

## **THE ROLE OF IRON IN THE CESL PROCESS**

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### **ABSTRACT**

CESL has developed a proprietary hydrometallurgical process for base metal concentrates, notably those of copper and nickel. The process is based on pressure oxidation (PO) of the sulphide minerals, which is done at elevated temperatures in mixed sulphate-chloride liquor at about pH 2 – 3. The process achieves maximum oxidation of the metals whilst minimizing sulphur oxidation to sulphate. Almost all base metal sulphide minerals are efficiently treated under these conditions. In the case of copper minerals, pressure oxidation does not generally put the copper into solution, because of the relatively high pH prevailing in this process. Therefore, PO is followed by an acidic leaching stage, which specifically aims at maximum copper dissolution with minimal leaching of iron. The overall copper recovery is largely determined by the efficiency of this stage. The process has low capital and operating costs, partly because there is minimal use of acid or neutralizing agents for iron dissolution or precipitation, respectively; this is achieved by minimizing iron leaching during both the oxidation and leaching stages. Iron sulphides in the feed concentrate deport almost entirely to the solid leach residue as hematite, which has superior handling characteristics for filtering and washing. Iron minerals play a key role in the process, with pyrrhotite and pyrite having very different responses to the oxidation process. Acid management for the whole process is affected by the iron mineralogy, and the flowsheet is therefore tuned to the specific concentrate.

## **INTRODUCTION TO CESL**

CESL was originally the engineering department of Cominco Limited, which grew into a full EPCM company in the early 1980s. CESL built a number of successful large projects in Western Canada, notably the world's first zinc pressure leach plant in Trail in 1982, which was (and still is) an outstandingly successful plant. Significantly, it was based on homegrown technology developed over many years at the Cominco Research Centre in Trail. Excellence in hydrometallurgy has always been a hallmark of Cominco Limited, which has over 100 years of history, and many historical firsts in the extractive metallurgy industry. What followed for CESL in the development of the process described herein is largely due to this heritage of Cominco Limited.

Most of the assets of CESL were merged with HA Simons Ltd. in 1994. The process development department of CESL, however, remained the property of Cominco Limited and it is now a fully owned subsidiary of Teck Cominco Limited, the successor company to Cominco Limited.

Development of the CESL Process began in 1992, as a project of the metallurgical department of CESL. At that time, treatment charges for copper concentrates were exceptionally high, and a number of mines with low grade (high iron) concentrates were operating in a deficit situation or were even closing because of the high downstream costs. The purpose was to produce a new hydrometallurgical process for copper concentrates, which could compete economically with the conventional smelting and refining process, but would be non-polluting. With the strong background in zinc pressure leaching, CESL felt it was possible to use the technology, with some modifications, for copper processing.

After a few false starts, a viable leaching process was discovered that had the required low sulphur oxidation. By uniting this leaching process with the known technology of SX/EW, a viable flowsheet was developed and then tested in a fully integrated pilot plant facility with a capacity of 35 kg/day of copper cathode (1995). Operation of the pilot plant on a number of copper concentrates confirmed the flexibility of the process to varying copper concentrate grades and mineralogies. It was then considered by Cominco Limited for commercial development, but the pilot plant left many engineering questions unanswered and the scale up risks were a concern. Therefore, in 1996, CESL designed and built a demonstration plant capable of producing ~500 t/y of copper cathode, using equipment which was specifically designed to be similar to commercially-available equipment.

Commercial implementation of the CESL Copper Process was originally planned for the HVC mine in 1997 – 1998, but was hindered by a sustained period of low metal prices from 1998 on, and also by the prevailing low treatment charges that were created by excess smelter capacity worldwide.

Despite the downturn in metal prices from 1998 to 2003, Teck Cominco continued to fund process development at CESL. In addition to copper concentrates, the CESL Process has been successfully adapted to the treatment of nickel and bulk nickel/copper concentrates. Further development of the process has also included processes for the recovery of precious metals and other base metals such as zinc, cobalt and molybdenum.

Commercialization is now progressing in a partnership between CVRD and Teck Cominco, which has been ongoing since 1998. CVRD has a number of attractive copper properties at an advanced stage of development in the Carajás region of Brazil, but some of them are unlikely to produce concentrates suitable for conventional smelters. CVRD is now building a CESL Process plant to produce 10,000 t/y Cu; this is intended as a prototype plant to prove the technology at a relatively small scale. Commissioning is currently scheduled for the first quarter of 2007, and it is anticipated that the 10,000 t/y copper plant will operate for about two years, processing principally Sossego copper concentrate. Following this successful development, a much larger 250,000 t/y copper facility will be considered for use on concentrates from both the Salobo and Alemão mines.

