

Teck – Aurubis: Un enfoque integrado desde la mina hasta el metal para desarrollar depósitos de cobre con alto contenido de arsénico usando el proceso CESL

Teck – Aurubis: An integrated mine to metal approach to develop high arsenic copper deposits using the CESL process

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Resumen

El fuerte avance experimentado por un grupo de grandes economías en vías de desarrollo está impulsando la demanda de cobre, que es necesario para el crecimiento urbano e industrial y para la construcción de infraestructuras. Con objeto de satisfacer en el futuro la creciente demanda será necesario poner en explotación también los recursos de minerales de cobre más complejos. Especialmente, el arsénico contenido en los minerales de cobre está creciendo tanto en los recursos que están en explotación como en los nuevos proyectos. La industria del cobre necesita una solución para el desarrollo sustentable de estos recursos minerales de cobre con alto contenido de arsénico. Teck Resources Limited ('Teck') y Aurubis AG ('Aurubis') están trabajando juntas para desarrollar una tecnología que sea aceptable desde los puntos de vista regulatorio, medioambiental, social y económico. Teck y Aurubis están combinando sus respectivos conocimientos en las áreas tradicionales de minería, producción y tratamiento de concentrados, procesamiento hidrometalúrgico y producción de metales para desarrollar un nuevo proceso con una visión sustentable integrada desde la mina hasta la obtención del metal. Este trabajo presenta los resultados obtenidos por Teck-Aurubis conjuntamente como consecuencia del programa técnico desarrollado desde 2010 para el tratamiento con éxito de concentrados de cobre con alto contenido de enargita usando la tecnología CESL. Se incluye el estudio de un caso en el que queda demostrada la viabilidad para desarrollar grandes depósitos minerales con alto contenido de arsénico, por medio de esta nueva tecnología integrada desde la mina hasta la producción de cátodo de cobre de alto grado (LME-A)

Abstract

Strong demand for copper is driven by urbanisation, industrialisation and infrastructure expansions in large developing global economies. The exploitation of more complex copper resources will be necessary to meet future demand. In particular, the arsenic content of copper ores and concentrates from existing and planned mining operations is on the rise. The copper industry needs a competitive solution for the sustainable development of these high arsenic-bearing copper resources. Teck Resources Limited ('Teck') and Aurubis AG ('Aurubis') are working together to develop a sustainable technology that is acceptable from a regulatory, environmental, social and economic perspective. Teck and Aurubis are combining traditional mine-concentrate expertise with established hydrometallurgical processing and copper metal production know-how to develop this new sustainable process. This paper will present the results from the 2010 joint Teck-Aurubis technical program which successfully treated high enargite bearing copper concentrate samples using CESL technology. The potential value of developing a "world class" integrated mine-refinery operation that produces LME Grade A copper cathode from high arsenic copper ores is demonstrated with a case study.

1. INTRODUCTION

Demand for mineral resources from large developing economies (e.g. the BRIC countries of Brazil, Russia, India, and China) is increasing as populations continue to grow and more people strive to achieve a higher standard of living as incomes rise [1,2]. Copper metal is required in a variety of infrastructure, electrical and power generation products making it a critical resource in the expansion of these emerging economies. Despite global efforts on recycling and dematerialization strong demand for primary copper mine supply is expected to continue well into the future [3]. This will largely be driven by rapid development from the BRIC economies, which will see copper mine supply requirements over the next 25 years surpass what has been mined historically [4]. This expectation will place increasing pressure on the industry to find and develop several new copper projects in order to satisfy demand. As a result, new supply will increasingly have to be mined from non-traditional copper resources, specifically those of lower grades, more complex mineralogy, and increasing levels of deleterious elements [5]. One specific element that has garnered considerable industry attention has been arsenic, where concentrations in existing and future mines appear to be on the rise [6,7]. Many of these projects are located in South America, particularly in Chile and Peru where over 40 percent of global copper mine production resides.

Recognizing this, while having a sound understanding of current hydrometallurgical and pyrometallurgical processing options, both Teck Resources Limited ('Teck') and Aurubis AG ('Aurubis') have formed a partnership to develop a new sustainable mine to metal solution to exploit future copper resources high in arsenic concentration. A detailed development program to advance towards profiting from using the CESL hydrometallurgical Cu-Au technology for unlocking high arsenic bearing copper resources has been undertaken. The pressure hydro-metallurgical approach to processing such concentrates is a favourable solution as mineral extraction and arsenic fixation can take place in a single autoclave vessel.

Under CESL pressure leaching conditions (150°C, 1380kPa) high copper extraction is achieved and arsenic is simultaneously precipitated as a stable ferric arsenate product [7].

This paper will review the results from the 2010 Teck-Aurubis copper-arsenic technical program while highlighting ongoing work between the two partners. Preliminary results from this work provide support for the application of a mine to metal operation as a new sustainable solution for high arsenic bearing copper ore bodies. In the latter part of this paper, a hypothetical case study is described from an economic, social, and environmental perspective to demonstrate the value of developing a "world class" integrated mine-refinery operation that produces LME Grade A copper cathode from high arsenic copper ores.

2. OPPORTUNITY

2.1 Strong Demand for Copper

Demand for copper has increased significantly due to global population, technological and industrial growth. It is unlikely that consumption of copper will slow down in the coming years as demand from large emerging markets (BRIC countries) continues to expand aggressively [8]. According to industry consulting services group Brook Hunt (a Wood Mackenzie Company), global refined copper demand is forecast to increase on average at a compound rate of 3.4% from 2010 to 2025 [9]. During this period copper demand is expected to grow by 8.5Mt from 16.6Mt (2010) to 25.1Mt (2025) [9]. More importantly, supply from Brook Hunt's current base case mines is expected to fall by 6.2Mt from a high of 18.0Mt (2014) to 11.8Mt (2025) [9]. Under this scenario the world would require a significant growth in new mine supply starting in 2015. The degree of this supply requirement is shown in Figure 1, which depicts the extent of additional new projects by the year 2020 to approach 6Mt of Cu. This equates to 40 projects at an average production rate of 150k tpa copper.

