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MINING AND METALLURGICAL WASTE MANAGEMENT IN THE CHILEAN COPPER INDUSTRY

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ABSTRACT

Waste management and disposal has become a major concern for the Chilean mining and metallurgical copper industry. New environmental regulations and a growing pressure from both national and international communities have brought the industry to face the problem and to develop new integrated strategies of waste management. The present work discusses and analyses the different types of waste generated, the related environmental problems and the recommended management sequences.

In order to identify and quantify the different wastes, the traditional copper production process from sulfide ores can be divided in four different stages. During the mining extraction, the mineral wastes generated are sterile overlying materials and low-grade ores. The environmental problems associated to these wastes are mainly related to acid mine drainage. During the mineral processing stage, the only wastes are the tailings that could also generate acid mine drainage. Physical stability and interaction with superficial and underground waters are other environmental problems associated to these tailings. The smelting stage generates a wide range of metallurgical wastes. The slags are the most important in volume but generally do not generate environmental impact. Their stability will depend upon their composition and cooling conditions. The dusts captured from the smelting gases are recirculated or processed in a separated unit to recover copper and other valuable metals and to eliminate arsenic and other contaminants. The gas cleaning also produces other wastes such as arsenic precipitates. Finally, the electrorefining stage also generates different precipitates containing the impurities present in the copper anodes such as arsenic and antimony. In the alternative leaching process of oxide and low grade sulfide ores, the main waste produced are the abandoned leached heap and dump materials that could still contain sulfide minerals and generate acid mine drainage.

The first waste management step is the quantification and the complete characterization of all the generated wastes. Usual chemical stability tests such as TCLP may not be applicable and new procedures must be investigated in order to determine short and long term stability of the wastes in the disposal environment. The conditions of local climate and geology will then determine the specific disposal requirements for each type of waste. The evolution of these wastes should be monitored to evaluate their long –term stability.

In conclusion, an integrated waste management in the copper industry should consider the following objectives:

- *reduce the different types and amounts of waste to be disposed;*
- *guarantee a long term stability of the wastes produced; and*
- *guarantee a safe disposal environment for the final wastes.*

INTRODUCTION

Chilean copper industry like any mining and metallurgical industry generates very large amounts of mineral and metallurgical wastes. During the last ten years, the copper production has significantly increased reaching in 1997 more than 3 millions of tons of metal equivalent. During the same time, a continuous decrease of the ore grade has been observed in the most important mining operations. Both factors have produced an important increase of the amount of wastes generated. As an example, in an open-pit operation with a copper grade ore of 1% and a sterile to ore ratio of 4 to 1, for each ton of copper produced, 500 tons of material must be removed and will remain as waste. Nevertheless, most of these wastes are just rocks and inert material and should not generate any significant environmental impact. Only a small fraction of the wastes could produce environmental problems and required specific treatment and disposal procedures (Hutchison and Ellison, 1992).

The potential environmental impact of a given waste will depend, on the one hand, on its own physical and chemical characteristics and, on the other hand, on the conditions in the disposal environment. A same waste could be disposed without any problem in a dry environment while it would require very careful disposal conditions in a rainy region.

The first type of potential impacts associated to mining and metallurgical wastes is related to their physical stability. This is critical in the case of flotation tailings. These geomechanical aspects of the waste management will not be addressed in the present work. Another type of environmental impacts is related to the chemical aspects of the wastes. The chemical and mineralogical composition of a waste will determine its chemical stability under different conditions. Both thermodynamics and kinetics aspects will determine the potential environmental impacts. The sulfur content of the waste, the presence of heavy metals and the reactivity and solubility of the different compounds are the major factors that will be analyzed to determine the potential impacts.

Mining activities in Chile cover a very wide extension and a wide range of climatic and geographical conditions. Waste management requirements would be very different under the different environmental conditions and should then be studied and defined case by case.

The present work discusses and analyses the different types of waste generated in the Chilean copper industry. A first distinction will be made between mineral and metallurgical wastes. The potential environmental problems associated to each type of waste are reviewed and a quantitative and qualitative approach of waste management is proposed. Finally, some possible integrated management objectives and procedures will be discussed.

