

THE CESL GOLD PROCESS

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ABSTRACT

The CESL Copper Process was developed as a hydrometallurgical alternative to smelting and refining for copper sulphide concentrates. As the majority of such concentrates contain appreciable gold and silver values, effective recovery of these metals is essential to the economics of this technology. Unfortunately, conventional cyanide processing cannot be used on the residue from the copper process, due to its unusual characteristics when compared with naturally occurring gold and silver ores. An abundance of elemental sulphur, as well as the presence of cyanide soluble copper, leads to the formation of both thiocyanate and copper cyanide which is detrimental to process economics due to excessive cyanide consumption. This, however, can be reduced to acceptable levels by process innovations such as pressure cyanidation and cyanide recovery. This paper outlines the successful application of the CESL Gold Process to various gold-bearing copper concentrates from bench to demonstration scale.

INTRODUCTION

The CESL Copper Process

The CESL Copper Process is a hydrometallurgical process for recovering copper from copper sulphide concentrates. The process flowsheet is shown in Figure 1 below. The heart of the CESL Copper Process involves pressure oxidation of the copper sulphides at elevated temperature in the presence of chloride ions and oxygen inside an autoclave. Under these conditions the copper is converted from copper sulphide minerals to basic copper sulphate. Any iron present in the concentrate is oxidized to hematite-type materials, and sulphur is predominantly converted to elemental sulphur.

The basic copper sulphate that forms is acid soluble and leaches either in the autoclave or in a subsequent enhanced atmospheric acid leaching step after discharge, depending on the acid balance in the pressure oxidation. The autoclave operates at 150°C and about 1400 kPag with a retention time of approximately 1 hour. Under these conditions, minimal sulphur to sulphate oxidation occurs, helping to reduce oxygen consumption as well as the subsequent need to neutralize excess acid. The enhanced atmospheric leach step is beneficial when processing gold bearing materials as it reduces the cyanide soluble copper in the residue, thus improving overall copper recovery.

The leached copper is recovered from the pregnant leach solution using conventional solvent extraction. The raffinate is then recycled back to the atmospheric leach or the autoclave to be reused. A small bleed stream is neutralized to remove excessive acid and other impurities that build up in solution.

The pregnant electrolyte produced from solvent extraction is processed using conventional electrowinning to produce London Metal Exchange (LME) Grade-A copper cathode. Copper recovery is generally 96-98%, which is comparable to a smelter.

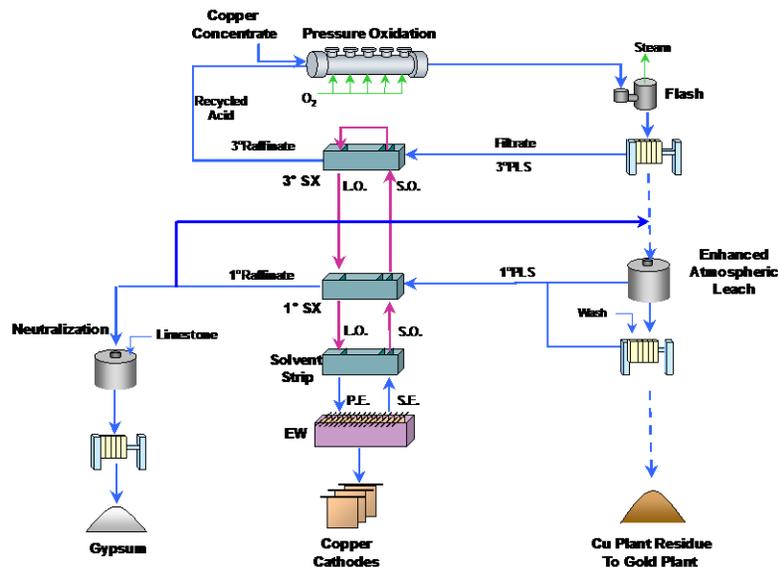


Figure 1 - CESL Copper Process Flowsheet

Gold and silver do not leach in the CESL Copper Process and depart entirely to the copper plant residue along with the elemental sulphur, hematite, and gangue material. These solids form the feed for the CESL Gold Process.