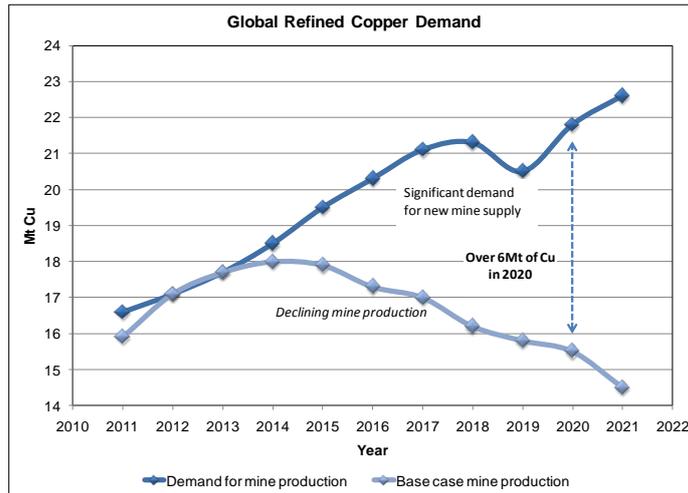


Figure 1 Copper Project Demand (Figure by authors, data sourced from Brook Hunt 2011)

Much of the world's future mine supply will evidently come from South America as it hosts significant geological potential for new projects [10]. Currently supplying over 40 percent of global copper output, South America is the world's leading copper producing region and will remain a key source of primary copper supply for decades to come. Together Chile, Peru, and Argentina boast some of the world's largest Greenfield copper projects with Peru leading the way [11,12].

2.2 The Arsenic Challenge

In order to satisfy future demand, it is likely that many global copper projects which have been on hold or precluded from development historically due to reasons related to lower economic grade, complex mineralogy, or increased levels of

deleterious elements will need to be considered for production [13]. Some of the largest known Greenfield copper projects in South America currently face issues related to arsenic management in the ore body due to the widespread distribution of enargite (Cu_3AsS_4) and tennantite ($Cu_{12}As_4S_{13}$). Based on future demand assumptions, the global content of arsenic in concentrates from existing mines as well as projects with different levels of probability for development will increase significantly (Figure 2). Preliminary evaluations indicate an increase in the average arsenic grade of concentrates of 0.17 % to 0.22 % by 2020. The largest increase is expected to take place between 2013 and 2016. In absolute value, the total arsenic content in concentrates is projected to increase from ~85 Kt in 2010 to ~148 Kt in 2015 and ~218 Kt in 2020.

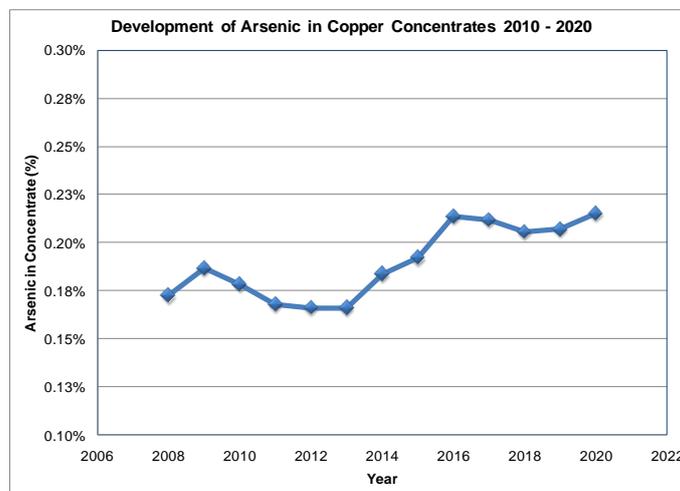


Figure 2 Rising Arsenic Trend in Global Concentrates (Figure by authors, data sourced from Brook Hunt Q4 2010)

High arsenic in ores is a growing concern for the industry as it reduces the marketability of the concentrate and exposes the miner to penalties by refiners when exceeding a concentration of 0.2% [14]. From a marketing standpoint, arsenic levels in copper concentrates greater than 0.5% are susceptible to rejection by the majority of smelters [14]. The reason for this is that arsenic is among the most challenging elements for copper smelters to control as it contributes to environmental concerns during metallurgical processing and waste disposal.

Throughout the smelting process, arsenic reports to the off-gas, slag and matte. The arsenic content accepted in the off-gases and the slags are limited by the related costs needed to comply with the environmental regulations. Arsenic reporting to off-gas is removed as arsenic trioxide. As there is a limited market for that product, the only feasible option is to dispose the arsenic as a waste residue. However, due to the everyday stricter occupational health standards and environmental norms, the management of these residues results in a major and growing cost for the smelters [13].

Additionally, there is a technical limit for arsenic-in-anode at the refinery. The means of arsenic control can be blending of low and high impurity concentrates, minimizing flue dust recycling as well as modifications of traditional process in order to enhance impurity removal. All of these measures result in significant cost increases: blending gives way to the need to maintain higher inventories and working capital; dust bleed from the smelter has to be treated by a hydrometallurgical process in order to recover the metal value. Such leaching processes are also effective for removing other deleterious elements from the smelter.