Separately, Teck Cominco is again considering the application of the CESL Copper Process to the HVC mine in British Columbia. A feasibility study is due for completion at the end of 2006, which hopefully will lead to the construction of a 130,000 t/y copper facility in 2007 – 2008.

## **DESCRIPTION OF THE COPPER PROCESS**

The CESL Copper Process begins with the oxidation of sulphide concentrates at elevated pressure and temperature in the presence of catalytic chloride ions. This is achieved using high purity oxygen, which rapidly and efficiently oxidizes all the common sulphide minerals under these conditions. The process is notable for its selective nature with respect to sulphur, despite the very effective oxidation environment for base metals. Sulphur in the concentrate is not oxidized to sulphate, but instead is converted primarily to elemental sulphur. This is a key cost driver for the process and accounts partly for its low costs compared to some other hydrometallurgical processes for copper concentrates.

The copper minerals are wholly oxidized in the autoclave. A portion of the copper is leached into solution and a portion is converted to basic copper sulphate (BCS), which is an acid soluble solid. Copper from the BCS is subsequently leached under mildly acidic conditions at ambient pressure and temperature. Copper is recovered from solution by solvent extraction (SX) and electrowinning (EW). Iron in the concentrate is converted almost entirely to hematite, a compact and environmentally stable residue suitable for disposal with mill tailings. In order to highlight the role of iron in the CESL Process, typical stream tenors for iron have been included in the overall flowsheet presented in Figure 1.

## COPPER PROCESS FLOWSHEET

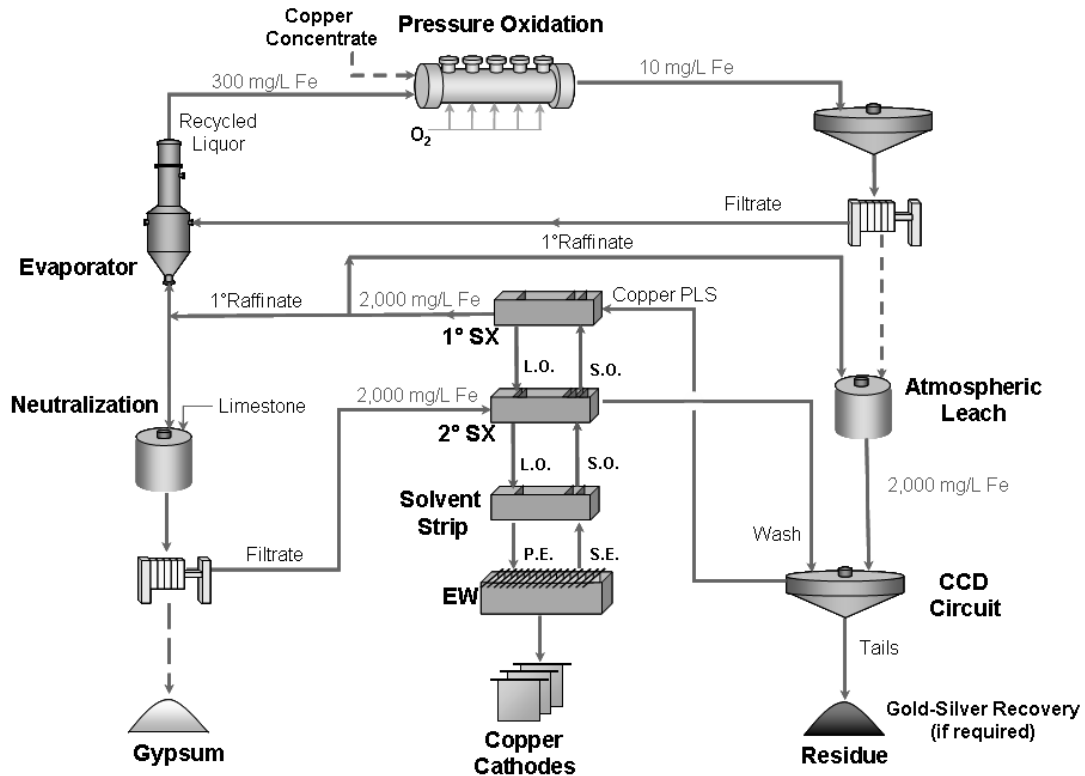


Figure 1 – Overall CESL copper plant flowsheet

The leaching stage (Atmospheric Leach) is specifically aimed at maximum copper dissolution with minimal leaching of iron; this is achieved by careful control of the pH and other variables, such as temperature and retention time. Because the concentration of iron is relatively low in the CESL plant liquor:

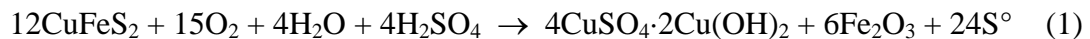
- Acid or neutralizing agents for iron dissolution or precipitation are not required;
- Contamination of the gypsum product is negligible;
- Iron loading onto the organic and its subsequent transfer to copper electrowinning is negligible.