MINERAL WASTES

Mineral wastes correspond to the mineral material removed during the ore extraction and to all the wastes that do not experiment any chemical or mineralogical change. The composition of the material does not change during the process. The only changes are physical. The material is fractured and exposed to weathering. This will accelerate the natural transformation of minerals. The bloc diagram of figure 1 shows the different mining operations and the corresponding main mineral wastes.

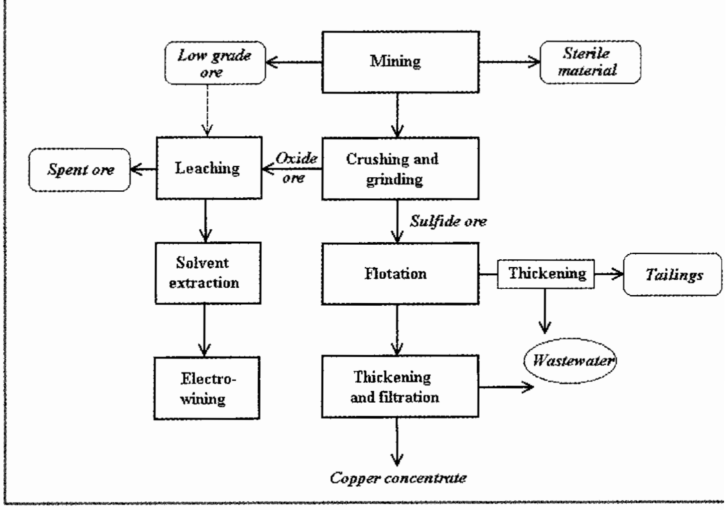

Figure 1. Bloc diagram of mining operations and related wastes.

Sterile material

The first and most abundant mineral waste is the sterile material removed in the open-pit operations. The amounts of sterile material removed will depend on the deposit and on the mining extraction. It is referred as sterile to ore ratio and will usually increase with the deep of the open pit. This material is usually dumped in very huge amounts that also generates visual impact and could produce local modifications of climatic conditions. This will produce an important impact on the dispersion of atmospheric contaminants.

Underground mining operations only produce small amounts of sterile materials. However, in some cases, subsidence effect of underground bloc caving produces fracturation of the overlying material that can be then considered as in place waste material. This material forms a kind of "crater" of broken rocks of high permeability (Ovalle, 1987).

The main potential environmental impact associated to the sterile dumps is the acid rock drainage. This potential acid generation will depend mainly on the chemical and mineralogical composition of the waste. Material with a high sulfur content, especially pyritic ores, and low acid consumption, mainly related to a low calcium carbonate content, will present a high potential acid generation. However, in dry regions like some part of the north of Chile, even those wastes with a high potential acid generation will not produce any significant environmental impact due to the absence of water (Hutchison and Ellison, 1992). Water and oxygen are the two factors that will determine if the potential problem will turn into an effective acid generation and the rate of supply of both compounds will regulate the kinetics of this process. In Chile, significant acid generation is only observed in the central and south regions and occasionally in some mining operations located in the north at very high altitude where rainfall and snowfall are significant. In place leaching of fractured material overlying underground mining operations has been observed specially in spring when the snow accumulated during the winter melts and percolates through the fractured rocks. Part of this solution is collected in the underground works and copper is recovered by solvent extraction. However, the great seasonal variations in the solution flow make very difficult an effective effluent treatment. The natural leaching process can be enhance by addition of acid water at the surface of the crater (Ovalle, 1987).

