Gestión y Economía Minera Ltda.

PERSPECTIVE N°13

FEEDING OPTIMIZATION OF PROCESSING PLANT: DIFFERENT STRATEGIES FOR ARSENIC MITIGATION

MAXIMIZING VALUE IN MINING

This 2016 maximize the value of your operation or project with the innovative solutions of GEM, the mining industry's leading consulting company.

EVALUATION

STRATEGY

ECONOMICS

OPTIMIZATION

TRAINING

R&D

TABLE OF CONTENTS

DISCLAIMER

This document has been published by GEM|Gestión y Economía Minera Ltda. under the understanding that its responsibility is limited to give a professional and independent opinion. Although its preparation has involved reasonable dedication and care, GEM does not guarantee the accuracy of the data set, assumptions, predictions and other asseverations. If the reader uses this document or its information to obtain resources or making decisions that involve other companies, GEM does not accept any responsibility against third parties, no matter its origin and without limitations.

This service has been delivered under the controls established by a Quality Management System approved by Bureau Veritas Certification according to ISO 9001. Certificate number: 8309

CONTACT INFORMATION

WEBSITE: *www.gem-ing.cl*

PHONE: *+ 56 2 2225 30 21*

PLEASE SEND YOUR COMMENTS TO THIS ARTICLE TO

EMAIL: *contacto@gem-ing.cl*

FEEDING OPTIMIZATION OF PROCESSING PLANT: DIFFERENT STRATEGIES OF ARSENIC MITIGATION

Valentina Chico, Christian Lichtin
GEM I Gestión y Economía Minera Ltda.

ARSENIC IN COPPER CONCENTRATES

The main product of flotation process is copper concentrate. Broadly speaking, this process aims to increase the copper concentration, usually about 30 times, in order to make the subsequent smelting process more efficient. Not only copper is recovered when producing concentrates, but also elements that generate additional profits, such as molybdenum, gold and silver (this obviously depending of the ore fed). However, besides the beneficial elements concentrated there are some impurities in the concentrate that affect performance downstream. Arsenic is one of them, and at high concentrations (generally greater than 0.5% in the concentrate) generates major challenges to operations because of its toxicity. Due to higher environmental requirements, smelters have begun to place further restrictions on concentrates with high arsenic content. As a matter of fact, in 2015 Zambia began to get rid of concentrates from Chile for its high content of arsenic (Minería Chilena, 2015), which shows how important it is for high arsenic mines to plan their productions taking into account restrictions coming from arsenic levels in concentrates.

Not all sulphide minerals have arsenic, and therefore, companies with deposits with low or zero levels of arsenic do not required to assess the impact of this impurity into their planning. These companies will aim to produce as much copper, and as soon as possible (considering relatively flat prices vectors because when consider increasing vectors the strategy might change). Nevertheless, deposits with high levels of arsenic must find ways to mitigate the arsenic's impact on the concentrate to be sold and/or processed.

> *Due to higher environmental requirements, smelters have begun to place further restrictions on concentrates with high arsenic content.*

The objective of this Perspective is to diagnose a possible future vulnerability of Chilean concentrates regarding environmental requirements, analyzing how Chilean copper exports have grown on concentrate, indicating a future trend. In order to show how mines could deal with these new requirements, some specific actions seeking to mitigate the impact caused by arsenic are then reviewed. Although the diagnosis of the vulnerability of the concentrate market is based on the Chilean industry, the mechanisms mentioned to mitigate the impact are valid in any country. Subsequently, through an example of optimization, the impact of adding new constraints associated with arsenic emissions is developed, and where, as result of the optimization, the feeding strategy of a concentrator or cast significantly changes respect the case without restrictions.

CHILEAN COPPER CONCENTRATE EXPORTS EVOLUTION

While much of the concentrate exported by Chile does not contain high levels of arsenic, there are some mines currently facing this problem or at least there are some signals that it will be a problem in the near future. The most important examples are two Codelco mines: Chuquicamata and Ministro Hales. However, the trend Chile shows is precisely an increase of copper production in the form of concentrate instead of SX-EW cathodes or anodes, possibly generating future vulnerability due to the extreme dependence of smelters. Additionally, if new local or international environmental requirements were implemented, the impact of arsenic in Chile would be even greater in the upcoming years.

FIGURE 1 shows the breakdown of Chilean copper production depending on the processing. It is important to note that since 2010 the mine copper production via concentrates has increased, going from 61% in that year to 69% by 2015. That proportion is expected to continue to increase. The main reason behind that is the depletion of economically viable leachable resources based on current technologies.