Each of the unit operations in the CESL Copper Process is detailed in the following sections. Highlighted within each section is the role that iron plays in the process chemistry.

## Pressure Oxidation – Absence of Iron Catalysis

The concentrate slurry is fed to the autoclave, where it is combined with oxygen and recycled process liquor containing approximately 12 g/L chloride, 25 g/L sulphate, and typically less than 1.0 g/L iron.

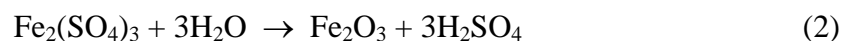
In pressure oxidation, all the copper sulphide minerals are oxidized almost quantitatively to form basic copper sulphate, hematite and elemental sulphur (some of this basic copper sulphate may subsequently dissolve, dependent on the mineralogy of the concentrate). The formation of the first two of these products appears to be a solid-to-solid reaction from the feed mineral (sulphur is liquid at the process temperature). The chalcopyrite oxidation reaction is presented below, and similar reactions can be written for the other common copper minerals.



It is important to note that iron is not required in the feed liquor to act as a catalyst for the process to proceed efficiently. At steady state, the iron concentration in pressure oxidation is typically only about 10 ppm, evidently an equilibrium determined primarily by the pH and temperature during pressure oxidation.

The process is apparently quite different from the many copper hydrometallurgical processes that rely primarily on the ferric-ferrous couple for oxidation, either as a catalyst or the actual oxidant. Here, oxygen itself is the prime oxidant, aided by the presence of chloride and copper ions in relatively dilute concentrations.

If significant iron is present in the feed liquor, under the typical conditions of pressure oxidation (150°C and pH 3), it readily precipitates in pressure oxidation as hematite, by the familiar hydrolysis reaction.



Solution assays from a recent pilot plant campaign are presented in Table 1. The results indicate that both ferric and ferrous iron precipitate if present in the acid feed. Because of the strongly oxidizing conditions in the pressure oxidation step, any ferrous iron originally present in the process liquor is quickly oxidized to the ferric state, and then is hydrolyzed.

Table 1 – Pressure oxidation feed and discharge solution iron concentrations

	Fe <sup>T</sup> (mg/L)	Fe <sup>2+</sup> (mg/L)	Fe <sup>3+</sup> (mg/L)
Pressure Oxidation Feed	521	78	443
Pressure Oxidation Discharge	10	1	9

The concentration of iron in the pressure oxidation discharge liquor is directly related to the pH, as illustrated in Figure 2. This phenomenon facilitates the use of the pressure oxidation step to control the iron concentration in the process solutions. This is especially true if the CESL plant is integrated with an operation, such as a heap leach, where high levels of iron can cause processing difficulties.

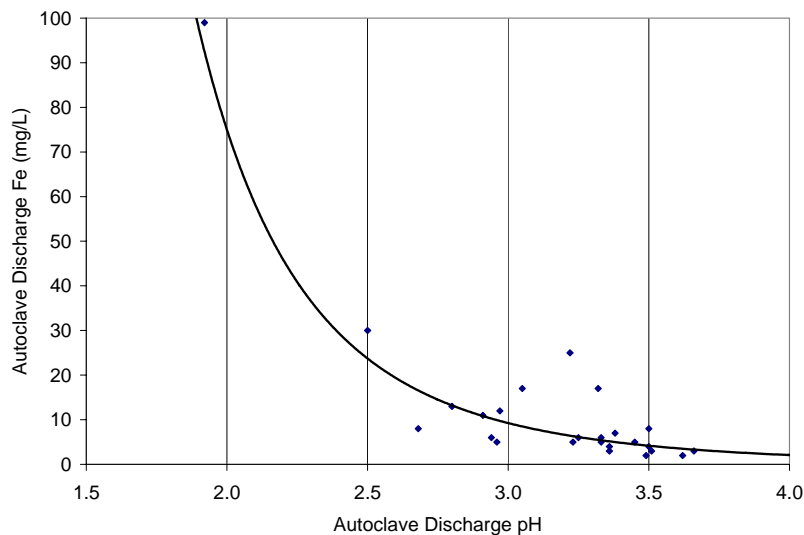


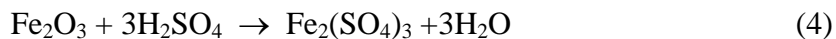
Figure 2 – Iron concentration versus pH in the pressure oxidation discharge solution

After pressure oxidation, the slurry is flash discharged, thickened and filtered. The thickener overflow is recycled back to the pressure oxidation step. The filter cake is repulped in raffinate and processed through the atmospheric leach.