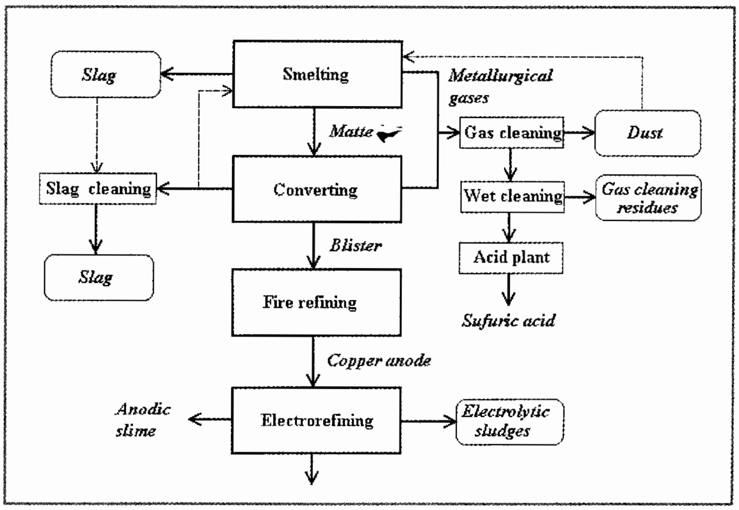

Figure 2. Bloc diagram of metallurgical processing of sulfide copper concentrates.

Low grade ores

In some mining operations, low grade ores are disposed in separated dumps for a possible future processing. Acid generation and metal dissolution may be a more frequent problem for low grade materials than for sterile materials due to higher sulfide contents. In some cases, low grade dump are located in an area that will allow further solution recovery during an acid or bacterial leaching operation of the dump. This also presents the advantage of a better control of effluent solution in case of any acid mine drainage.

Flotation tailings

Flotation is the concentration process commonly used in the mineral processing of copper sulfide ores. The ore is finely ground and the sulfides are separated from the gangue material. This process generates large amount of tailings, containing the gangue minerals and part of the sulfides (mainly pyrite). The tailing is characterized by fine grained minerals mostly liberated and by a high water fraction. Due to the copper flotation conditions, the pH of the tailing is usually high. This will help to prevent any potential acid generation. The low permeability of the material will also limit oxygen access and slow down the oxidation process (Dold et al., 1996).

METALLURGICAL WASTES

Both hydrometallurgical and pyrometallurgical processes generate different metallurgical wastes (Figures 1 and 2). In the first case, when the leaching process is applied directly to the crushed ore, no flotation tailings are produced and the only metallurgical wastes are the leaching residues. In contrast, pyrometallurgical wastes are numerous and present a great physical and chemical diversity.

Spent leached ore

The hydrometallurgical wastes correspond to leaching residues released at the end of the leaching operations. The leached material contains partially reacted minerals and a variable remaining metal content as well as some pregnant leaching solution, usually acid and with significant dissolved metal concentrations. These conditions may be favourable for the oxidation of the remaining sulfides and then mineral transformations will proceed. The potential impact of these wastes will depend essentially on the residual metal and sulfur contents and, again, on the conditions under which the wastes will be disposed. Depending on the heap leaching configuration, permanent expanding heaps or reusable pads, the spent ore will remain on the same place in the area specially designed for solution recovery or will be removed from the pad and disposed in a separate facility. Valley leaching is also used in the case of low grade ores when a valley is used to form the leaching area. The spent ore will then remain at the same place.

Slags

The most important pyrometallurgical waste is the slag, composed of iron oxides and silicates in a glassy structure. Due to this structure, slag is usually considered as a very stable waste with low disposal requirements. Nevertheless, depending on the cooling conditions and on the impurity content, especially arsenic, some slag could present some stability problems and required special disposal conditions. This is particularly important when slag is used as construction material for transit way stabilization. Special leach test protocols have been developed for slags (Koren et al., 1997).