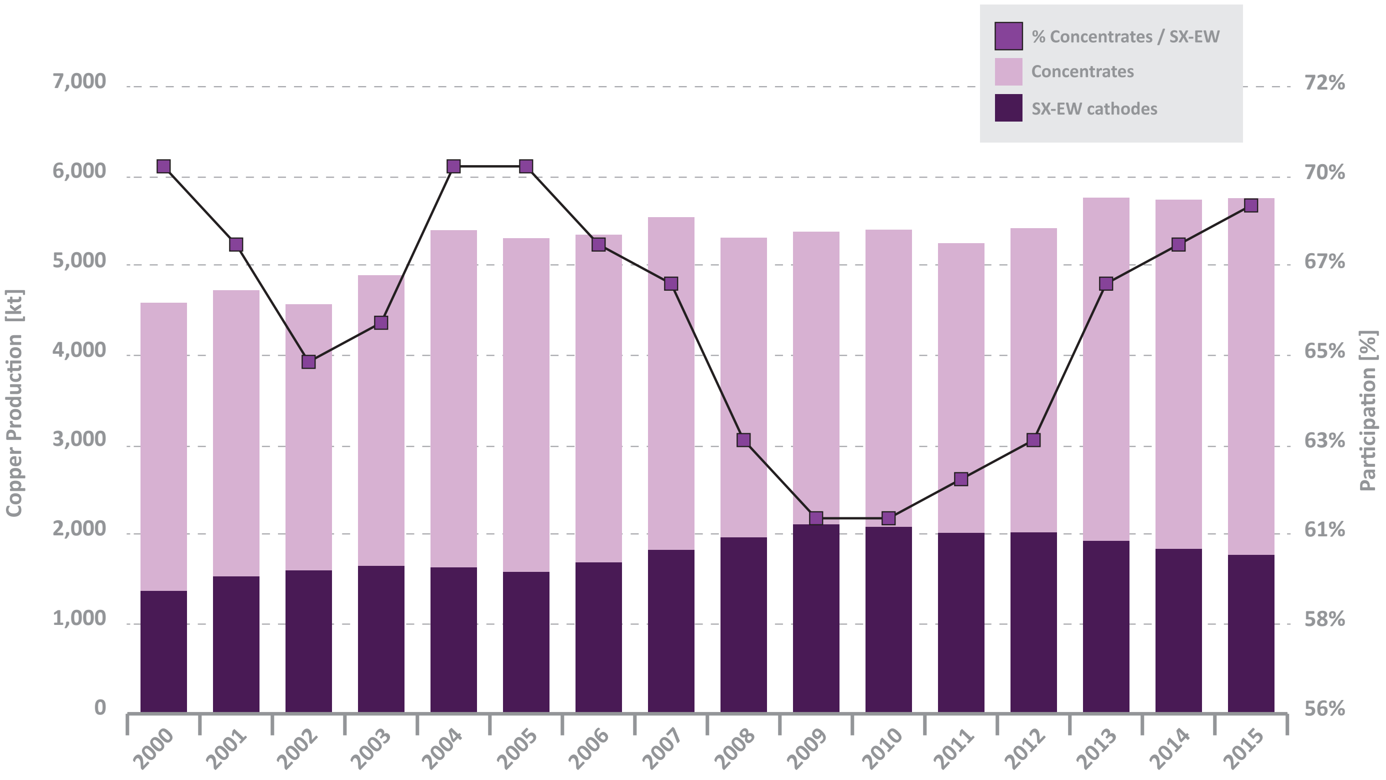
FIGURE 2 illustrates that in 2015 almost half of Chilean copper exports were sold in concentrate form. The increase in the share of exports via concentrate shows a similar behavior than the participation of concentrate in Chilean production since 2010, showed in ***FIGURE 1***. Concentrate export participation grew from 34% in 2010 to 47% in 2015, showing signs that additional copper production, over that period, has been exported as concentrate.

The production of Chuquicamata and Ministro Hales accounted for almost 10% of Chilean copper production in 2015. This production is not sold as concentrate but in the form of cathodes produced by Chuquicamata smelter, in part enabling the commercialization of copper that would otherwise be difficult to sell in the form of concentrate due to its high arsenic content. However, the current installed smelting capacity in Chile has no margin to increase its cathode production, and therefore, the only way to increase copper exports or just to maintain it is through the export of concentrates. This is exhibited when comparing the behavior since 2010 in ***FIGURE 1*** and ***FIGURE 2***.

How much of the Chilean production of concentrate in the future will be penalized for content of impurities is beyond the scope of this Perspective. The objective is rather to show that the increase in the participation of concentrate in the Chilean exports might increase its exposure to eventual environmental constraints, such as arsenic, and then present what measures mines could take to face and mitigate the impact of this impurity in its economic indicators.

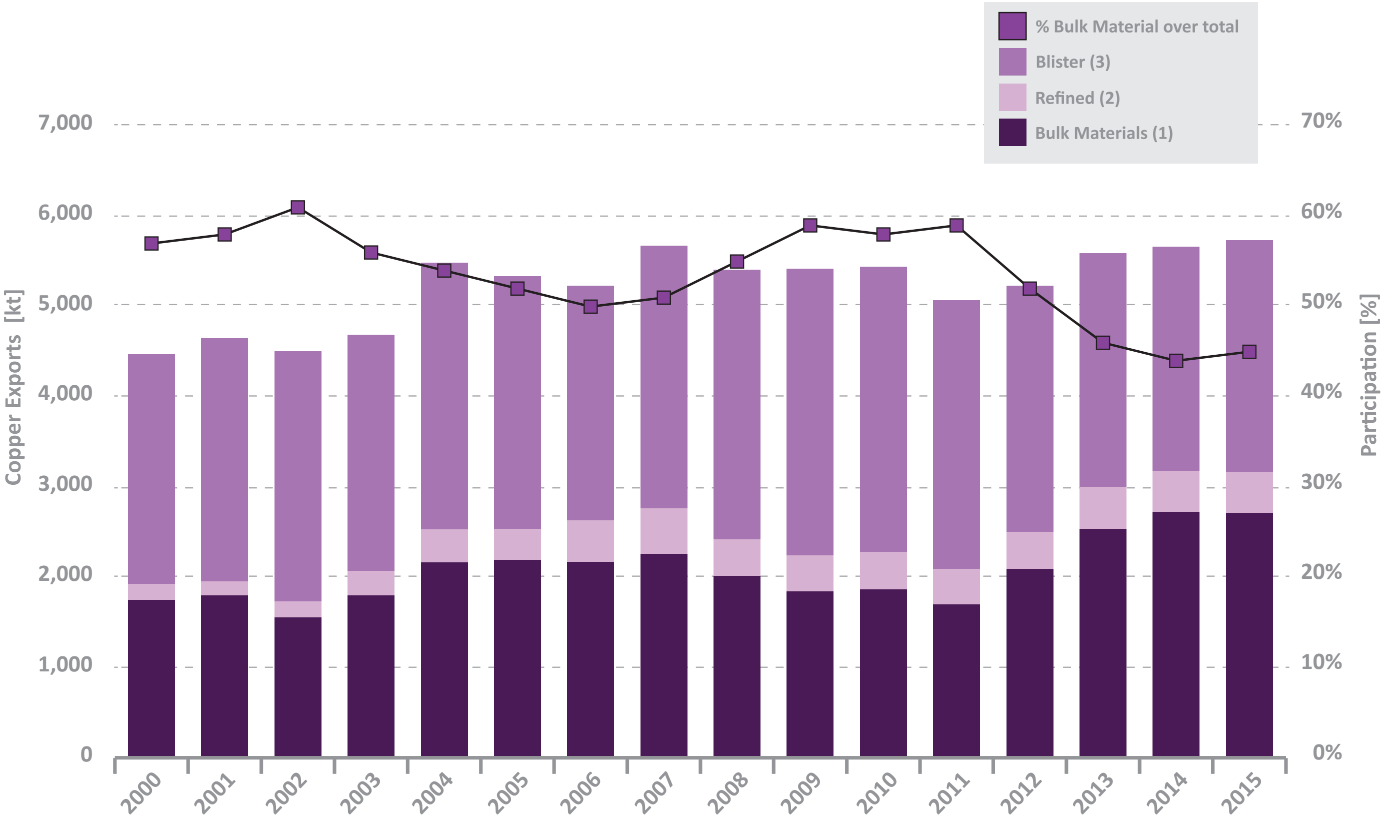
Before continuing with the objectives describe above, it is important to stop and review relevant aspects of arsenic in order to understand this impurity.