### Atmospheric Leach

The PO residue is repulped in raffinate and pumped to the atmospheric leach (AL) circuit, a series of reactors operated at ambient temperature with a total retention time of about one hour. Additional raffinate is added in the reactors to maintain a pH of 1.4 – 1.8, to ensure that the acid soluble BCS is leached as much as possible, typically about 96 – 98%. The pH of this stage is kept relatively high so as to limit the simultaneous leaching of hematite:





At the operating pH of 1.4 – 1.8, about 1% of the hematite leaches, on a one-pass (batch) test with recirculation of the raffinate. This leads to about 1 – 3 g/L of iron in solution, as suggested by the data in Table 2. However, in continuous operation, the iron concentration reaches equilibrium at this level, so that there is little or no net dissolution of iron.

Table 2 – Typical atmospheric leach raffinate and PLS liquor iron concentrations

	Fe (g/L)
Raffinate	2.0
PLS	2.1

Figure 3 illustrates the effect of the leach train temperature on both iron leaching and copper extraction. The results indicate that iron leaching increases modestly above 40°C with no improvement to copper extraction.

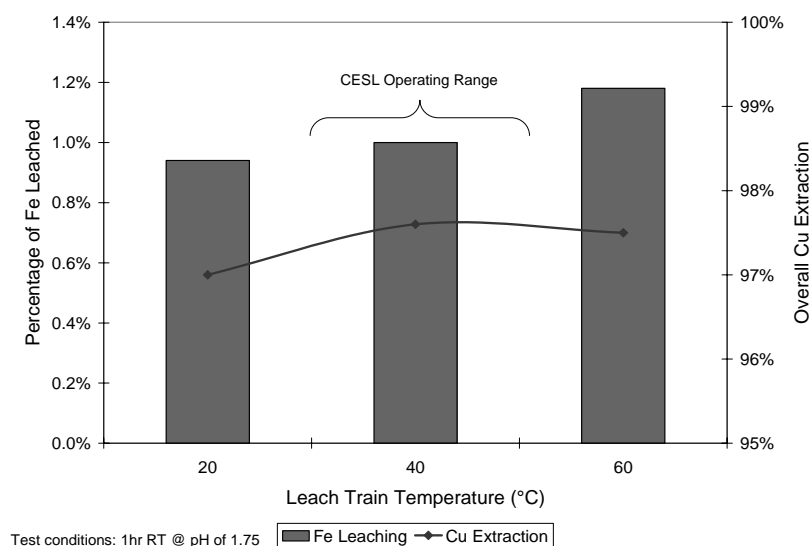


Figure 3 – Fe and Cu extractions versus atmospheric leaching temperature

The final reactor slurry from the acid leach train is washed in a CCD circuit to recover the soluble copper from the leach residue, and produce a clear pregnant leach solution (PLS) feed for SX. Wash water to the CCD circuit is a combination of fresh water and recycled neutralized raffinate.

The formation of hematite in the pressure oxidation step, instead of basic iron hydroxides or jarosites, eliminates major settling and filtration engineering concerns that

have arisen with other hydrometallurgical processes. The residue has excellent settling characteristics in the CCD circuit as shown in Table 3.

Table 3 – Settling results for the CCD (hematite residue) solids

	CCD
Instantaneous Settling Rate (m/h)	9.2
Settling Unit Area (m <sup>2</sup> /tpd)	0.09

A photo of the pilot plant CCD circuit is shown in Figure 4. The pilot plant CCD operates continuously, with the PLS stream containing about 100 ppm solids and an underflow density of 50%.

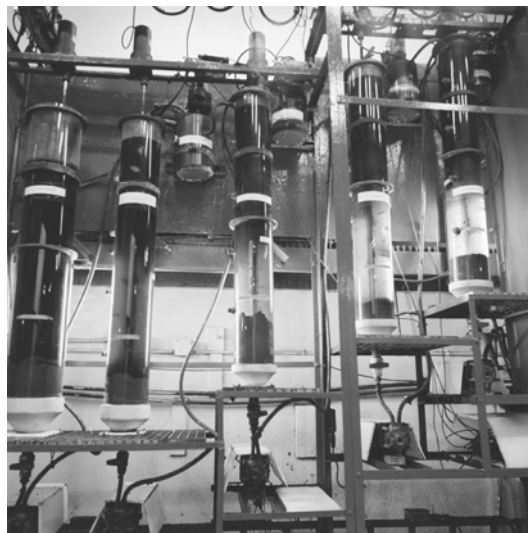


Figure 4 – Photo of the CESL pilot plant counter-current decantation circuit

If gold or silver are present in the concentrate, they remain unaffected by the process and report to the residue. In the absence of gold or silver, the final washed residue from the CCD circuit is sent to a tailings pond.