As it stands custom smelters are beginning to see their capacity for treating high-arsenic concentrates is decreasing due to the following factors:

- Increase of the arsenic base load due to changes in the mineralogy of certain mines previously considered as suppliers of clean copper concentrates.

- Strict regulations introduced in China by banning the import of copper concentrates when the arsenic content is higher than 0.5% (this limit could be reduced even further in the future). This is resulting in the appearance in the custom smelters' market of concentrates with more than 0.5% arsenic, which were previously treated in China.
- The recent closing of several smelters exclusively dedicated to treating high arsenic concentrates has increased the amount of these concentrates in the market.

Based on the above information it is highly unlikely that future copper projects bearing significant quantities of arsenic will be developed through the traditional mine to market mechanism. Rather, due to increasing regulatory, environmental and social awareness of arsenic in copper mining and copper metal production, a new sustainable solution is required.

2.3 Technical Considerations

The high arsenic in some copper concentrates is not only a problem for the smelters, but to the mines as well, as such concentrates cannot be easily marketed and imply higher costs from penalties and elaborate handling. Theoretically, this problem can be partially alleviated at the mine site by selective mining in which the arsenic bearing zones in the deposit are avoided, or blended with lower arsenic ones. Nevertheless, this practice is limiting, as it is not only costly, but also precludes the capturing of the whole value of the deposit.

Once produced, concentrate with an arsenic content above the smelter threshold can be either processed to remove the arsenic and processed as a clean concentrate, or treated hydrometallurgically. The list of the potential treatment methods below is not intended to be fully exhaustive and the selection of the appropriate option is ultimately impacted by several project specific factors that were not considered in this report.

2.3.1. Selective Flotation

An approach to minimize the arsenic content in concentrate is through flotation

(bulk sulphide or selective), whereby the arsenic bearing minerals are separated from the copper and copper-iron sulphides by regulating the conditions during the flotation process in order to obtain a clean concentrate suitable for smelting and a 'dirty' one with high arsenic content [15]. Fornasiero et al [16,17] shows that the separation poses some practical challenges. Nonetheless, the flotation approach does not offer an overall solution but enables the arsenic to be concentrated into a smaller stream.

2.3.2. Roasting

Roasting has been used commercially for treating large quantities of enargite concentrate (El Indio, Boliden, Lepanto). Roasting has also been chosen by Codelco for the Mina Ministro Hales deposit with a planned start-up in 2013 [18]. At temperatures of 600-750°C arsenic reports to the gas phase as sulphides and are subsequently oxidized to arsenic oxide dust. The resulting calcine product is arsenic depleted and can be sold to a smelter although its sulphur content is lower than that of conventional sulphide concentrates. Overall metal recovery is determined by the losses in flue dust and whether the contained metal value is recovered. The process itself is not capital and operating cost intensive and might offer a potential economic advantage for treating refractory minerals [19]; nevertheless, its application suffers from an image problem due to historic sulphur oxide emissions and failures to control arsenic and other hazardous materials. Roasting will require fixing of the arsenic and sulphur dioxide using the best available technology.

The arsenic in the dust can be processed to form ferric arsenate in either an autoclaves or under atmospheric conditions [20]. Both involve additional capital and operating cost implications due to the energy requirements in the case of an autoclave process and reagent cost for an atmospheric fixation process where a high Fe:As molar ratio is required [21].

Due to the lower sulfur content, calcine can only be smelted at a higher cost or blended with other concentrates. Therefore it is likely to be sold in smaller lots and with higher treatment charges than a traditional copper concentrate. Depending on the

location, high volumes of calcine and sulfuric acid imply dedicated infrastructure and port facilities, which are capital cost intensive.

2.3.3. Hydrometallurgical Approach

The hydrometallurgical approach for arsenic bearing concentrates involves direct leaching of the copper minerals to produce copper cathode and a disposable arsenic residue.

The Albion (Xstrata) process consists of ultrafine grinding followed by atmospheric sulphate leaching in agitated tanks with oxygen injection. It has been commercialized at Mt. Isa for arsenic containing smelter flue dusts, but the process may not readily leach enargite from concentrate [20].

FreeportHT (Freeport McMoRan) is an autoclave process run at a temperature of 220°C in sulphate media, where almost total copper recovery without regrinding is achieved. It has been demonstrated on clean concentrates in Arizona, as well as Kansanshi. This technology had also been planned for the high enargite Chelopech mine [22]. The process is the hydrometallurgical equivalent of smelting as it is not sensitive to mineralogy except in regards to the heat balance, but at the expense of high oxygen and acid neutralization requirements. Moreover, total oxidation may be the most expensive option in terms of capital cost as well [23].

To alleviate the higher cost arising from the severe conditions at HTPOX, the CESL (Teck) medium temperature pressure oxidation process has been developed. The CESL process reduces the oxygen consumption by limiting the oxidation of sulphur to sulfuric acid, which also results in lower neutralization costs. The process operates at 150°C in the presence of chloride ions in solution. It has been proven on a 10,000 t/a copper industrial plant operated by Vale at the Sossego Mine in Brazil. The successful treatment of refractory minerals (i.e. enargite) is demonstrated further in this paper.

2.4 Teck-Aurubis Partnership

The management of arsenic in the copper industry ultimately needs an integrated approach involving each stage of the value

chain, from exploration through to mining, milling, refining, and eventual mine closure. Recognizing the long-term strategic benefit of a new sustainable mine to metal solution for the development of high arsenic bearing copper deposits, Teck and Aurubis formed a working partnership in 2009. This partnership combines traditional mine-concentrate expertise with established hydrometallurgical processing and refined copper metal production know-how. The technical foundation for both copper-gold recovery and arsenic fixation from high arsenic bearing copper concentrates is the CESL copper-gold hydrometallurgical technology. Teck is Canada's largest diversified resource company, committed to responsible mining and mineral development with major business units focused on copper, steelmaking coal, zinc and energy. Aurubis is the largest copper producer in Europe and the world leader in copper recycling. Aurubis produces some 1 million tonnes of copper cathodes each year which are subsequently processed to a variety of copper products.