FIGURE 1. COPPER PRODUCTION EVOLUTION GIVEN THE PROCESSING LINE



Source: Cochilco

FIGURE 2. CHILEAN COPPER EXPORTS BREAKDOWN



(1) Includes cements, concentrates, and secondary copper
(2) Includes blister copper and copper anodes
(3) Includes cathodes, semis, and fire-refined

Source: Cochilco

ARSENIC: PRODUCTION, CONSUMPTION AND EFFECTS

Arsenic is a metalloid that exists naturally in the earth's crust, being the 20th most abundant element in it. Arsenic is commonly associated with mineral deposits containing sulphides such as copper, nickel, lead and cobalt among others (Mandal & Suzuki, 2002).

Sources of arsenic in the environment have an anthropogenic or natural origin. The first group includes mainly mining, metal smelting and coal burning, where these are responsible for 60% of emissions of arsenic. Environmental arsenic is also generated by natural processes of chemical and physical weathering, biological activities and volcanic emissions (Martin et al., 2014). During the processes of metals production, particularly for copper, emissions to the environment of arsenic are mainly due to gas emissions during the smelting stage.

The copper production process of sulphide deposits starts from exploitation at the mine, crushing and grinding to the flotation, where copper concentrate is obtained. In copper deposits, arsenic is usually found in hydrothermal veins as tennantite ($Cu_{12}As_4S_{13}$) or enargite (Cu_3AsS_4). These materials contain a high percentage of copper (51.6% and 48.4%, respectively), so they tend to float in a similar manner to other copper sulfides increasing the levels of arsenic in the concentrate.

Subsequently, the copper concentrate goes to a roaster and then a smelter, where most of the arsenic is volatilized and concentrate reaching up to a 95% of purity from arsenic. The combustion powders produced by smelting contain arsenic trioxide (As_2O_3), which can be treated and then marketed. Arsenic trioxide is mainly used in the production of preservatives for wood, and other arsenic compounds are widely used because of its toxicity in fertilizer, herbicides and insecticides. The biggest producers of arsenic trioxide is China (25,000 t), followed by Chile and Morocco with 10,000 t and 8,800 t in 2014, respectively (U.S. Geological Survey, 2015 and 2016).

The exposure to sources of arsenic is hazardous to health because there is evidence that proves it is carcinogen, being specially associated to lung cancer. Due to this and to environmental regulations, smelters have raised their restrictions on the concentrates they buy imposing financial penalties if the products exceed their permitted arsenic limits.

> *During the processes of metals production, particularly for copper, emissions to the environment of arsenic are mainly due to gas emissions during the smelting stage.*

ARSENIC LEVES IN COPPER CONCENTRATES AND MECHANISMS TO MITIGATE THE IMPACT

As mentioned above, the presence of arsenic in copper deposits is mainly in the form of tennantite and enargite, generating copper concentrate that could have important amounts of arsenic, reaching even 4% or more. Smelters are subject to environmental restrictions due to arsenic emissions released into the atmosphere, conditioning the mixture of products that feeds them. ***TABLE 1*** shows the Chilean regulation limits for some of the main Chilean smelters.

Within the Artículo N°8 del D.S. N°28/2013 (article of Chilean law) it is stated that for new emission sources, during each calendar year the amount of arsenic that can be released into the environment must be no more than 2% of the arsenic entering the emission source.

TABLE 1. MAXIMUM LIMITS PERMITTED FOR CHILEAN EMISSION SOURCES

EMISSION SOURCE	As [t/ayear]
Altonorte	126
Caletones	130
Chagres	35
Chuquicamata	476
Hernán Videla Lira	17
Potrerillos	157
Ventanas	48

Source: D.S. N° 28/2013

Although these regulations vary among countries, penalties are imposed for the purchase of high-grade arsenic concentrate, or "dirty concentrate", because of environmental restrictions. Therefore, demand for dirty concentrate could be penalized and even limited, precluding the sale of dirty concentrate.

The general practice in the industry of copper smelters is that copper concentrate with less than 0.2% of arsenic is sold without any penalties. Concentrates with higher arsenic grade are affected by incremental penalties. Finally, those concentrates with over 0.5% of arsenic are normally rejected (Haque et al., 2012). In some cases, smelters cannot process concentrate with higher contents of arsenic, as the Chilean concentrates rejected by Zambia during 2015.

Because of this, to regulate arsenic levels is important when concentrate is obtained, otherwise, emissions of arsenic must be subsequently managed by other methods to meet environmental regulations. To do this, different methods have been studied and experimented with.

One method currently used is the usage of roasters before the smelting process, which volatilizes the arsenic present in the concentrate. This method has been used in Ireland, with tennantite concentrates containing levels up to 4.7% arsenic, and Chile at mines El Indio and Ministro Hales. Despite being a proven model that lowers the level of arsenic, it does not necessarily solve all the problems of toxic emissions associated with the separation process of the elements (Long et al., 2012).