Table 4 presents the composition of the residue from the plant. The main constituents of the residue are hematite and elemental sulphur, with minor amounts of unreacted sulphides such as pyrite. A small portion of the sulphur reports as sulphate. The deportment of sulphate to the final residue is due to a combination of basic copper sulphate that was not solubilized in the atmospheric leach, gypsum (which forms in the pressure oxidation step), and a minor amount of jarosite. Most of the copper in the residue is in oxidized form, and only a minor amount (0.1 – 0.2%) is present as unreacted sulphides. This also indicates the remarkable effectiveness of the pressure oxidation step in treating chalcopyrite concentrates in such a short reaction time, (1 hour).



Table 4 – Final residue composition

Cu (%)	Fe (%)	S <sup>TOT</sup> (%)	S <sup>o</sup> (%)	S <sup>2-</sup> (%)	S as SO <sub>4</sub> (%)	Au (g/t)	Ag (g/t)
1.28	33.8	31.9	28.3	2.2	1.4	3.0	168

Using the residue composition and mineralogical reports (MLA, and light microscopy), a reconciled mineralogy was determined. Table 5 presents the estimated mineral constituents of the leach residues.

Table 5 – Reconciled residue mineralogy

Hematite Fe <sub>2</sub> O <sub>3</sub>	S <sup>o</sup>	Pyrite FeS <sub>2</sub>	BCS, Gypsum, Jarosite	Gangue
59%	29%	4%	3%	5%

The CESL Process produces a compact and stable residue. The p80 for this residue is ~35 microns, with the coarser particles being elemental sulphur.

### Neutralization

Sulphate enters the plant liquor through sulphur oxidation in pressure oxidation and through sulphuric acid additions in electrowinning. To maintain a sulphate balance, an equivalent quantity of sulphate must be removed from the plant liquor. This is accomplished through acid neutralization with limestone, at a pH of 1.8. At this pH, iron does not precipitate.

### Solvent Extraction

The CESL Copper Process utilizes an unusually strong extractant, 40% LIX 973N<sup>®</sup> to selectively extract copper from the PLS stream, because of the high grade of the PLS. A typical configuration for the main SX circuit is two stages of extraction, a single wash stage and two stages of stripping. A secondary SX circuit (two stages of extraction) is used to generate wash water from neutralized primary raffinate. The raffinate from secondary SX is recycled to the CCD circuit.

One of the reasons that LIX 973N<sup>®</sup> is used in the copper industry is its high selectivity for copper over iron. LIX 973N<sup>®</sup> has a copper/ferric selectivity of greater than 2300. Because CESL solutions have a Fe:Cu ratio of approximately 1:20, iron loading is not a concern in CESL SX, and iron transfer to the electrolyte is negligible.

### Electrowinning

Pregnant electrolyte (PE) from SX is fed to a conventional copper electrowinning circuit, and pilot plant campaigns have consistently produced LME Grade A cathode or better. Typically, the CESL pilot and demonstration plant copper cathodes contain less than 1 ppm iron. Iron levels in the electrolyte are exceptionally low because of the high

Cu:Fe ratios in the PLS, and this of course is an aid to achieving high current efficiency in EW.

## DESCRIPTION OF THE NICKEL PROCESS

The CESL Nickel Process was a development from the copper process, and uses similar pressure oxidation conditions. Nickel sulphides all oxidize very efficiently under these conditions, but nickel behaves differently to copper in that it all goes into solution in PO. There is much less tendency to form a basic nickel salt, comparable to BCS; basic nickel salts require a higher pH and/or temperature. Thus, no atmospheric leach is required for nickel concentrates and all nickel recovery is based on treating the solution from pressure oxidation. (Similar comments apply to zinc and cobalt, if these elements are present in the concentrate). See Figure 5.

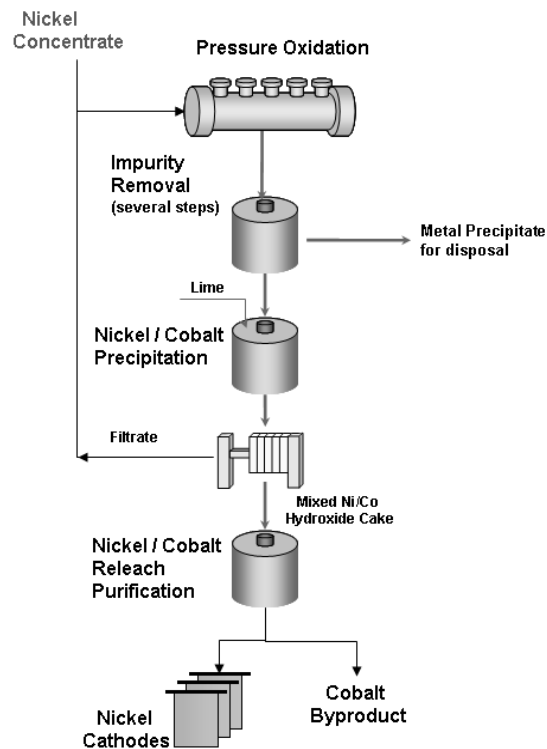


Figure 5 – The CESL nickel process

The pH of the pressure oxidation step for nickel concentrates is generally kept slightly lower than that for copper concentrates to minimize losses of any valuable metals