Gold and Silver Value in Copper Concentrates

Gold and silver occurring in copper sulphide ores generally follow the copper into the flotation concentrate in fairly high yield and, given current precious metal prices, the amount of gold and silver required to be economically significant is quite low.

A survey of copper concentrates (Figure 2) shows that the average concentrate contains the equivalent of about US\$0.10 - 0.50 /lb Cu in gold and silver (using first quarter 2011 gold and silver prices). More importantly, about 95% of the copper concentrates in the world have a payable gold and silver value above 10 ¢/lb copper in the concentrate. The operating cost for the CESL Gold Process averages 5 ¢/lb copper which makes a CESL Copper – Gold plant an economical alternative to smelting.

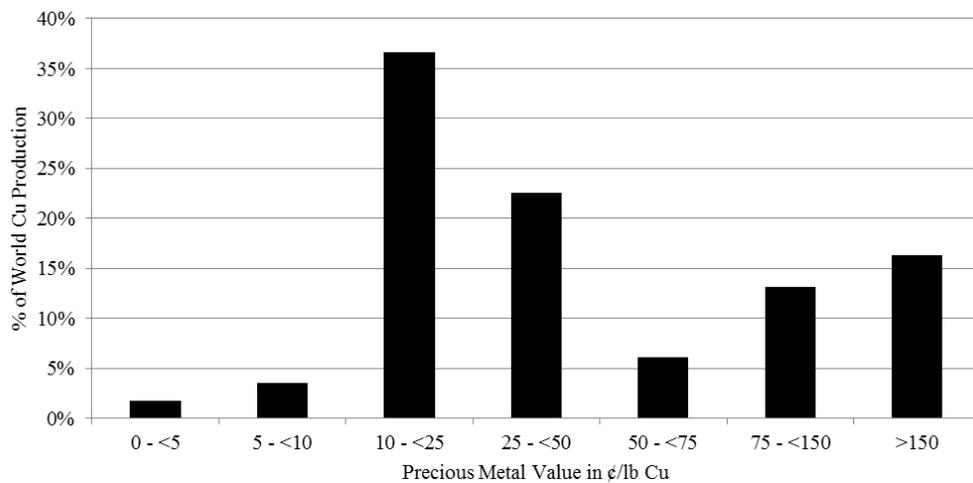


Figure 2 - Precious Metals Value in Copper Concentrates [1-2]

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Challenges of the CESL Copper Plant Residue

The Copper Plant residue presents challenges that must be overcome in order to efficiently recover gold and silver. It has several unique qualities when comparing it with typical gold ores or concentrates that are subjected to conventional cyanide leaching procedures.

First, despite already having been processed through the CESL Copper Process for copper recovery the residue still contains 1% Cu, in addition to small amounts of entrained copper due to imperfect washing, of which a portion is cyanide soluble. This copper, along with that which is entrained, readily forms copper cyanide complexes when contacted with a cyanide leach solution, limiting the cyanide available to leach gold and silver.

Second, the residue usually contains 15-35% elemental sulphur. In the presence of cyanide leach solution, a small portion of this will leach and form thiocyanate. Once the cyanide has formed thiocyanate

it is no longer available for gold and silver leaching and it is difficult to recover cyanide from thiocyanate once formed.



Third, the elemental sulphur can exist as a coating on some of the copper plant residue particles. Because of the operating temperature in the autoclave, the elemental sulphur exists in its liquid state during the pressure oxidation step of the CESL Copper Process. Upon discharge, the solution flashes to atmospheric pressure and the sulphur becomes a solid (elemental sulphur $T_{\text{Melting}} = 115^\circ\text{C}$). During this phase transition a small portion of the gold and/or silver can become encapsulated within elemental sulphur.

Standard cyanide leaching of the residue, using long retention times, 24-72 hours, at atmospheric conditions leads to cyanide consumption two orders of magnitude greater than the consumption typically experienced in conventional cyanide leaching of gold ores, i.e. 35-100 kg NaCN/tonne residue [3].