Another method is the mineral selective flotation, which is carried out after the traditional concentration. This floating seeks to separate the compounds with arsenic (tennantite or enargite) from the rest of the concentrate, generating two products, a concentrate with high arsenic content and low copper grade, and another with higher copper concentration and low arsenic. Studies in bodies of copper and gold in Northparkes state that concentrate of 61% of copper with less than 2% of arsenic can be recovered from concentrates with high arsenic concentration (Smith & Bruckard, 2007). The experimental study performed with a concentrate coming from Collahuasi showed that arsenic from a dirty concentrate can be extracted, producing an even more arsenic concentrated product with an arsenic recovery of almost 72% and 26% of copper recovery, with a weight recovery of 21% (Mendez, 2009).

The selective flotation process has been tested experimentally, but in order to consider it in a real production process, it would require more studies and research. Initially, a review of the own ore mineralogy to determine the characteristics of the selective flotation as well as establishing the necessary modules for it correct implementation in the production process (Long et al., 2012). Similarly, the selective flotation has proven to be a cost-effective alternative, especially if there are restrictions on selling dirty concentrate (Haque et al., 2012).

Another method for extracting arsenic from concentrates consists in precipitating the arsenic by oxidation under pressure in an autoclave. The extraction of arsenic requires a complete procedure to manage and treat the arsenic precipitated. The CESL process corresponds to a hydrometallurgical method experimentally tested in pilot plants generating cathodes from concentrate with high amount of impurities (Bruce et al., 2011).

> *The goal is to optimize the process not only in terms of produced copper, but also considering other elements that directly affect the income of the company such as arsenic.*

In addition to decreasing the level of arsenic in their products by separation methods or by reduce the emissions casting produces, it is important to regulate the levels of arsenic coming into the plant before obtaining the concentrate. This can be done by mixing minerals with different properties (different concentrations of arsenic and copper in this case). For example, ore coming from different mine sectors can be combined in order to produce concentrate with acceptable levels of arsenic. The goal is to optimize the process not only in terms of produced copper, but also considering other elements that directly affect the income of the company such as arsenic.

EXAMPLE: FEEDING STRATEGY OPTIMIZATION CONSIDERING ARSENIC CONSTRAINTS

The previous section concluded by mentioning that one way to mitigate the impact of high concentrations of arsenic in the concentrate produced is changing the concentrator feeding sequence. The example that is going to be presented consists in analyzing how the feeding strategy can change when considering additional restrictions to the problem of value maximization. In these cases, the goal is no longer just to process higher ore grade as soon as possible, but also to maximize the concentrate sold without penalties. One way to achieve this is to optimize the plant feeding strategy, maintain the average grade of arsenic under certain thresholds, minimizing penalties. This is precisely what the example presented below seeks to illustrate.

EXAMPLE CHARACTERIZATION

The example considers a period of 20 years, with the plant being fed with three different mineral sources. These sources might be different sectors of the mine or even minerals coming from various mines. Each of these sources has associated cooper and arsenic grade profiles. ***TABLE 2*** shows the details of three possible mine extractions going to be procced in the plant. Extraction 1, Extraction 2 and Extraction 3 could feed the plant and each of them has an associated tonnage and grade of copper and arsenic. It is noteworthy to say that that these flows are not necessarily sent directly to the plant, since they can be accumulated in a stockpile.

Furthermore, the concentrator's yearly capacity is 30,000 kt, meaning that in each period there is material that should be sent to certain stocks. The aim of the example is to compare three different plant feeding strategies, both considering and not considering restrictions on arsenic. As presented in the table above, Extraction 1 has an increasing grade of arsenic. On its part, Extraction 2 presents a constant arsenic grade and the same copper grade of Extraction 1. Finally, Extraction 3 has no arsenic, and has a copper grade higher than the others. If there were no environmental restrictions, Extraction 3 would have priority over the others since it maximizes the produced copper (it is assumed that the recovery of copper and arsenic is constant for all periods). However, what happens if additional restrictions are incorporated? To answer this question, three different feeding strategies were defined

TABLE 2. MINE EXTRACTION DETAILS

	EXTRACTION								
	1			2			3		
PERIODS (YEARS)	Tonnage [kts]	Cu grade [%]	As grade [%]	Tonnage [kts]	Cu grade [%]	As grade [%]	Tonnage [kts]	Cu grade [%]	As grade [%]
1	15,000	0.72	0.01	15,000	0.72	0.18	10,000	0.82	0.00
2	15,000	0.72	0.02	15,000	0.72	0.18	10,000	0.82	0.00
3	15,000	0.72	0.03	15,000	0.72	0.18	10,000	0.82	0.00
4	15,000	0.72	0.04	15,000	0.72	0.18	10,000	0.82	0.00
5	15,000	0.72	0.05	15,000	0.72	0.18	10,000	0.82	0.00
6	15,000	0.72	0.06	15,000	0.72	0.18	10,000	0.82	0.00
7	15,000	0.72	0.07	15,000	0.72	0.18	10,000	0.82	0.00
8	15,000	0.72	0.08	15,000	0.72	0.18	10,000	0.82	0.00
9	15,000	0.72	0.09	15,000	0.72	0.18	10,000	0.82	0.00
10	15,000	0.72	0.10	15,000	0.72	0.18	10,000	0.82	0.00
11	15,000	0.72	0.11	15,000	0.72	0.18	10,000	0.82	0.00
12	15,000	0.72	0.12	15,000	0.72	0.18	10,000	0.82	0.00
13	15,000	0.72	0.13	15,000	0.72	0.18	10,000	0.82	0.00
14	15,000	0.72	0.14	15,000	0.72	0.18	10,000	0.82	0.00
15	15,000	0.72	0.15	15,000	0.72	0.18	10,000	0.82	0.00
16	15,000	0.72	0.16	15,000	0.72	0.18	10,000	0.82	0.00
17	15,000	0.72	0.17	15,000	0.72	0.18	10,000	0.82	0.00
18	15,000	0.72	0.18	15,000	0.72	0.18	10,000	0.82	0.00
19	15,000	0.72	0.19	15,000	0.72	0.18	10,000	0.82	0.00
20	15,000	0.72	0.20	15,000	0.72	0.18	10,000	0.82	0.00

and presented in the following tables, which have some initial stock. In this case, Feeding *i* will be referenced to the mineral that is sent directly to plant from the Extraction *i* or from Stock *i.*