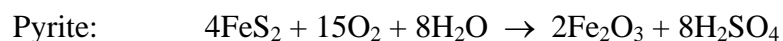
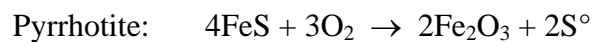
(copper, nickel and cobalt) to the residue; this tends to put more iron into solution, which typically has a concentration of about 1 – 3 g/L iron in the product solution.

Nickel recovery from PO solution involves removal of numerous impurities as a preliminary step to nickel recovery, and finally Ni:Co separation. Key impurities to be removed (other than cobalt) include Cu, Cd, Zn, Fe, Al, Mg and Mn. This process has been described elsewhere and is outside the scope of this paper. Iron removal in particular is quite important because most nickel concentrates have high iron contents. Under the CESL pressure oxidation conditions, iron is at equilibrium at the operating pH targeted, and final iron concentrations are independent of the iron content in the concentrate. Iron removal is primarily by limestone neutralization at a carefully controlled pH, to minimize Ni/Co losses. A final neutralization with lime at a higher pH, to remove the last traces of iron from solution before nickel recovery, creates a nickel-rich iron precipitate which is recycled for nickel leaching.

### **EFFECT OF PYRITE AND PYRRHOTITE IN THE CONCENTRATE**

Despite not having any direct role in the oxidation of copper or nickel sulphides, the iron sulphides in the concentrate do play a crucial role in the metallurgy of pressure oxidation. Pyrrhotite is oxidized almost quantitatively to hematite and elemental sulphur, without any sulphate formation. This reaction is very fast, has only a minor effect on the overall processing cost, and generates an ideal “gangue” material or dilution mineral for the concentrate. In other words, if a concentrate is of low grade by reason of an abundance of pyrrhotite, it has a minimal effect on costs.

However, for pyrite the reaction is very different as it is fully oxidized to hematite and sulphate; i.e., to sulphuric acid. Typically only about 50 – 75% of the pyrite actually reacts as it is a relatively slow reaction, but it adversely affects the economics of the process. A copper concentrate high in pyrite, therefore, is less economical than a concentrate high in pyrrhotite. The oxidation reactions for these two iron minerals are shown below:



Note that pyrite requires 5 times more oxygen per tonne of iron than pyrrhotite, and thus roughly generates 5 times more heat per tonne of iron during PO. In turn, this leads to an autoclave that must be 5 times larger, as PO is generally run autogenously, and the heat balance is maintained by varying the percent solids in the feed to the autoclave. Figure 6 shows how oxygen consumption affects the autoclave volume, and therefore the leaching costs.

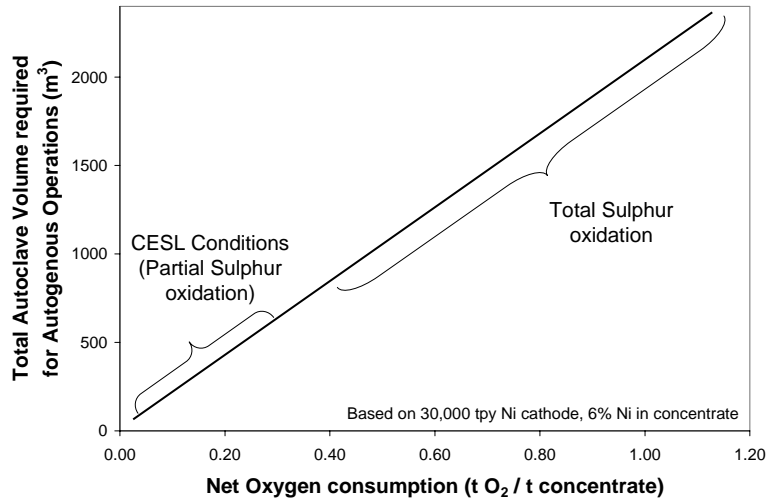


Figure 6 – Pressure oxidation capacity for a 30,000 t/y nickel refinery (at 6% Ni)

In addition to the extra oxygen costs for pyrite, the acid generated has to be neutralized eventually. More important, however, is the fact that the acid generated by pyrite oxidation causes the dissolution of BCS within pressure oxidation and necessitates copper removal (by SX) from the pressure oxidation liquor before recycling. Hence, the whole flowsheet is affected by the amount of pyrite in the concentrate.