Following a thorough market opportunity analysis in 2009, a detailed metallurgical pilot plant campaign (i.e. technical program) was undertaken beginning in 2010 to validate CESL hydrometallurgical technology for high arsenic bearing copper-gold concentrates. The details of this work along with a description of the CESL copper-gold hydrometallurgical technology is described below.

3. COPPER-ARSENIC CESL TECHNOLOGY

3.1 Process Description

The recovery of copper and gold from concentrate using the CESL process occurs in two distinct phases. Initially, copper is removed from the concentrate through pressure leaching in an autoclave using the CESL Cu Process. The gold and silver remain in the leach residue. This residue is fed into the Gold Plant, where cyanide is used to solubilize the precious metals. The CESL Cu Process consists of the following main steps:

- **Pressure oxidation** of concentrate in the presence of catalytic chloride ions at medium temperature and pressure, where the copper is solubilized and the arsenic reacts

with iron to precipitate as a ferric arsenate precipitate;

- **Residue washing** using a counter current decantation (CCD) circuit or belt filter;
- **Solvent extraction** of copper from the leach solution to produce a high purity electrolyte followed by **electrowinning** to recover copper to commercial LME Grade A cathodes; and,
- **Neutralization** of a portion of the raffinate to remove excess sulphate.

As the majority of arsenic-rich copper concentrates contain appreciable gold and silver values, effective recovery of these metals from the Copper Plant residue is essential. The CESL Au Process consists of the following process steps:

- **Pressure cyanide leach** of repulped residue at ambient temperature and an oxygen over pressure to leach gold and silver into solution, followed by filtration to produce pregnant solution and washed residue (the arsenic does not solubilize during this process and departs quantitatively to the leach residue);
- **Precious metals recovery** by carbon absorption from the pregnant solution in carbon columns, and then conventional stripping and electrowinning to recover gold and silver in a commercial product form (doré);
- **Cyanide recovery** by acidification, volatilization and reneutralization (AVR). During this process, the copper is removed from the barren solution by acidification and is recycled to the Copper Plant for recovery. A portion of the acidified solution proceeds to a stripper and absorber in order to recover the cyanide while providing a low cyanide feed stream for cyanide destruction; and,
- **Cyanide destruction** by conventional means on the bleed stream from cyanide recovery.

A graphical representation of the Cu-As CESL technology flowsheet is shown in Figure 3. Further details of the CESL Process have been well documented in previous publications [24,25].

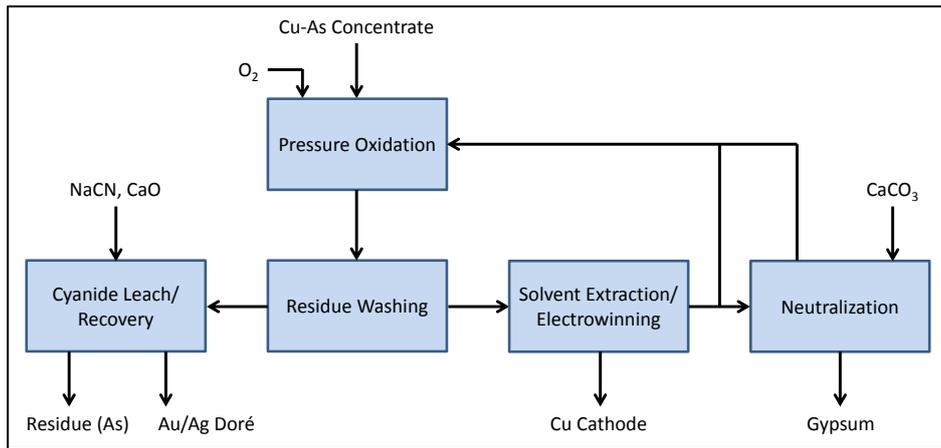


Figure 3 CESL Process Cu-As Flowsheet

The CESL process for arsenic bearing copper concentrates has the following advantages:

- Low sensitivity to the copper and/or arsenic grade of the concentrate; potentially providing higher mill recoveries and eliminating the need to stockpile high-As ore;
- High copper recovery while precipitating arsenic in a single stage. The ferric arsenate type precipitate is a compact residue that exhibits excellent settling and filtration characteristics;
- Oxidation of sulphur contained in the concentrate is limited, resulting in low oxygen and limestone costs;
- Effective treatment of a wide range of impurities (in addition to arsenic), from operational cost and environmental perspectives;
- Closed-loop process produces no liquid effluents or sulphur dioxide and the only solids produced are gypsum and a stable leach residue; and,
- Application has been thoroughly tested and successfully assessed on a semi-industrial scale [26].

3.2 Technical Program

Recognizing that copper recovery from enargite bearing concentrates poses metallurgical, environmental and economic challenges, a detailed work program was created to assess the technology. Included in the program were bench- and pilot-scale testing to demonstrate that the CESL

process could attain high copper recoveries from arsenic bearing concentrates (1.4%-4.6% As) and stability tests to ensure that the residue could be stored long-term in an environmentally acceptable manner. Items related to gold recovery from the residues are beyond the scope of this paper as test work is still ongoing.