From ***TABLES 3, 4*** and ***5*** is possible to say that Strategy 1 consists in feeding the plant with major proportion of Feeding 3, in order to maximize the fine copper produced in the early years. Strategy 2 consists on feeding the plant with equal proportion of all feedings (the percentages are not 33% each because extractions are different). Finally, Strategy 3 corresponds to the optimization of the problem, considering that concentrate over certain thresholds has penalties. Such optimization was performed using a model, which keeps the properties of flows of certain period regardless of the time they are processed. For example, if feeding the plant by Feeding 3 was postponed, which is the one with lower levels of arsenic and higher copper grades, these grades would be kept in stock and will be available for processing later when the grade of arsenic in concentrate is greater than allowed. Simply taking, and despite the delay of processing best grades at the beginning, Feeding 3 might be used to dilute the arsenic grade in the concentrate, creating more concentrated that can be sold.

In order to show the conditions under which each Strategy is better, two analyses were performed. The first is to review under what levels of Feeding 3 cooper grades, the

TABLE 3. FEEDING STRATEGY 1

PERIODS (YEARS)	1-3	4-6	7-9	10-12	13-15	16-20
Feeding 1	30%	30%	30%	33%	38%	38%
Feeding 2	30%	30%	30%	33%	38%	38%
Feeding 3	40%	40%	40%	34%	24%	24%

TABLE 4. FEEDING STRATEGY 2

PERIODS (YEARS)	1-3	4-6	7-9	10-12	13-15	16-20
Feeding 1	38%	38%	38%	38%	38%	38%
Feeding 2	38%	38%	38%	38%	38%	38%
Feeding 3	24%	24%	24%	24%	24%	24%

TABLE 5. FEEDING STRATEGY 3

PERIODS (YEARS)	1-3	4-6	7-9	10-12	13-15	16-20
Feeding 1	50%	50%	51%	55%	52%	45%
Feeding 2	41%	32%	25%	5%	2%	4%
Feeding 3	9%	18%	24%	40%	46%	51%

Strategy 3 is the optimal one. Subsequently, an additional variable was added to the analysis, the Feeding 2 arsenic grade, to estimate under which scenarios of both Feeding 3 copper grade and Feeding 2 arsenic grade, each feeding strategy is optimal.

TABLE 6 shows the present value of income discounting penalties of each strategy by varying the copper grade of Feeding 3, which has the highest original copper grade. This in order to estimate up to what extent it is desirable to delay the copper production by processing the highest grade feeding first in order to dilute the arsenic in later years. Regarding penalties, it is assumed a stepped discount according to the arsenic considered in concentrate. Concentrate with grades lower than 0.5% is not subject to penalties. Between 0.5-1.5% the penalty is 10% of the sales value, from 1.5-2% of 15%, from 2-3% of 20% and a concentrate with arsenic grades higher than 3% arsenic cannot be sold.

FIGURE 3 shows the arsenic grade profiles in the concentrate according to the feeding strategy. It is noted that from year 10, Strategy 2 stops producing salable concentrate. In turn, from 2013 onwards Strategy 1 also fails to produce salable concentrate. On the contrary, during all the period of analysis Strategy 3 produces salable concentrate, although during the first 10 years it presents higher penalties than Strategy 2.

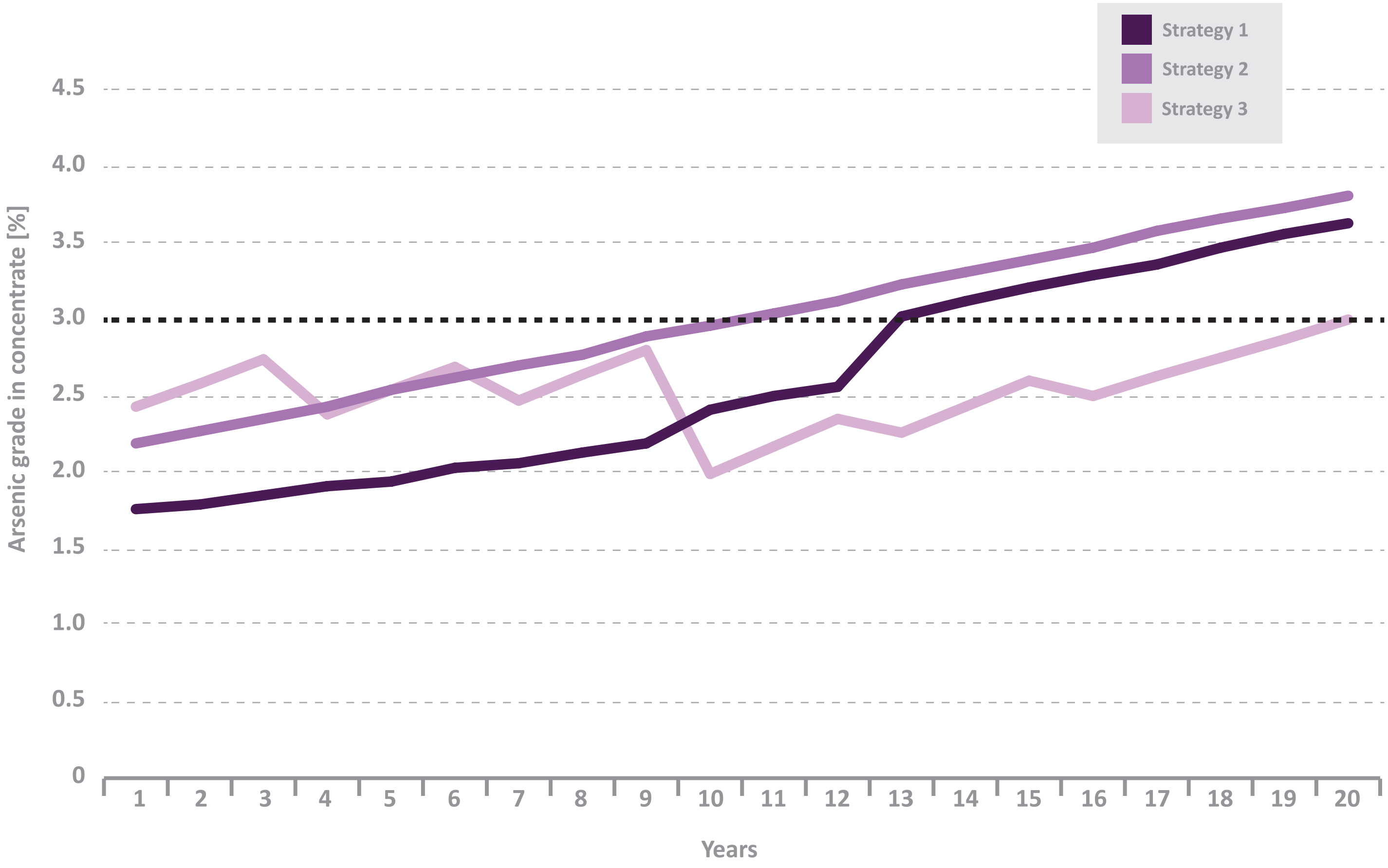
In this example it is possible to conclude that Strategy 1, which consists on feeding with higher copper grades earlier, is consistently better than the other two in a scenario without restriction over arsenic. The conclusion changes