Alternative Gold Recovery Options Explored

Several attempts were made to overcome the difficulties of achieving high gold and silver extraction in a cost effective manner. A flowsheet was developed that was a technical success when piloted, involving a flotation step on the Cu Plant residue followed by a sulphur leach on the flotation concentrate using an organic solvent, a total oxidative leach (TOL) to eliminate last traces of elemental sulphur, and finally, cyanidation of the TOL residue for gold and silver extraction. The process resulted in excellent precious metal recoveries (>95%) with low cyanide consumption, and was successfully demonstrated in 1999- 2000 on several Cu Plant residues at a 4.0 tonne/day scale. Unfortunately, the process involved a complex flowsheet that had relatively high operating and capital costs, so a cheaper and simpler process was sought.

The CESL Gold Process Flowsheet

A second simpler process has been developed, which minimizes cyanide consumption without recourse to sulphur removal, TOL, etc., and still achieves high gold and silver extraction. This flowsheet (Figure 3) consists of four main process steps:

- **Pressure cyanidation:** carried out at high pressures of oxygen with short retention times, at ambient temperature. These conditions minimize thiocyanate formation, while effectively leaching gold and silver. This is followed by a filtration step that produces a pregnant copper-gold-silver solution and washed residue.
- **Carbon-in-column:** gold and silver from the pregnant solution are recovered through conventional adsorption-desorption-recovery (ADR) processes. A major portion of barren solution is recycled to pressure cyanidation directly after gold and silver recovery.
- **Cyanide recovery:** cyanide and copper recovery by acidification, volatilization and reneutralization (AVR). During this process, the copper is removed from a portion of the barren solution by acidification, and forms a copper thiocyanate precipitate. The copper precipitate is removed in a filter and recycled to the Copper Plant. A portion of the acidified stream is reneutralized with caustic and recycled to PCN with the balance being volatilized to produce a

low cyanide stream for treatment in order to control the plant water balance. The volatilized cyanide is reabsorbed through the use of caustic and recycled to pressure cyanidation.

- **Cyanide destruct:** uses conventional techniques on the stream from volatilization to meet discharge permit requirements and to maintain the water balance.