3.2.1. Copper Technology

To assess the application of CESL technology to arsenic bearing concentrates, several concentrates were obtained from commercial operations. The mineralogy and elemental composition of the materials processed are presented in Table 1.

The concentrates were tested on the bench scale to establish optimal conditions for pilot testing, specifically regarding copper extraction and arsenic precipitation in the autoclave. Optimal leach conditions of 150°C, 1380 kPa and retention times of 60-

Table 1 Elemental and Mineralogical Composition of Materials Processed

Sample	Assays(%)						
	Cu	Fe	S	As			
A	25.8	24.5	36.0	1.4			
B	27.1	24.9	33.9	1.5			
C	29.5	19.6	33.5	4.6			
Sample	Mineralogy(%)*						
	Cp	Bn	En	Tn	Cc	Cv	Py
A	22	6	5	1	13	5	38
B	49	10	6	2	-	4	20
C	38	7	20	2	-	5	18

* Cp: chalcopyrite, Bn: bornite, En: enargite, Tn: tennantite, Cc: chalcocite, Cv: covellite, Py: pyrite.

90 minutes yielded 98% copper extraction and 99% of the arsenic deporting to the residue solids.

Based on the excellent results achieved at the bench scale, the materials were processed through the copper pilot plant. The extensive operations took place over a five month period, operating on a 24 hour per day, 5 day per week schedule. In total, 4.8 tonnes of concentrate were processed at an overall availability of 91% with a cathode design rate of 35 kg/day. The copper pilot plant operated a fully integrated flowsheet and included all product streams and inventory management measures that would be incorporated in a full scale Cu-As CESL refinery.

One of the main objectives of the pilot campaign was to achieve high copper extraction from arsenic bearing minerals such as enargite while minimizing arsenic dissolution. Table 2 provides average extraction results for copper and arsenic during the demonstration phases of the campaign. Copper extraction results ranged from 97% to 98%, while arsenic extraction did not exceed 1%.

Table 2 Pilot Plant Metallurgical Results

Sample	Overall Extractions (%)		Autoclave Discharge Solution (g/L)	
	Cu	As	Cu	As
A	98	<1	43.0	<0.1
B	97	1	42.4	<0.1
C	97	<1	48.9	0.2

The copper in the leach liquor was recovered to LME Grade A cathode through standard SX-EW technology. The arsenic in the leach liquor was recycled through the SX raffinate stream back to the autoclave. There were minor entrained losses for both copper and arsenic in the final residue stream, but this was washed in a CCD circuit prior to being processed in the Gold Plant.

The department of metals through the process must be well understood and controlled, specifically when processing arsenic materials. The mineralogy and elemental composition of the residue from sample B is presented in Table 3. Results confirm that both enargite and tennantite

contained within the concentrate are effectively oxidized, while the arsenic deported to the residue as a ferric arsenate type product. Further mineralogical work is ongoing to characterize the residue.

Table 3 Elemental and Mineralogical Composition of Residue from Sample B Feed Material (as determined by MLA)

Assays (%)	
Cu	1.0
Fe	34.2
S	27.4
As	2.0
Mineralogy (%)*	
Cp	1
Bn	trace
En	trace
Tn	-
He-S	77
Fe-As	5
Py	5
Gangue	12

* Cp: chalcopyrite, Bn: bornite, En: enargite, Tn: tennantite, He-S: hematite and elemental S, Fe-As: Fe(III)-As species, Py: pyrite.

In addition to arsenic, several other smelter penalty elements were contained in the concentrates processed through the pilot plant. These elements included antimony, bismuth, mercury, and tellurium. The processing of such constituents showed near quantitative deportment to the residue stream, with no concentration increase detected across the concentrate leach.

3.2.2. Residue Stability

When considering the processing of a concentrate containing arsenic, the stability of the final plant residue must be assessed. A detailed residue stability program was developed with external consultants to assess residue stability through short and medium-term testing.

Short-term testing of the residue samples took place throughout the pilot plant campaign, with samples taken from the plant and subjected to the USEPA Toxicity Characteristic Leaching Procedure (TCLP). Of the 64 residue samples submitted for TCLP analysis, 34 resulted in an arsenic concentration in filtrate below the ICP-OES detection limit of 0.1 mg/L. Of the remaining 30 samples the average

concentration of arsenic detected was 0.15 mg/L with a standard deviation of 0.06 mg/L. All values fell well below TCLP limits for arsenic, which range from 2.5 to 5.0 mg/L depending upon jurisdiction.

Medium-term stability testing was conducted on each residue at an environmental laboratory. A test work program was developed where residues (at a liquid to solid mass ratio of 20) were subjected to a mild agitation leach over a range of pH values, potentials, and temperatures for a period of 8 weeks. During the test program the pH and potentials were either maintained at pre-defined targets to assess the intrinsic chemical behavior of the solid or allowed to drift in an effort to replicate residue storage conditions. Scheduled samples of the test filtrate were taken throughout the test period and analysed.

Reporting of the results of this test work is still ongoing with preliminary analysis of the data providing key conclusions. The tests with the most favourable performance resulted in arsenic concentrations of less than 0.1 mg/L from residues containing 6% arsenic. These results were achieved for all tests, regardless of starting pH, that were allowed to reach a natural equilibrium without pH or Eh adjustment during the testing. This has favourable implications for full scale applications as continuous pH control of a tailings impoundment would be difficult and costly. The arsenic content in the filtrate was detectable (0.1 to 0.6 mg/L As) for tests conducted at elevated temperatures and tests conducted at controlled reducing conditions. These results are preliminary and a full assessment of the test work, as well as characterization of the residues tested will be published upon completion.