TABLE 6. DISCOUNTED NET INCOMES AMONG STRATEGIES GIVEN CERTAIN FEEDING 3 COPPER GRADES

STRATEGY	WITHOUT ENVIROMENTAL RESTRICTION [MUS$]			WITH ENVIROMENTAL RESTRICTION [MUS$]		
FEEDING 3 COPPER GRADE [%]	Strategy 1	Strategy 2	Strategy 3	Strategy 1	Strategy 2	Strategy 3
0.60	11,543	**11,768**	11,729	7,910	7,215	**10,556**
0.65	11,848	**11,981**	11,958	8,139	7,345	**10,762**
0.70	12,153	**12,193**	12,186	8,369	7,475	**10,968**
0.75	**12,458**	12,406	12,415	8,599	7,606	**11,174**
0.82	**12,913**	12,723	12,756	8,941	7,800	**11,481**
0.85	**13,068**	12,832	12,873	9,058	7,867	**11,585**
0.90	**13,373**	13,045	13,102	9,288	7,997	**11,791**
1.00	**13,983**	13,470	13,559	9,747	8,258	**12,203**
1.10	**14,593**	13,896	14,017	10,206	8,519	**12,615**
1.15	**14,898**	14,108	14,245	10,436	8,649	**12,821**
2.50	--	--	--	16,635	12,172	**18.380**
5.00	--	--	--	28,116	18,694	**28,675**
7.00	--	--	--	**37,300**	23,912	36,911

Note: The best strategy in terms of discounted net income is marked in bold. Regarding the Unconstrained scenario, cases considering copper grades higher than 1.15% were not analyzed because it is clear that Strategy 3 is always superior and because grades higher that such level are impossible to find.

FIGURE 3. CONCENTRATE ARSENIC GRADE EVOLUTION GIVEN CERTAIN FEEDING STRATEGY



when considering environmental constraints, where unless the copper grade of Feeding 3 is lower than 7% (a specific situation) Strategy 3 is optimal.

Regardless of the numbers shown in the example, the relevant thing is to sensitize the results, and calculate certain rules that support the operation of the concentrator. In this case, it was possible to determine a threshold which determines what percentages for each feeding generate greater profits.

It is also possible, as a second analysis, to sensitize the decision-making not only for Feeding 3 copper grade, but also for the arsenic contained in Feeding 2. In this case, a pair of points was calculated, consisting in copper and arsenic grade, where certain strategy turns out to be better than the others, creating planes of optimal strategies. This analysis is reflected in ***TABLE 7***, which shows the optimal strategy according to the copper grade of Feeding 3 and the arsenic one of Feeding 2.

Based on ***TABLE 7***, it could be determined that sending a major proportion of higher copper grade and lower arsenic ore earlier is optimal if the Feeding 2 arsenic grade is lower than 0.10%. If the arsenic grade of Feeding 2 is greater than 0.15%, processing higher copper grade at first is not longer the optimal decision, because ore with low arsenic content is consumed during the first years, therefore not available for diluting the arsenic grade of future concentrates.

> *Processing higher copper grade at first is not longer the optimal decision.*

TABLE 7. OPTIMUM FEEDING STRATEGY GIVEN CERTAIN FEEDING 3 COPPER GRADES AND FEEDING 2 ARSENIC GRADES

	ARSENIC GRADE [%]	0.00	0.05	0.10	0.15	0.20
COPPER GRADE [%]	0.6	Str 1	Str 1	Str 1	Str 3	Str 3
	0.7	Str 1	Str 1	Str 1	Str 3	Str 3
	0.8	Str 1	Str 1	Str 1	Str 3	Str 3
	0.9	Str 1	Str 1	Str 1	Str 3	Str 3
	1.0	Str 1	Str 1	Str 1	Str 3	Str 3
	1.1	Str 1	Str 1	Str 2	Str 3	Str 3
	1.2	Str 2	Str 1	Str 2	Str 3	Str 3

As in the previous analysis, beyond the threshold found, it is important to optimize deriving decision rules that allow making optimal decisions as ore grades are observed or when some certainty of how these will evolve exists. This example does not consider the price or costs, which also have an important role to play when it comes to establishing the best strategy based on the determination of thresholds to guide the decision-making process.

CONCLUSIONS

Emissions of arsenic produced by copper obtainment is a relevant issue for smelters because of the environmental implications associated to them. Moreover, due to the increase of fine copper produced through concentration, it is becoming more important for mining companies and smelters to keep in mind what mechanisms can be undertaken to avoid suffering penalties for their concentrate, or the simple fact that they cannot sell the concentrate to the market. This Perspective revised some of the alternatives, and showed through a simple example how feeding strategies can change when considering environmental constraints at the moment of planning. Beyond the values presented, the main idea is to promote the generation of decision rules seeking to improve plants or smelters management, modifying upstream processes in order to get better results. In this case, and considering some arsenic restrictions, it was shown that the optimal solution is not to supply the plant with the best copper grades at first, but to maintain the arsenic grade in concentrates under certain levels, thus maximizing concentrate produced under minimal levels of penalties.