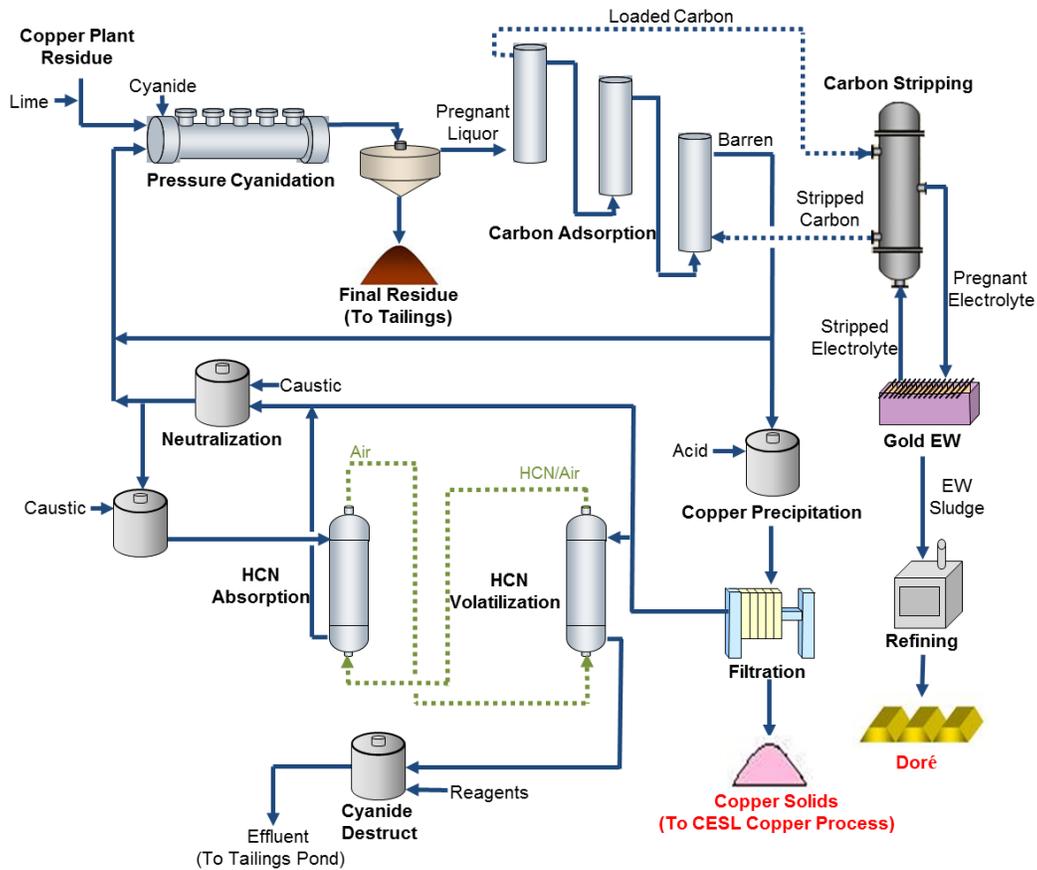


Figure 3 - CESL Gold Process Flowsheet

A process description of the unique unit operations in the CESL Gold Process, pressure cyanidation and cyanide recovery, is presented in the following sections.

Pressure Cyanidation

There are two main feed streams to the PCN vessel: cyanide bearing feed liquor and repulped copper plant residue. The solids are fed at 600 g/L slurry density into the pressure vessel via high-pressure pumps where the slurry is diluted to 250-400 g/L solids with feed liquor. The feed liquor is a combination of recycled barren liquor and AVR product.

Oxygen, sodium cyanide, and hydrated lime are also added to the pressure cyanidation circuit. Oxygen is injected in-line with the feed liquor to maximize the dissolved oxygen tenor in the first compartment. Fresh cyanide is pumped into the vessel compartments as a stock solution via metering pumps. To prevent hydrogen cyanide evolution, hydrated lime slurry is added to the repulped Copper Plant residue to maintain a slurry pH of 10.5.

After the slurry leaves the pressure vessel, it is discharged into a filter feed tank which feeds a thickener. The underflow slurry is filtered and washed with the overflow sent to a CIC circuit for precious metal recovery. The CIC barren solution is split, with the proportion dependent on the overall plant copper balance, with ~60% of the solution fed to the AVR circuit and ~40% recycled back to the feed liquor tank.

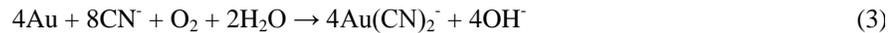
In certain cases, it has been shown to be beneficial to perform a light regrind on the copper plant residue prior to cyanide leaching. These cases include: (i) where the gold within the feed concentrate is submicroscopic (i.e. less than 1 micron) which promotes a higher degree of unreacted sulphide and sulfur encapsulation of such gold, and (ii) where the gold mineralogy is refractory in nature, with minerals such as calaverite (AuTe₂), petzite (Ag₃AuTe₂) and sylvanite ((Au,Ag)₂Te₄). Grinding has been shown to enhance the recovery of such gold.

One of the most important aspects in making the CESL Gold Process a success is minimizing cyanide losses through thiocyanate formation by reducing contact time between the cyanide leach liquor and the Copper Plant residue. Test work indicated the formation rate of thiocyanate under the conditions seen in the CESL Gold Process to be a first order equation with respect to the cyanide concentration, regardless of whether or not it was under atmospheric cyanidation or pressure cyanidation.

$$\frac{dC_{SCN}}{dt} = K * C_{CN} \quad (2)$$

K represents the formation rate constant and is dependent on the surface area, and crystalline state of the sulphur.

In conventional cyanide leaching technology, the oxygen is the limiting factor in the gold leaching reaction (Elsner's Equation).



