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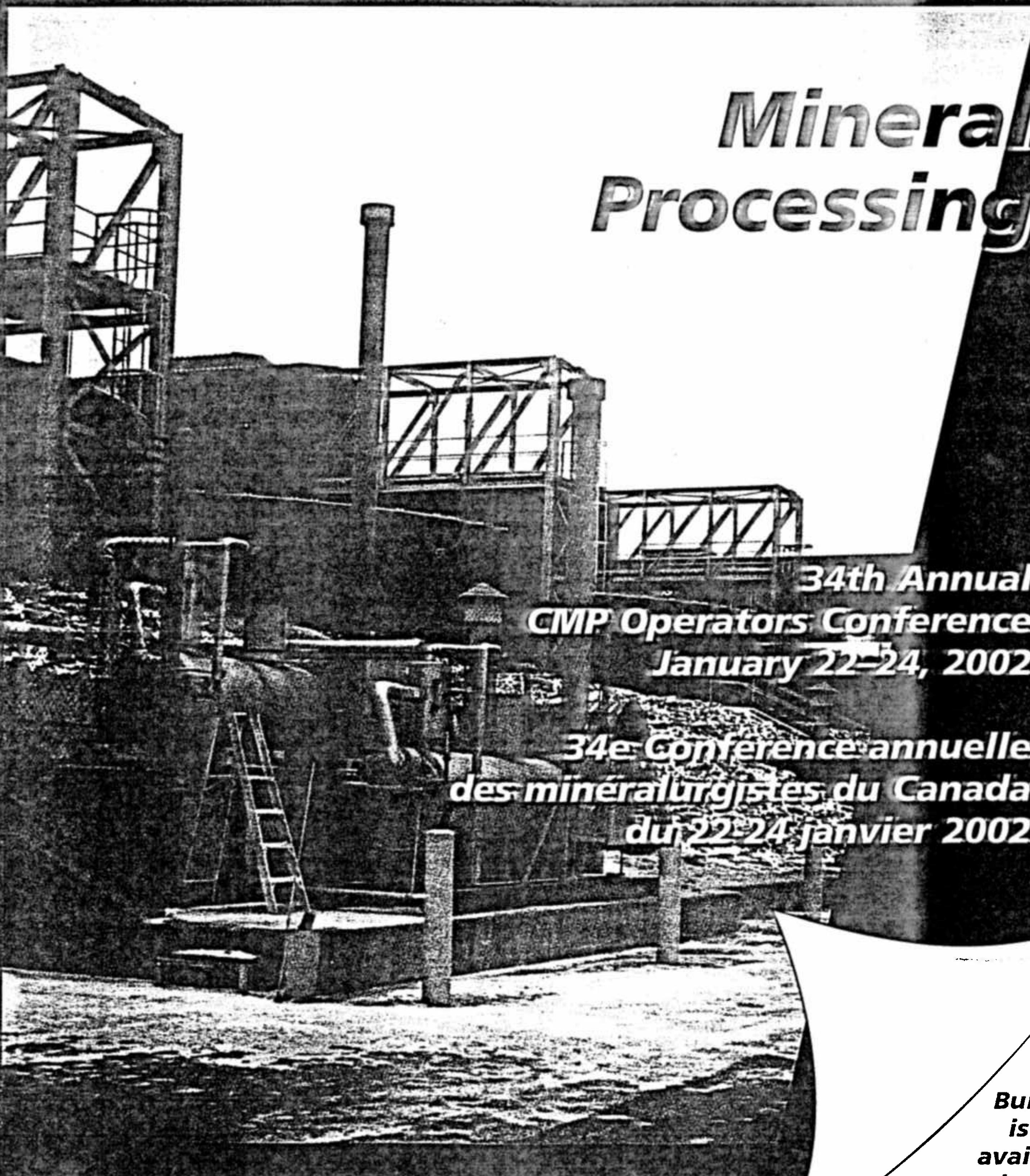

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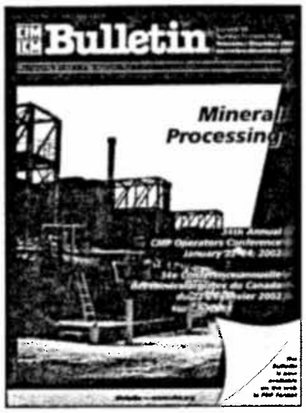


This Month's Cover

CCD thickeners, Key Lake operation.
Photo courtesy of Chuck Edwards, Cameco Corp.