The data shows a high degree of stability of the arsenic contained in the residues. This high-stability could be a result of the level of gypsum saturation present in the autoclave solutions which has been demonstrated to increase the stability of ferric arsenate type species [27].

3.2.3. Health & Safety

During the campaign there was a focus on controlling arsenic exposures, with an emphasis on data collection to effectively

address future questions from external stakeholders. In order to ensure that occupational exposure to arsenic was at a low level during pilot operations, personal monitoring of worker's air quality and monitoring of inorganic arsenic in the urine of selected workers was conducted. The air quality results during the campaign were all below the limit set by WorkSafe BC for exposure to arsenic during a 12-h shift of 0.005 mg/m³. All biological monitoring samples during the Cu-As campaign were also well below the action limit of 50 µg As/g creatinine. These samples were taken at the beginning and end of an operator's shift rotation (i.e. spanning a period of days while the individual was at work) to identify whether an increase in arsenic levels had occurred.

In addition to employee monitoring, the various residue samples from the plant were tested for bioaccessibility. These tests can be used to estimate the amount of the ingested substance that disassociates during transit through the gastrointestinal tract. These tests are of particular importance with arsenic as occupational or community exposure to inorganic arsenic residues in mining processes is typically low through intact skin absorption but can be high through incidental ingestion [28].

An outside lab was contracted to perform SBRC bioaccessibility testing on plant residue materials arising from the pilot work. In order to provide a point of reference, samples of arsenic-containing intermediate materials from a smelter were also assessed. Results of the bioaccessibility tests are summarized in Table 4 with both the arsenic grade and bioaccessibility of each sample provided. The tests show that the arsenic contained in each of the CESL pilot plant samples exhibit a very low level of bioaccessibility with values ranging from 0.8% to 2.1%. As anticipated, the smelter samples exhibited high bioaccessibility.

Table 4 Summary of Bioaccessibility Measurements

Description	Sample			Smelter	
	A	B	C	A	B
As grade (%)	2.0	2.0	6.4	13.6	28.8
Bioaccessible As (%)	2.1	0.8	1.1	10.3	100

A secondary objective of the program was to determine if a relationship could be established between measured levels of inorganic urine arsenic in workers and the inherent bioaccessibility of the materials encountered during the pilot campaign. As the biological samples all showed low levels, no such correlations could be made. To that end, bioaccessibility may still find value in evaluations of possible impacts on community health, for which the operational and exposure controls that benefit workers in an industrial setting are not present.

4. CASE STUDY

Northern Peru is home to several large copper-gold deposits, some of which contain significant amounts of arsenic. As such deposits are amenable to processing via CESL technology, a case study analysis was conducted to assess the feasibility of developing an arsenic containing copper-gold deposit in Northern Peru. The case study includes the mine, mill and CESL refinery costs associated with developing a project which would produce 200,000 t/a copper cathode, 64,700 oz/a gold and 1,295,000 oz/a silver. The mineralogy and elemental analysis of the concentrate assumed for the study is shown in Table 5.

Table 5 Case Study Concentrate Mineralogy and Elemental Analysis

Assays (%)							
Cu	Fe	S	As	Au	Ag		
27.4	22.5	30.6	1.5	3 g/t	60 g/t		
Mineralogy (%)*							
Cp	Bn	En	Tn	Cc	Cv	Py	Gangue
51	1.5	7	1	3	4	15	18

* Cp: chalcocopyrite, Bn: bornite, En: enargite, Tn: tennantite, Cc: chalcocite, Cv: covellite, Py: pyrite.

4.1 Economic Assessment

4.1.1 Operating Costs

The mine and mill operating costs were estimated at US\$ 0.966/lb Cu based on the Peru costs to concentrate cited by Brook Hunt in their Metals Cost League Reporting Tool [9]. The refinery operating costs were divided into labour, power, consumables and maintenance costs. The total refinery labour requirement was estimated to be 192 people and labour costs include shift

allowances, benefits and bonus allowances. The refinery power consumption was estimated based on power consumption factors for each major area of the refinery. The estimated annual power consumption for the refinery is 622,000,000 kWh. The annual refinery consumable costs were determined based on copper production and concentrate throughput factors which were verified by extensive data collected during pilot plant campaign test work. The maintenance costs were factored based on 2.5% of the installed mechanical and electrical equipment costs.

The operating costs were divided into fixed and variable components to accurately reflect the costs in the initial production years. The refinery operating costs are estimated at US\$ 21M/a plus a variable cost of US¢ 15/lb Cu Eq. The project operating costs are summarized in Table 6.

Table 6 Case Study Operating Cost Summary

Cost Element	US\$/a	\$/lb Cu Eq
Mine Mill Total	428	0.91
Labour	7.3	0.02
Power	34	0.08
Consumables	41	0.09
Maintenance	8.6	0.02
Refinery Total	91	0.21
TOTAL	519	1.10

4.1.2 Capital Costs

The mine and mill capital costs were estimated at US\$ 10,986/annual tonne Cu based on the in-construction Greenfield capital costs for projects cited in the Brook Hunt Copper Mine Cost Service Summary and Analysis [9]. The capital cost estimate for the CESL refinery was based on equipment sizing generated from a process heat and mass balance which utilized extensive data collected from numerous demonstration and pilot plant campaigns. The equipment costs were scaled using equipment specific design factors and similar sized equipment costs quoted in feasibility level studies completed for the CESL copper and gold technologies. All equipment costs in the benchmarked studies were estimated by independent third-party engineering consultants and all factoring was completed by CESL Limited

staff. The historic equipment costs were converted to 2011 costs using a GDP deflator factor.