By operating the leach inside a pressure vessel fed with oxygen, the dissolved oxygen concentration can be increased such that the leaching time can be reduced to 60-90 minutes thereby minimizing cyanide deportment to thiocyanate. To enable the fast kinetics, the CESL Gold Process operates at an active cyanide concentration of 0.5-1.0 g/L as determined by the following formula which accounts for the majority of copper being present as Na₃Cu(CN)₄.

$$\text{Active Cyanide (mg/L)} = \text{Total Sodium Cyanide (mg/L)} - 3.1 * \text{Copper Concentration (mg/L)} \quad (4)$$

Using the molar ratio of 6:1 [CN⁻]/[O₂], which was calculated to meet the rate limiting condition [4], and an active cyanide concentration of 1 g/L NaCN, in order to avoid the oxygen being the rate-limiting factor in the leaching reaction, the vessel is operated at a pressure of at least 1,400 kPa. This is well above theoretical requirements to drive the mass transfer of oxygen into the slurry, and of importance, to the surface of the gold particle. Published results by CESL[3] indicate a six times reduction in thiocyanate production when pressure leaching is used in place of conventional atmospheric leaching which resulted in a fivefold reduction in cyanide consumption.

Cyanide Recovery

The ability to recycle cyanide in a tailings stream back to the leach is termed cyanide recovery. The two commercially practiced methods of cyanide recovery are: (i) to simply recycle a portion of the tailings stream back to the front-end of the cyanide leach, usually a thickener overflow stream, and (ii) to concentrate the cyanide in the tailings into a smaller stream containing “free” cyanide, and recycle this back to the front of the cyanide leach.

The CESL Gold Process utilizes both methods of cyanide recovery. The major method of cyanide recovery is through the use of AVR technology which has been used elsewhere, though only occasionally. The process as at CESL involves acidification of a portion of the barren stream in a closed vessel to a pH of 2.0 to 2.5. Upon acidification, the cyanide disassociates and forms hydrogen cyanide gas. The associated copper precipitates out in the acid as, primarily, copper thiocyanate. The acidified stream is filtered to remove the copper precipitate which is recycled to the Copper Plant and recovered to cathode. The hydrogen cyanide gas is volatilized from a bleed solution dictated by the plant water balance, and then scrubbed back into solution in a separate column via contact with caustic. The concentrated cyanide stream is then recycled back to the front-end of the cyanide leach. The resulting bleed solution is low in cyanide (<30 mg/L NaCN) and largely devoid of Cu, Zn and Fe thus potentially negating the requirement for cyanide destruct depending on the tailings pond environmental requirements.

The application of cyanide recovery within the CESL flowsheet is highly beneficial as it: (i) reduces cyanide consumption, (ii) reduces associated cyanide destruct costs, (iii) provides a copper credit which more than offsets the circuits operating costs, and (iv) has significant environmental benefits.

RESULTS AND DISCUSSION

Bench Leach Results

CESL has extensively examined the recovery of Au and Ag from copper plant residues at the bench scale. Table 1 provides bench results from ten different materials, labeled residue A through J. Despite a wide variation in Au grade, extractions in excess of 84% were realized for all samples.

Table 1 - CESL Gold Process Bench Testwork Extraction Results

Residue	Residue Grade			Metallurgical Results		
	Cu %	Au g/t	Ag g/t	Cu Ext. %	Au Ext. %	Ag Ext. %
A	0.8	25.4	711	16	84	94
B	1.0	2.6	70	12	86	91
C	1.1	5.2	91	10	87	90
D	1.4	10.7	102	14	91	95
E	1.2	10.8	13	16	92	90
F	1.1	13.7	62	11	94	96
G	1.1	18.7	30	12	94	99
H	1.2	16.2	38	16	97	58
I	0.4	17.3	39	6	97	85
J	1.1	102	83	18	98	83

Gold extraction from the residue samples were 86-87% for residues that contain 5 g/t or less of gold, while extractions range from 91-98% for materials with a higher head grade. The one exception to this is the concentrate denoted 'A' in Table 1; this represents a material processed at CESL where Mineral Liberation Analyser (MLA) found significant refractory silicate gold. Silver extraction is typically above 90% but can vary lower for concentrates that contain high pyrite (>35%) tenors as causes a portion of the silver to form the non-cyanide soluble mineral argentojarosite in the autoclave. Copper extraction typically ranges from 10-15%. This copper is precipitated and recycled to copper plant, which provides a significant byproduct (represents 15-20% of Gold Plant operating costs).