Pyrometallurgical dust

Pyrometallurgical dusts are recovered in the metallurgical gases from both smelting and converting reactors. This dust has two different origins (Hoffmann, 1993). Part of the dust is formed by partially reacted concentrate particles carried away by the gas. Due to the high temperature and the oxidizing atmosphere, these concentrate particles are partially roasted and oxidized and lose an important fraction of their sulfur content. The other origin for metallurgical dust is the condensation of volatile compounds, like arsenic oxides, during the cooling of the gases. These compounds usually condense at the surface of concentrate particles blown out by the gas. This will mean that in the first stage of dust recovery from the gas, the fraction of concentrate particles in the dust if high and dust composition is similar to that of the concentrate with a significant decrease of the sulfur content. This dust is usually returned to the smelting stage and used to control the temperature of the smelting furnace. The dust recovered in the later stages of gas treatment, where the temperature of the gas has significantly decreased, contain a higher fraction of condensed impurities and may not be returned to the furnace to avoid an increase of impurity concentration. Part of these dusts produced in the Chilean smelting plants are treated in a reduction roasting process where arsenic and antimony are eliminated as sulfides or as oxides. Dusts are usually mixed with high arsenic concentrates and the calcine is returned to the smelting process. In other cases, dusts are partially or completely leached. Arsenic and other impurities (Sb, Bi, Zn, ...) dissolved readily is an acid solution. In the case of a partial leaching, the solid residue free of arsenic and other impurities is returned to the smelting process. Dissolved arsenic and impurities are removed of the solution by precipitation after oxidation and neutralization of the solution. Arsenic is precipitated as ferric arsenate which stability will depend on the iron to arsenic ratio (Swash et al., 1994). In one of the important Chilean mining operation, smelting dusts and electro-refinery wastes are treated in a single leaching process. The leaching solution is mixed with large volumes of leaching solutions coming from other leaching operations. Copper is recovered in a solvent extraction plant and the refinate acid solution with arsenic content is sent to a dump leaching process. Arsenic precipitates with ferric in a gravel level of alkaline type rocks under the dump where the leaching solution is partially neutralized. The pH increase is sufficient to produce precipitation of ferric hydroxide and jarosite and the coprecipitation of arsenic (Farias et al., 1996).

Gas cleaning residues

Metallurgical gases treated in acid plant to remove SO_2 and produce sulfuric acid must be previously cleaned. The gas cleaning treatment includes wet scrubbers and wet electrostatic precipitators where all the remaining impurities and volatile compounds are efficiently removed. Due to the presence of SO_3 in the gases, the gas cleaning solution is acidified and most of the