The indirect refinery costs include EPCM, temporary construction facilities, camp and catering, third party engineering and field services, major spares, first fills, freight, operating manuals and training. A contingency of 10% was used on the refinery total direct and indirect costs. The project capital costs are summarized in Table 7.

Table 7 Case Study Capital Cost Summary

Cost Element	US\$M
Mine Mill Total	2,197
Site Preparation	5.3
Process and Utilities	380
Buildings and Facilities	40
Power Supply	25
Indirects	197
Owners Costs	25
Contingency	67
Refinery Total	740
TOTAL	2,937

4.1.3 Assumptions

The main assumptions underlying the economic analysis are a long-term copper price of US\$ 2.47/lb, a long-term silver price of US\$ 15/oz and a long-term gold price of US\$ 900/oz. The long-term metal price assumptions are from the Brook Hunt Copper Mine Cost Service Summary and

Analysis [9]. Net Present Values are discounted at 8% to Q1 of 2011. A mine, mill and refinery performance factor of 50% and 85% were assumed for year one and year two of the operations respectively. The mine and mill sustaining capital was estimated at 1% of the capital costs and the refinery sustaining capital was estimated at 2% of the capital costs.

4.1.4 Financial Results

Table 8 presents a summary of the operational information and Table 9 presents the valuation results for the case study.

A sensitivity analysis was completed for the case study. The results are presented in Figure 4.

The sensitivity analysis demonstrates that the project is most sensitive to changes in the copper price and that sensitivities to the capital and operating expenses are comparable.

The case study economic valuation results show that developing an arsenic containing copper-gold deposit can be economically feasible with today's long-term metal price assumptions. With a break-even copper price of approximately US\$ 1.81/lb, the economics associated with a project of this scale are robust enough to show a noteworthy positive return given the current market forecasts.

Table 8 Case Study Operational Valuation Results

Metal Production	Year 1	Year 2	Year 3
Copper (T)	100,000	170,000	200,000
Gold (oz)	32,300	55,000	64,700
Silver (oz)	647,000	1,100,000	1,294,000
Operating Costs (US\$M)	259	441	518
Sustaining Capital Costs (US\$M)	37	37	37
Pre Tax Cash Flow (US\$M)	299	535	636

Table 9 Case Study Economic Valuation Results

Financial Metric (Pre Tax)	Project
NPV (US\$M)	2,225
IRR (%)	17.2
Copper Break-Even Price (US\$/lb)	1.81

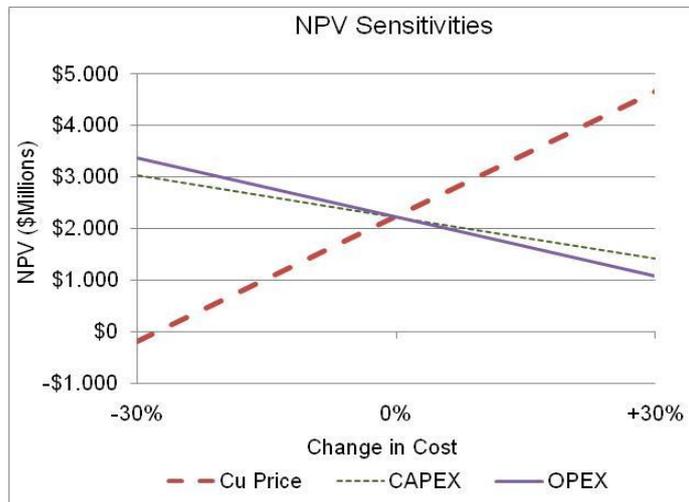


Figure 4 Case Study Sensitivity Analysis

4.2 Environment, Health, Safety & Community Aspects

The biggest challenges in developing the arsenic containing copper-gold deposit outlined in the case study are the safe management of the arsenic and the social support and acceptance of the public. A thorough and comprehensive social and environmental impact assessment (SEIA) is the fundamental basis required to sustainably develop, operate and close a mine-mill-refinery project of this nature in compliance with environmental regulations and social best practices. As the current best technical practices are assumed for the mine-mill component of the case study, only the aspects relating to the hydrometallurgical refinery are considered below.

4.2.1 Residue Management

The management of residues, in the context of the proposed case study, relate mainly to the handling of arsenic. The main focus lies in the transfer of arsenic into an environmentally acceptable and stable form. Furthermore it is desirable to use an integrated technical approach to effectively control the arsenic during metal beneficiation.

Under CESL process conditions, copper extraction and arsenic fixation occur within the autoclave vessel. No additional treatment for the solid residues is necessary besides washing with process water prior to disposal. Short-term TCLP stability test work indicates that the ferric arsenate containing residue is a non-hazardous waste stream. Initial results of ongoing test work have also demonstrated

high arsenic stability through a medium term test program and these results are consistent with data found in scientific publications that propose arsenic fixation as ferric arsenate as the most preferred disposal option [29]. For the proposed case study, a lined pond and long term monitoring of the residue was assumed as co-disposal with mill tailings cannot yet be proven as a viable option.

4.2.2 Air Quality

A general advantage of hydrometallurgical processes is the comparatively low impact on air quality. In the above case study the concentrate enters the CESL refining process as a slurry. The residues typically exhibit a moisture content of 25 - 30% when disposed. In total, no bulk handling or conveying of any dry particulate material occurs thereby preventing any dust emissions. Enclosure of the different process stages ensures that no fugitive gaseous emissions are released. The minimal vent flow from pressure oxidation, which is essentially steam, is scrubbed prior to discharge and emissions are distinctly below USEPA regulatory limits for particulate and acid mist. SO₂ or other gaseous emissions are not present in the CESL process.