Pilot Plant Results

The promising bench results have led to several integrated pilot plant campaigns, which represents several thousand hours of test work. The continuous pilot plant processes 50 kg of CESL Copper Process residue per day. Campaign results for the CESL Gold Process performed on Copper Plant residues are shown in Table 2.

Table 2 - CESL Gold Process Pilot Plant Extraction Results

Residue	Feed Grade		Metallurgical Results		
	Au g/t	Ag g/t	Au Ext. %	Ag Ext. %	NaCN Consumption kg/t
I	18	42	90	87	4.0
II	12	34	91	70	2.3
III	12	34	92	87	2.5
IV	11	16	91	91	2.4
V	14	81	90	87	5.2
VI	18	35	87	71	5.0

Campaigns have typically resulted in gold extractions of 90% or above, and silver extractions ranging from 70-91%. These results are comparable to those achieved through bench testing. Overall recovery of the extracted precious metals to carbon averaged >98% for the campaigns.

Overall cyanide consumption averaged from 2.3 to 5.2 kg/t NaCN. The largest single source of cyanide loss is to thiocyanate formation; consuming 20-55% of the cyanide added. Through the use of an AVR circuit the cyanide that associates with copper is largely recycled, averaging a recovery of 95% for the campaigns. The use of a cyanide recovery circuit reduced cyanide consumption by 0.5 kg/t to >2 kg/t depending on the residue processed. Unaccounted cyanide losses, either from volatilization of HCN or due to unknown sources, represents up to one-third of the overall cyanide added. It is believed that this unaccounted value will be reduced significantly through larger scale operations.

Demo Plant Design and Construction

The successful work on the pilot scale led to the construction of CESL's Gold Demonstration Plant which is capable of processing 2 tonnes of CESL Copper Plant residue per day. The planned gold and silver production from the feed material is 1.5 oz/day and 2.0 oz/day respectively.

Engineering, procurement, construction management (EPCM) of the demonstration plant was performed in-house by CESL by a dedicated process engineering team. The plant construction was both on schedule and budget, costing \$5,000,000 over the design and construction period of 18 months. A brief description of the design requirements for various components of the plants are described below.

PCN Design Description

The pressure cyanidation operation is carried out in a 21” horizontal pressure reactor constructed of 316L stainless steel. It is divided into 5 cascading compartments, each agitated by an Ekato Viscoprop agitator. One of two Milton Roy piston-diaphragm pumps delivers slurry to the vessel while a higher capacity Milton Roy pump delivers the feed liquor. Sample ports are installed on each compartment. The first 4 compartments are independently supplied with NaCN solution by Milton Roy pumps.

The PCN reactor discharges into an agitated atmospheric pressure 316L stainless steel tank via a letdown pot containing jasper rock for abrasion resistance. The PCN residue is thickened in a 1m diameter FRP thickener before being washed on a 1.3m² Komline-Sanderson belt filter. The PCN reactor vessel is shown below in Figure 4.