## APPLICATIONS OF THE CESL PROCESS

### Copper Concentrates

#### Range of Concentrates and Mineralogy

The CESL Copper Process can successfully treat many different types of concentrates, with widely varying Fe:Cu ratios, as suggested by Table 6.

Table 6 – CESL leaching results for a range of copper concentrate grades

Concentrate	Cu %	Fe %	Fe:Cu	Cu ext %	O <sub>2</sub> ratio	Pyrite %
HVC	40.6	18.8	0.5	97.8	0.23	9
Los Pelambres	30.0	26.7	0.9	97.7	0.23	15
Salobo <sup>1</sup>	22.9	20.4	0.9	98.0	0.09	<1
Cananea	26.1	24.8	1.0	97.0	0.28	32
Alemão	29.1	29.1	1.0	96.1	0.19	<1
Gibraltar (low grade)	17.9	29.4	1.6	95.0	0.37	38
Brisas <sup>2</sup>	10.6	18.6	1.8	94.7	0.19	13

1. Magnetite constitutes 81% of Fe in Salobo concentrate

2. Limonite constitutes 30% of Fe in Brisas concentrate

From Table 6 it can be seen that concentrates having Fe:Cu ratios ranging from 0.5 to 1.8 can be treated successfully, although there is a discernible trend towards lower copper extraction with higher Fe:Cu ratios. This occurs because the Fe-rich hematite phase in the leach residue tends to absorb more (oxidized) copper and makes the atmospheric leach less efficient. Note that the two concentrates with oxide iron (magnetite and limonite) yield relatively high copper extractions, considering the respective Fe:Cu ratios compared to the other concentrates.

### Integration with Heap Leaching

The precipitation of iron during pressure oxidation can be utilized for iron removal from solution, and this can be useful when integrating the concentrate leach with a heap leach operation.

There are other advantages to such integration, such as providing acid to the heap leach, and simultaneously providing neutralization for any excess raffinate from the concentrate leach. In general, there is significant iron in the circulating solution from heap leaching to SX, typically 2 – 10 g/L Fe, which is a manageable concentration with the excellent selectivity of modern SX reagents. However, some heap leach operations have a problem with excess iron in the solution inventory, with iron concentrations reaching as high as 50 g/L Fe. Such iron levels can cause serious metallurgical problems in the leach (high viscosity), and in the SX/EW plant (iron co-extraction with copper, low current efficiency). There are few viable alternatives for reducing such iron concentrations, as the solution volume can be very large. Membrane-based processes have been tried for this purpose but were found wanting in some cases.

The integration with a CESL pressure oxidation plant can provide a solution to this problem, as shown in Figure 7. The recycling feed solution from PO is blended with a bleed stream from the heap leach liquor, and the extra water is first removed by evaporation before feeding the solution again to pressure oxidation. It is estimated that about 30,000 t/y of iron can be removed from a heap leach inventory if it is integrated with a CESL plant having a nominal capacity of 100,000 t/y copper. The main cost would be the evaporation requirement, which is significant but manageable. A byproduct steam from PO can help in this regard, by keeping the costs of evaporation down. The iron from the heap leach liquor eventually departs to the final residue as hematite, along with the iron in the sulphide concentrate.

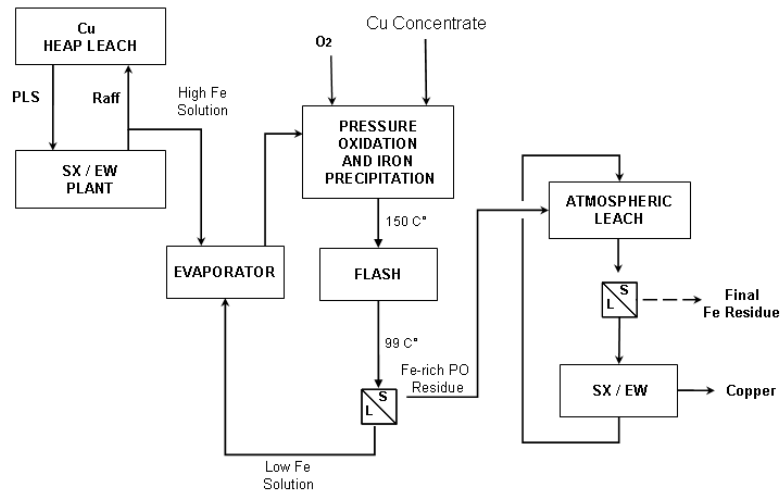


Figure 7 – Iron removal from heap leach solutions using pressure oxidation

### Nickel Concentrates

Test results on a number of nickel concentrates are presented in Table 7 and Table 8. Included are some bulk Cu-Ni concentrates and a high grade ore. The nickel contents ranged from 3.2% to 19.2% Ni. Over this range, the nickel extractions were excellent (97-99%), whilst the iron extractions were minimal. However, the oxygen consumption varied widely, from 1.2 to 5.9 tonne O<sub>2</sub> per tonne of payable metals (nickel + copper); this is largely a result of the varying iron content. So, the main disadvantage of a low grade nickel concentrate is to increase oxygen consumption per tonne of metal produced, and hence, increase the size of the pressure oxidation equipment.