REFERENCES

- Bruce, R., Mayhew, K., Mean, R., Kadereit, H., Nagy, A. and Wagner, O., 2011. Unlocking Value In Copper Arsenic Sulphide Resources With The Copper–Arsenic CESL Technology. *En Hydro-copper Conference Proceeding.*
- D.S. N° 28/2013. Diario Oficial de la República de Chile, Santiago, Chile, 12 de diciembre de 2013.
- Haque, N., Bruckard, W. and Cuevas, J., 2012. A techno-economic comparison of pyrometallurgical and hydrometallurgical options for treating high-arsenic copper concentrates. *XXVI International Mineral Processing Congress, New Delhi, India.*
- Long, G., Peng, Y. and Bradshaw, D., 2012. A review of copper–arsenic mineral removal from copper concentrates. *Minerals Engineering, 36,* pp.179-186.

- Mandal, B.K. and Suzuki, K.T., 2002. Arsenic around the world: a review. *Talanta, 58*(1), pp.201-235.
- Martin, R., Dowling, K., Pearce, D., Sillitoe, J. and Florentine, S., 2014. Health effects associated with inhalation of airborne arsenic arising from mining operations. *Geosciences, 4*(3), pp.128-175.
- Méndez Muñoz, E.G., 2009. Flotación Selectiva de Enargita desde un Concentrado Final de Sulfuros de Cobre de Collahuasi. Disponible en http://repositorio.uchile.cl/tesis/ uchile/2009/mendez_e/sources/mendez_e.pdf
- Minería Chilena, 2015. Zambia ordena desechar cobre que importó de Chile por niveles de arsénico. Revista Minería Chilena. Revisado en http://www.mch.cl/2015/09/14/zambia-ordena-desechar-cobre-que-importo-de-chile-por-contener-altos-niveles-de-arsenico/
- Smith, L.K. and Bruckard, W.J., 2007. The separation of arsenic from copper in a Northparkes copper–gold ore using controlled-potential flotation. *International Journal of Mineral Processing, 84*(1), pp.15-24.
- U.S. Geological Survey, 2015. Mineral commodity summaries 2015: U.S. Geological Survey, 21 p.
- U.S. Geological Survey, 2016. Mineral commodity summaries 2016: U.S. Geological Survey, 27 p.

VALENTINA CHICO

Industrial Engineer Mention in Mining, Pontificia Universidad Católica de Chile.
vchico@gem-ing.cl

CHRISTIAN LICHTIN

Industrial Engineer Mention in Mining, Pontificia Universidad Católica de Chile.
Diploma in Mineral Economics, Universidad de Chile.
clichtin@gem-ing.cl

NOT SO RARE

By **Juan Ignacio Guzmán**

In the last decade, the mining industry has become aware of a group of special metals known as *rare earth elements* (REE). Rare earths is the common name used for seventeen elements: scandium, yttrium and the fifteen lanthanides (lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium).

Although most people have never heard of them, we are increasingly more exposed to these elements in our day-to-day life. In fact, nowadays practically all high tech devices have some amount of rare earth elements as a component. Hard drives, smartphones, flat screen TVs and monitors, as well as rechargeable batteries, all have some amount of one or more elements from this group.

Up until the end of the last decade China produced practically all of the rare earths in the world, reaching the point where it was responsible for around 97% of world production. Taking advantage of its monopoly position and realizing how critical these metals were for the manufacturing process of strategically relevant devices, the Chinese government established export quotas in 2009 with the intention of restricting the production of these final goods outside China (the reasons given by the government, however, where linked to stricter environmental regulations rather than protecting the local manufacturing industry). In practice, the imposition of these export quotas did nothing more than increase exploration and project development outside China, to the point where the country's market share went down to approximately 85% of total world production in 2015. Following this trend, rare earth elements production coming from other parts of the world is expected to continue to increase in the following years.

In this way, rare earth elements are becoming increasingly more common, as shown by the recent publication of tree books. The first one, Voncken (2016), is written for a public specialized in mining. This book describes the history of how the different elements that are part of the rare earths group where discovered, as well as the minerals and mines they are extracted from. The physical and chemical properties that make rare earth elements so critical when manufacturing modern appliances are also explained. In summary, Voncken (2016) is a great technical introduction for the reader who is looking to increase its understanding of rare earth elements' geology, mining, processing and economics.

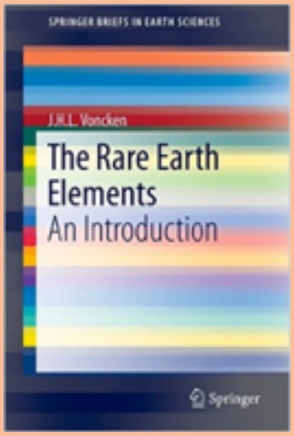
For a broader audience, Abraham (2015), which has been already extensively reviewed, is a good recommendation. In this book, the author traces in a simple and educational way the journey of these elements from the mine to the final consumer. Abraham (2015) shows that these elements are increasingly gaining relevance in the current international context, giving a strategic advantage to the companies and countries which produce them and ensuring a share of the modern and future manufacturing industry for them in a sustainable way.

Finally, and for the reader who specializes in extractive metallurgy, Krishnamurthy and Gupta (2016) is the second edition of the classic first published in 2004. This second edition incorporates the main developments in the rare earth elements industry in the last decade. Given the sharp increase in the use of these elements in the last years, this new edition includes a whole chapter on the recycling of rare earth elements form magnets, batteries and other final goods.

The growing interest in rare earth elements and their potential applications in the future makes this metal group one with the highest potential in terms of demand growth. This has allowed producers to keep expectations high in order to ensure supply for future requirements, which has triggered a “rare earth elements fever” around the world. Hence and in line with what the three books reviewed suggest, it is likely that in the future these elements will not be so rare anymore.