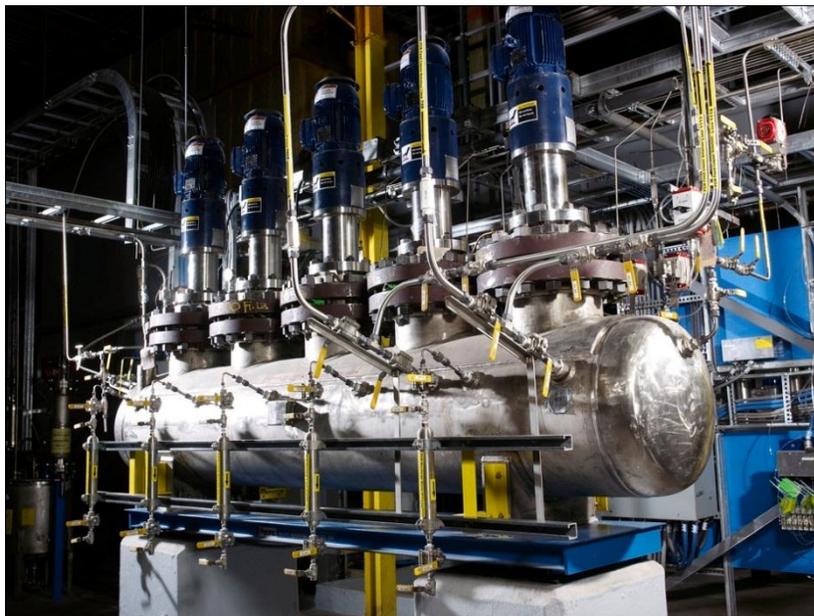


Figure 4 - CESL Gold Demonstration Plant Pressure Cyanidation Vessel

ADR Design Description

The ADR plant was designed and constructed externally and shipped on 7 modular skids. The CIC area consists of 6 PVC carbon columns arranged in series. Each column is equipped with an overflow tank and pump for collecting the liquor and feeding the next stage. Each of these overflow tanks is also capable of receiving fresh feed liquor and pumping out of the circuit. By configuring the valves on these pump tanks, the columns can be indexed through the six loading stages. Once loaded, the carbon can be transferred out of any column to the acid wash tank using eductors and a carbon transport water system.

The washed carbon is transferred to a carbon steel strip vessel capable of handling 25 kg/day of carbon. Two heat exchangers heat the strip solution using exiting hot strip solution and fresh steam. The stripped carbon is regenerated in a natural gas fired rotary kiln, sized with a Sweco vibratory screen, and returned to the CIC circuit for loading. The pregnant electrolyte from the strip stage is heated in an in-line heater before feeding the electrowinning cell. The stainless steel cell is hooded and ventilated through a scrubber. The cell operates with 316 stainless steel wool cathodes and 316 stainless steel mesh anodes. Upon completion of the plating cycle, the Au-Ag-Cu sludge is collected by pressure washing the cathodes. The ADR circuit is shown below in Figure 5.



Figure 5 - CESL Gold Demonstration Plant ADR Circuit (CIC and EW Cells)

AVR Design Description

The barren solution is acidified upstream of a ¾" PVC inline mixer. The copper precipitate that is formed in the acidification process is thickened in a stainless steel clarifier and neutralized in the clarifier underflow tank. The clarifier overflow is pumped to a packed tower stripper, constructed of FRP, where the HCN is volatilized into recirculating air and sent to an FRP packed tower absorber. A vacuum pump maintains negative pressure in the towers. The stripper and absorber are shown in Figure 6.



Figure 6 - CESL Gold Demonstration Plant Cyanide Recovery Stripper and Absorber Columns

CND Design Description

The cyanide destruct circuit uses the conventional SO_2 /air process in a series of 3 mechanically agitated tanks. Two large tanks provide surge capacity to allow for testing before discharge to sewer.

Gold Demo Plant Operations

From June 2007 to May 2008, 275 tonnes of copper concentrate was processed through CESL's Copper Demonstration Plant to produce over 200 tonnes of residue scheduled to be fed to the CESL Gold Demonstration Plant. At the time of writing this paper, the CESL Gold Demonstration Plant was commissioned and initiating continuous operations. The campaign began in March 2011 and is scheduled to be completed by September 2011.