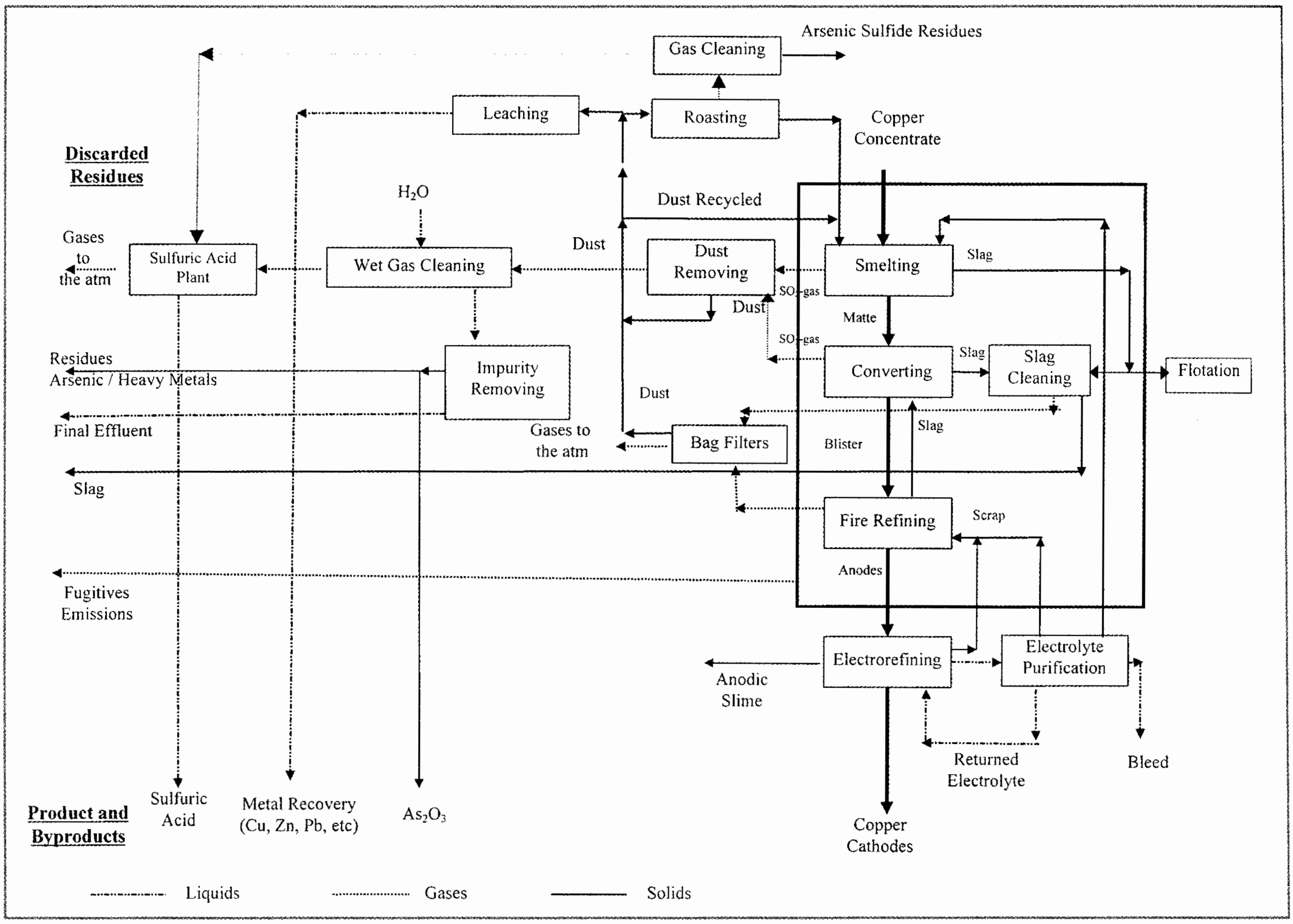

Figure 3. Flowsheet for integrated arsenic management in cooper production.

impurities and volatile compounds are dissolved in this solution. There are two different ways to remove impurities from the system. In the first process, the concentration of impurities in the cleaning solution is maintain at the limit of solubility and the impurities are eliminated as precipitated solids with small volumes of solution. In the alternative process, part of the solution is continuously withdrawn and treated in a separated process where impurities are precipitated by addition of a neutralizing compound. The solids are separated from the solution that returns to the gas cleaning process.

MASS BALANCES

A first estimation of the amount of waste produced can be obtained using simple mass balances. The global mass balances of the different processes will be calculated on the basis of copper balance and copper analysis in the main process flows. This balance can be completed using iron and sulfur balances. Once the main flows are estimated impurity balances are performed using distribution coefficients to calculate the concentration of the different impurities in the different flows. Distribution coefficients are estimated on the basis of operation data of different mining operations.

For mineral wastes, the distribution of an impurity is quite simple and will follow the distribution of the minerals that contain it. For example, in those deposits where arsenic is mainly present as enargite, arsenic distribution will just depend on enargite distribution. Antimony, that is also associated to enargite as replacement impurity will follow the same distribution pattern. Then, based on a complete chemical and mineral characterization of the ore, it would be possible to estimate the distribution of impurities in mineral wastes. As most of the impurities are associated to the sulfide minerals, they will be preferentially go to the concentrate with a concentration factor somehow similar to that of copper.

Impurity behavior in metallurgical processes is much more complex and required specific studies. Impurity distribution in pyrometallurgical processes has been the subject of numerous studies (Itagaki, 1986). Volatile impurities such as arsenic, bismuth and lead will concentrate in the gas phase while noble metals will preferentially remain in the copper phase. Arsenic distribution has been studied for different smelting plants and different types of furnaces (Wiertz and Rozas, 1996). While in reverberatory furnaces a significant fraction of arsenic will remain in the slag and in the matte, in flash smelters and Teniente converter, arsenic will mainly follow the gas phase. Distribution coefficients of the different impurities depend on a great number of factors such as arsenic concentration in the feed, composition of slag, oxygen enrichment, copper concentration in matte, fraction of dust returned to the smelting, temperature, etc.

Once established the general distribution of main elements and impurities, the global flowsheet of the process can be developed and a first estimation of waste flows and characteristics can be calculated. An example is shown on Figure 3 that illustrates the problem of arsenic management in a smelting and electrorefining plant.