Table 7 – CESL leaching results for a range of nickel concentrate grades

Concentrate	Feed Composition				Leaching Results	
	Ni (%)	Cu (%)	Fe (%)	S (%)	% Ni Extracted	% Fe Extracted
Voisey Bay – Ore	3.2	1.2	57.7	39.9	98.8	<0.2
Keivitsa	3.7	8.0	36.2	26.5	98.0	2.4
Luanga	4.0	1.1	14.6	10.3	97.4	1.7
Voisey Bay – Conc	14.1	6.3	44.5	34.8	96.8	<0.2
Mt Keith	15.6	0.1	27.8	24.7	97.7	1.2
Cosmos	19.2	0.9	41.9	30.8	98.1	0.1

Note that the oxygen ratios for the CESL Nickel Process (Table 8) are also compared to the values which would be expected from a total oxidation process, where all the sulphur is converted to sulphate. The oxygen consumption is anticipated to be four to five times greater for the total oxidation process.

Table 8 – Oxygen consumption comparison for CESL and total oxidation

Concentrate	CESL Process		Total Oxidation *
	(t O <sub>2</sub> /t conc)	t O <sub>2</sub> /(t Ni + Cu)	t O <sub>2</sub> /t (Ni + Cu)
Voisey Bay – Ore	0.26	5.9	33.1
Keivitsa	0.22	1.9	8.4
Luanga	0.12	2.4	7.5
Voisey Bay – Conc	0.30	1.5	6.3
Mt Keith	0.28	1.8	5.8
Cosmos	0.25	1.2	5.8

\* theoretical

### Effect of Iron Minerals on the Nickel Process

Pyrrhotite is far more common in nickel concentrates than pyrite; this is fortuitous, as pyrrhotite can be treated without major cost implications, unlike pyrite, as explained above. Thus the CESL process has a great advantage over conventional smelters which cannot efficiently treat low-grade nickel concentrates with large amounts of pyrrhotite. In smelters, the sulphur associated with pyrrhotite is converted to sulphuric acid at a considerable cost. Thus, most nickel mines aim to produce a nickel concentrate with at least 12% nickel and 18 – 20% nickel is preferred. This restriction on grade at some nickel mines means that nickel recovery can suffer; pyrrhotite is frequently intergrown with nickel minerals like pentlandite, and satisfactory separation is never achieved without some nickel loss. For a nickel concentrate being processed by the CESL Process, such restrictions on concentrate grade can usually be relaxed, and it is even conceivable to process whole ore in exceptional cases.

## CONCLUSIONS

The CESL Process effectively handles the iron content of base metal concentrates. Iron departs almost entirely to hematite, providing a residue with excellent settling and filtration characteristics. Atypical to other copper hydrometallurgical processes, the CESL Process does not put iron into solution in significant concentrations, and actually precipitates soluble ferrous or ferric sulphate that is fed to the process.

Iron is not required for the oxidation reaction of the copper minerals, and is not a catalyst for the pressure oxidation. Very little net iron dissolution occurs in atmospheric leaching, and iron is kept relatively low in the PLS to SX, thus alleviating iron complications that can occur in solvent extraction and electrowinning. This leads to significant cost savings compared to other processes where iron is a catalyst or is solubilized and has eventually to be precipitated (leading to water balance issues and possible environmental issues).

There is an important difference between the behaviour of the two main iron minerals in base metal concentrates, in the CESL Process. Pyrrhotite is mostly benign

from a costing point of view whereas the presence of pyrite has significant cost implications for the process. Pyrite is converted mostly to sulphate which has cost implications related to oxygen consumption, acid production, etc., whereas pyrrhotite produces only elemental sulphur, an oxidation process which costs very little. For copper concentrates where pyrite is a common constituent, this has a limiting effect on the (low) grade of concentrates that can be handled efficiently in the process. For nickel concentrates on the other hand, where pyrrhotite is the common diluent, very low-grade concentrates can be handled efficiently, thus allowing a mine to produce low-grade nickel concentrates where necessary to achieve maximum mill recovery.