Pre-Feasibility Study: Economics of a Commercial Gold Plant

A pre-feasibility operating and capital cost estimate was prepared by an external engineering firm in March 2008 for a CESL copper and gold refinery to be built onsite at a large, high altitude copper-gold mine/mill complex in South America. The Cu refinery was designed to produce 150,000 tonnes per year copper cathode from processing 645,000 tonnes/year copper concentrate. The study showed the economics to be quite promising. The design for the gold refinery was based on processing 500,000 tonnes/year of Copper Plant residue containing 13.6 g/t gold and 84.1 g/t silver to produce 200,000 troy ounces of gold and 1,200,000 troy ounces of silver per year. The capital cost for the refinery was estimated at \$104.5 million. The operating costs were estimated at \$17.6 million per year which, after calculating the gold

equivalent worth of the silver, works out to \$78 per troy ounce of recovered Au equivalent in doré. This value was calculated using a gold-to-silver-value ratio of 54. This is equivalent to 5 ¢/lb Cu in the original concentrate. Costs are in fourth quarter 2007 US dollars and do not include the consultant's 10% contingency allowance.

The estimated operating cost breakdown can be seen in the table below.

Table 3 - Annual Operating Costs

Cost Element	Annual Operating Cost (\$US000)	Cost Distribution
General and Administration	\$120	1%
Labour	\$2,256	13%
Utilities	\$2,731	16%
Reagents and Consumables	\$9,877	56%
Maintenance Supplies	\$2,613	15%
Total	\$17,597	100%

The majority of the operating cost was estimated to be for reagents and consumables. Sodium cyanide, hydrated lime, and caustic combined represented 84% of the reagent and consumable costs, each approximately equivalent. The cyanide consumption used for the study was 3.1 kg/t of residue based on pilot testing and METSIM modeling.

Because the two processes are directly coupled, it is easier to think of the gold refinery as an add-on to the copper refinery, which has an estimated capital cost of \$550 million, and an estimated operating cost of \$75 million per year. This is also a contributing factor in the general and administration costs estimate which appears quite low, allowing it to be accounted for in the CESL Copper Plant nearby. The following table breaks down the capital and operating costs of the copper and gold refineries as well as the operating costs relative to the copper produced.

Table 4 - Capital and Operating Costs for CESL Copper and Gold Refineries

	CESL Copper Refinery	CESL Gold Refinery	Total
Capital Cost (US\$M)	\$550	\$104.5	\$655
Operating Cost (US\$M/year)	\$75.5	\$17.6	\$93
Operating Cost (US\$/lb Cu)	\$0.23	\$0.05	\$0.28

The additional capital and operating costs of the gold refinery, compared to the stand-alone copper refinery, were estimated to be 19% and 23% respectively. At the estimated 90% gold recovery value used for this pre-feasibility study, the added value of the gold produced at the refinery works out to 35 ¢/lb of copper assuming a gold price at \$650/troy ounce, and more than double that with current gold prices at the time of writing (June 2011). This does not take into account additional copper credits received from the copper recovered from the gold plant which increases overall revenues.

In addition to competitive costs, the CESL Cu-Au Process provides several unique advantages for the mine-mill. It makes the mine independent of market terms allowing the treatment of low grade

concentrates, bulk concentrates or concentrates with penalty elements. In cases where there is existing SX/EW infrastructure in place, the economics are improved as the capital is significantly reduced. The CESL Process is also not water intensive as it has a closed-loop water balance, and in cases where fresh water is scarce, sea water can be used as process water for most areas within the plant.

CONCLUSIONS

CESL provides the operational flexibility to process high-impurity (eg. As, F, Sb, U, etc.) ores, and allows the processing of lower grade copper concentrate thereby providing a higher recovery of both copper and gold in the mill. The CESL Process has been proven to successfully treat such concentrates with a wide variety of mineralogies and grades. The pre-feasibility study showed attractive capital and operating costs for a CESL Copper-Gold refinery producing 150,000 tonnes/year copper and 200,000 oz/year gold.

New technology inevitably involves a high degree of risk. In order to reduce that risk, successful lab, pilot and demonstration testing of a process must be completed. In addition, reducing the complexity of the process increases the chance of commercial success. The CESL Copper Process underwent extensive testing and optimization leading to a 10,000 tonne per year semi-commercial facility. The CESL Gold Process has undergone years of development and optimization the final product of which is now a simple flowsheet utilizing pressure cyanidation and cyanide recovery in conjunction with already commercial processes such as conventional ADR and cyanide destruct.

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