WASTE STABILITY AND DISPOSAL

Waste toxicity is usually determined by standardized tests such as EPA-TCLP (Toxicity Characteristic Leaching Procedure). This test was developed to evaluate metal mobility in a sanitary landfill. However, environmental conditions are quite different in the disposal area of mining and metallurgical wastes and this kind of test will be of limited application to really determine the waste stability in the disposal environment. Most of the tests and procedures developed for solid waste characterization are focused to acidic environment. Nevertheless, some disposal areas such as flotation tailings are mostly alkaline and the tests will not allow the determination of the waste stability in those environments. Stability tests must be developed and adapted for the different types of waste and for each type of disposal environment in order to determine the behavior of wastes under the environmental conditions in their disposal area (Koren et al., 1997).

In Chile, solid industrial wastes are not yet regulated by any specific standard but a new regulation is under study. There are some specific regulations for dumps and tailings in the mining industry mostly oriented to the problem of physical stability. Waste management is also included in the environmental impact study required for any new mining project. During the last few years in Chile, the main regulatory advances have been oriented towards the atmospheric and water contamination problems. In the next years, a similar regulatory process will be undertaken for solid waste management. Due to the importance of mining industry in Chile, the new regulations should consider the specificity of mining and metallurgical wastes and the great diversity of disposal environments. Waste stability and disposal safety must be considered as a single environmental problem of waste management.

INTEGRATED WASTE MANAGEMENT

An integrated approach of waste management should consider the following objectives: reduce the different types and amounts of waste to be disposed; guarantee a long term stability of the wastes produced and guarantee a safe disposal environment for the final wastes.

The amount of mineral wastes depends principally on the characteristics of the deposit and in a minor grade on the mining process and very little can be done to reduce it. Efforts should then be oriented to the characterization of the wastes and to design an appropriate disposal strategy, balancing potential acid generator wastes with acid *consuming wastes or* preventing the contact of them with air o water. The requirements will be greatly affected by the level of precipitation in the disposal region. It is also important to consider extreme event in the design of the disposal area.

The types and amounts of metallurgical wastes generated will depend in a high grade on the characteristics of the processes applied. In order to reduce and simplify the waste treatment requirements, it is possible to treat different types of wastes in a single combined process. Such approach can be applied in the case of arsenic wastes. Smelting dusts with high arsenic content can be leached with acid solution from gas cleaning and/or with electrolyte from the electrorefining process. Arsenic would then be eliminated in a single precipitation process under controlled conditions. In some cases, the cost of the process can be partial o totally compensated by the recovery of some valuable impurity such as germanium.

CONCLUSIONS

Chilean copper production has significantly increased during the last years reaching in 1997 a total of 3,392,000 tons of metal equivalent. More than 60% of the production corresponds to copper cathodes while the remaining fraction was exported as copper concentrates. Leaching and bioleaching of copper oxide ores and secondary sulfide ore represent an increasing fraction of the copper production. The increase of copper production means also an important increase of mineral and metallurgical wastes. Great part of the mineral wastes produced by the Chilean copper industry do not represent any significant environmental problem due to the their low acid generation potential and to the dry conditions in most of the mining area. Only some very specific problems of acid mine drainage have been observed in mining operations in the Central Region of Chile. Efforts are oriented towards the control of the effluent solutions and the recovery of copper.

Exacting standards nowadays regulate flotation tailings dams. New tailing facilities are design to minimize environmental risks. However, abandoned tailing pounds constitute very serious environmental liabilities.

The increasing participation of copper leaching operations to the Chilean copper production corresponds to new operations that were submitted to the environmental assessment regulation. The environmental impact studies required for the new mining and metallurgical projects should guarantee a safe disposal of spent leached ore.

The main environmental problems are related to metallurgical wastes produced in the smelting plants. An integrated waste management program should be design and developed. New dust treatment processes should be developed and the problem of arsenic wastes must be solved in an integrated way, trying to minimize the types of wastes and to produce safe and easy to handle final residues.