Traffic due to transportation by truck can be significant in large mining operations, which often leads to high levels of exhaust emissions. Besides internal traffic, external transportation has an impact on air quality, especially for remote projects. For CESL technology concentrate and residue are conveyed as slurries in pipes. External transportation is reduced, since the product

of interest – the metal itself – is shipped in the purest form of cathodes.

A look at the indirect emissions shows that the proposed integrated hydrometallurgical approach is reasonably on par to average industrial standards in copper production. Internal Aurubis calculations on the basis of data published by Brook Hunt indicate over 32 smelter and refineries show an energy requirement varying from 7.5 to 25 GJ/t copper for producing Cu cathodes from concentrate with an average of 14.5 GJ/t. The CESL process is calculated at 11.2 GJ/t for the case study. In terms of carbon dioxide direct and indirect emissions, CESL produces 2.33 t CO₂/t Cu compared to a range of 1.0 to 2.5 t CO₂/t Cu for smelting and electrorefining with an average of 1.98 t CO₂/t Cu. For smelting it was assumed that 35% of the total consumption was in the form of natural gas and the remainder for electricity. The CESL process uses electrical energy only. Conversion factors used for calculating the CO₂ footprint are 0.208 t CO₂/GJ for electric energy consumption and 0.056 t CO₂/GJ for natural gas consumption. Concentrate transportation to a smelter was not taken into account when assessing either energy consumption or carbon dioxide emissions.

4.2.3 Water Use & Emissions

The CESL process consists of several internal recirculation loops to maximize the reuse of aqueous solutions, which in return minimizes effluent flow. The concept of balancing the process inventory includes the recirculation of water to lower the impacts on natural resources. Both the demand and effluent flows are reduced through the application of an evaporator. The plant also recycles pond effluents and utilizes a treatment plant to assure operability in accordance with environmental regulations.

The net water demand for the CESL process is approximately 5 - 10 t/t of copper cathode, which compares well to the traditional copper market standards of 8.4 t/t of copper [30]. It is also important to note that the CESL process is capable of utilizing input water of lower quality, such as seawater, thereby preserving natural pristine water resources.

4.2.4 Health & Safety

Work safety in base metal refining is a big responsibility, especially when elevated levels of arsenic are present. As a result, a monitoring program was implemented during recent pilot plant operations to measure the level of occupational exposure. The results obtained reflect the intrinsic advantages of hydrometallurgical processes: the absence of dusty materials and enclosed process equipment greatly reduce the contact between hazardous components and both employees and the public. This aspect is also reflected in the shipping of non-hazardous cathodes compared to concentrate from mine-only operations. Consequently, the low public exposure to operational emissions and those resulting from residues is a key advantage of the proposed integrated approach.

4.2.5 Community Social Responsibilities & Potentials

In general, socially-responsible practices play a decisive role in developing large scale mining projects. Only a mutual understanding between the project developer and the public can guarantee a mutually beneficial relationship throughout the life of the project. A great number of sustainable opportunities can grow from the basis of a good relationship between a community and an industrial project. Depending on project and community constraints, high potential is seen in developing subsequent processing sectors to further follow the value added chain of copper products. The benefit would immediately be felt in the community as the project developer would provide infrastructure necessary as part of the project. As a result of such local developments, a general increase of economic activities is not only expected in the near vicinity of the project site, but also in the rapidly increasing Peruvian copper market. This would consequently lead to further direct benefits in the form of an increased level of employment, income, education and overall quality of life. Peru would also benefit from additional tax revenues generated from mine to metal processing compared to conventional mining and shipping of concentrate.

Overall, the policies and guidelines of both Teck and Aurubis fully support the strengthening of sustainable development

by setting new environmental standards in complex ore refinement. The key element for this basis is the introduction of a novel integrated low-emission mine-to-metal process based on the CESL Cu-Au technology.

5. CONCLUSIONS

With copper demand forecast to rise in the coming decade, the development of projects with complex mineralogy or impurity challenges is necessary to meet demand. Arsenic challenged copper deposits located in South America have the potential to address this shortfall in supply. Teck and Aurubis have formed a partnership to pursue the development of such deposits through the application of the CESL Cu-As technology.

The technical program completed in 2010 by Teck and Aurubis has served to advance this initiative in several key ways:

- Metallurgy: The pilot plant achieved high copper extraction (98%) from concentrates containing significant enargite with near quantitative arsenic deportment to the plant residue. Copper recovery was high and LME Grade A cathode was produced.
- Economics: A case study conducted on a theoretical 200,000 t/a Cu project in Northern Peru showed a favourable NPV of US\$ 2.2 billion and an IRR of 17.2%.
- Environment: Results of TCLP testing show the arsenic containing residue from the CESL process to be quite stable. Longer term stability testing is currently underway and initial results show excellent performance under a variety of simulated residue storage conditions.
- Safety: Worker exposure to arsenic as measured by air quality measurement and inorganic arsenic in urine samples was maintained at very low levels during the pilot plant campaign. Bioaccessibility test work results also support that the arsenic contained in the CESL residues does not readily leach under conditions simulating the human digestive system.

The implementation of CESL Cu-As technology through a sustainable mine-to-metal approach is an attractive option for the processing of arsenic challenged copper concentrates. This is based on excellent metallurgical performance, robust project economics, and sound environmental and safety performance.

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Teck – Aurubis: Un enfoque integrado desde la mina hasta el metal para desarrollar depósitos de cobre con alto contenido de arsénico usando el proceso CESL

Teck – Aurubis: An integrated mine to metal approach to develop high arsenic copper deposits using the CESL process

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