefit
Pre-tax NPV (US$M)	280	704	424
Pre-tax Payback (Years)	8.3	8.2	n/a
Breakeven Ni Price (NPV=0, $/lb Ni)	8.5	7.7	n/a
Pre-tax Annual FCF (US$M)	130	269	139

Producing nickel cathode on-site would pay back the refinery in just over eight years with a breakeven nickel price of 0.76 US$/lb lower than concentrate sales. A CESL refinery more than doubles the project NPV and free cash flow when compared to selling concentrate.

6   Conclusions

With the progressive depletion of world class massive sulphide deposits the development 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 require unique processing methods and extractive technologies.

Disseminated sulphides are widely distributed around the world and are present at most nickel sulphide deposits. Despite their unique metallurgical complexity and mineralogical diversity, their

value can be unlocked by Teck's CESL process which represents a competitive and reliable technology. The paper has discussed this advancement in several key areas:

- Metallurgy: The CESL pilot plant has achieved high Ni extraction (>97%) from various concentrates that have been generated from disseminated Ni orebodies. High recovery of LME grade Ni is achieved.
- Economics: An external case study was conducted using a conservative approach to minimize technical risk for the project. The study was conducted on a theoretical 31,700 t/a Ni refinery in central Canada and showed a favourable improvement to NPV of 424 million US$/annum for onsite refining versus concentrate sales.

The implementation of CESL technology through a mine-to-metal approach is an attractive option for the processing of disseminated nickel concentrates. This is based on excellent metallurgical performance, minimizing technical risk, and robust project economics.

7   References

[1] R. Mean, D.L. Jones, K. Mayhew, M. Neef, "Unlocking Disseminated Nickel Sulphides Using the CESL Nickel Process", ALTA 2010, May 2010.

[2] AMEC, "CESL Nickel Project Economic Study: Economic Study Report", 2012