NOT SO RARE.

REFERENCES

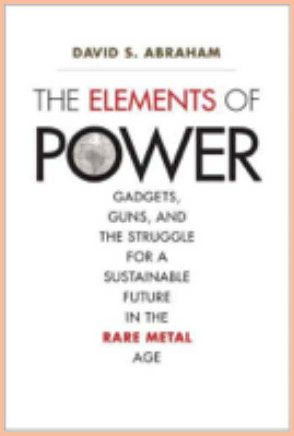


The Rare Earth Elements: An Introduction

J.H.L. Voncken

Springer, 2016

127 pp.

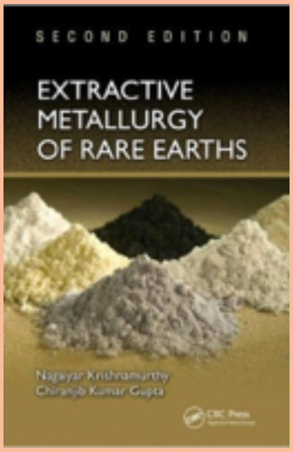


The Elements of Power: Gadgets, Guns, and the Struggle for a Sustainable Future in the Rare Metal Age

D. Abraham

Yale University Press, 2015

336 pp.



Extractive Metallurgy of Rare Earths, 2nd Edition

N. Krishnamurthy y C.K. Gupta

CRC Press, 2016

869 pp.

GEM Recommended

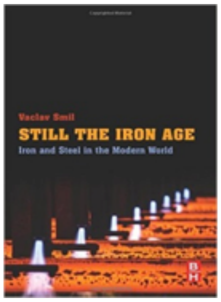
LATEST BOOKS

Still the Iron Age: Iron and Steel in the Modern World

Vaclav Smil

Butterworth-Heinemann, 2016

280 pp.



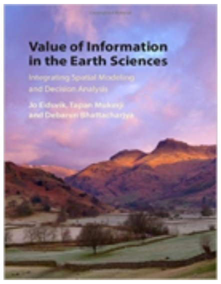
Value of Information in the Earth Sciences: Integrating Spatial Modeling and Decision Analysis

Jo Eidsvik, Tapan Mukerji y

Debarun Bhattacharjya

Cambridge University Press, 2016

396 pp.

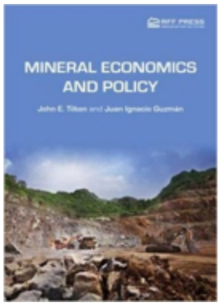


Mineral Economics and Policy

J.E. Tilton y J.I. Guzmán

Resources for the Future, 2016

270 pp.



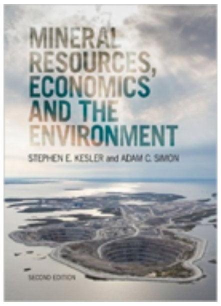
Mineral Resources, Economics and the Environment 2nd Edition

S.E. Kesler y A.C. Simon

Cambridge University Press,

2nd Edition, 2016

446 pp.

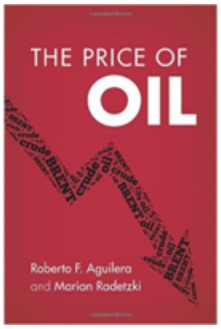


The Price of Oil

R.F. Aguilera y M. Radetzki

Cambridge University Press, 2015

252 pp.



LATEST PAPERS

ECONOMICS

- **Rawashdeh, R. Xavier-Oliveira, E. y Maxwell, P. (2016). The potash market and its future prospect.** *Resources Policy*, Vol. 47, 154-163.
- **Redlinger,M. y Eggert, R. (2016). Volatility of by-product metal and mineral prices.** *Resources Policy*, Vol. 47, 69-77.
- **Zhao, L., Zhang, X., Wang, S. y Xu, S. (2016). The effects of oil price shocks on output and inflation in China.** *Energy Economics*, Vol. 53, 101-110.

GEOSCIENCES

- **Miao, S.-J., Cai, M.-F., Guo, Q.-F. y Huang, J. (2016). Rock burst prediction based on in-situ stress and energy accumulation theory.** *International Journal of Rock Mechanics and Mining Sciences*, Vol. 83, 86-94.
- **Shiers, D.W., Collinson, D.M., Kelly, N.J. y Watling, H.R. (2016). Copper extraction from chalcopyrite: Comparison of three non-sulfate oxidants, hypochlorous acid, sodium chlorate and potassium nitrate, with ferric sulfate.** *Minerals Engineering*, Vol. 85, 55-65.
- **Talebi, H., Sabeti, E., Azadi, M. y Emery, X. (2016). Risk quantification with combined use of lithological and grade simulations: Application to a porphyry copper deposit.** *Ore Geology Reviews*, Vol. 75, 42-51.
- **Williamson, B.J., Herrington, R.J. y Morris, A. (2016). Porphyry copper enrichment linked to excess aluminium in plagioclase.** *Nature Geosciences*, Vol. 9, NA.
- **Zhang, P., Peterson, S., Neilans, D., Wade, S., McGrady, R. y Pugh, J. (2016). Geotechnical risk management to prevent coal outburst in room-and-pillar mining.** *International Journal of Mineral Processing*, Vol. 148, 9-18.

MINING AND PROCESSING

- **Choubey, P., Kim, M., Srivastava, R., Lee, J.-C. y Lee, J.-Y. (2016). Advance review on the exploitation of the prominent energy-storage element: Lithium. Part I: From mineral and brine resources.** Minerals Engineering, Vol. 89, 119-137.
- **Weerasekara, N.S., Liu, L.X. y Powell, M.S. (2016). Estimating energy in grinding using DEM modelling.** Minerals Engineering, Vol. 85, 23-33.

GEM
Gestión y Economía Minera Ltda.

MINERAL ECONOMICS

10-11 August 2016

OPEN INSCRIPTIONS

10% Discount
until 20-05-16

CARLOS HINRICHSEN
Chief Business Development Officer
chinrichsen@gem-ing.cl
+56 22 225 3021

www.gem-ing.cl