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# CIM ICM Bulletin

## THIS MONTH'S THEME

▲ The papers in this issue touch on just a part of the wide range of methodologies and expertise that are continually being developed and refined in the minerals processing industry. Today's mineral processing engineer is faced with an increasing number of issues, problems, obstacles, and opportunities. A knowledge of others' experience in these same areas is a powerful tool that helps tackle these with direction and confidence.

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Mineral Processing

# ▲ In situ acid leaching of copper tailings deposits: A case history

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**KEYWORDS:** Acid leaching, Tailings, Copper, In situ leaching, Simulation.

Paper reviewed and approved for publication by the Canadian Mineral Processors Division of CIM.

## ABSTRACT

*The results of a field-scale study involving in situ leaching of copper ore tailings using sulphuric acid as the leaching agent, injection wells to introduce the leaching solution and extraction wells to recover the copper-enriched pregnant leaching solution are presented. The study was performed at an abandoned tailings disposal site using a battery of injection and extraction wells. The medium was characterized through the determinations of physical, chemical, mineralogical, and hydrodispersive properties based on laboratory and field tests, including a tritium tracer test, a pumping test, particle size analyses, and hydraulic conductivity tests. Numerous horizontal strata with different hydraulic conductivities were identified. A previously developed model was used to simulate the leaching of copper ore tailings. Although the study confirms the feasibility of using in situ leaching for recovery of residual copper from tailings deposits, the efficiency of the technology depends significantly on the medium stratigraphy and hydraulic conductivity.*

## Introduction

Copper mining and milling operations generate large amounts of wastes in the form of tailings that are deposited in tailings ponds containing, in some cases, minerals with copper grades of close to 0.3%. In the last 50 years in Chile, copper mine operators have worked primarily mixed iron and copper sulphide ores (chalcopyrite and bornite) with grades initially running as high as 12% Cu, although the grades of the ore today are only around 1% Cu. As a result, the large volumes of tailings material stored in numerous tailings ponds in Chile constitute a potentially valuable source of minerals. However, these tailings deposits also represent a potential source of groundwater contamination resulting from natural processes (e.g., from rainfall and bacteria existing in the medium) that slowly leach metals contained in the mine tailings (Glynn and Brown, 1996). Thus, extracting copper contained in tailings is an interesting proposition, not only because it offers an economically viable alternative to conventional copper-producing techniques, but also because the need exists to clean up these tailings ponds to ameliorate the potential for environmental degradation.

In situ leaching is a technology used to extract minerals by means of circulating leaching solutions. In situ leaching with injection and extraction wells involves introducing a fresh leaching solution through injection wells and recovering a pregnant leaching solution from extraction wells. This type of extraction has important advantages to offer for mining, from an environmental standpoint, since it involves the movement of a significantly smaller amount of rock than conventional mining, making subsequent clean up and reclamation activities simpler.

In recent years, in situ leaching technology with injection and extraction wells using sulphuric acid as the leaching agent (solvent) has been studied theoretically and experimentally, with significant progress achieved towards the understanding and modelling of the phenomena that govern it on a laboratory scale

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(Briceño et al., 1993; Montero et al., 1994; Muñoz et al., 1997).

The objective of this study is to evaluate the potential application of the technology at the field scale. In support of this objective, the results of an in situ leaching test performed at an abandoned copper tailings pond are presented in this paper.

Site Description

This study was performed on tailings deposited in the Tranque Barahona No. 2 tailings pond of the El Teniente Division of Codelco, Chile. This old, abandoned tailings pond covers a surface area of 1.6 $km^2$ and has depths ranging between 30 m and 50 m. The impoundment area was made by damming a small side valley having several smaller ravines as tributaries in a mountainous Andean area of central Chile.

The stratigraphy of this tailings deposit is predominantly horizontal since the deposit was formed through the settling of solids from a mixture of tailings water and solids, with the water either running off or evaporating. Interbedded among the strata of tailings material are layers bearing eroded material that was mobilized in the upstream watershed and transported to the tailings by storm water or run-off from melting snow. The impoundment is saturated, and the phreatic surface is located at an average depth of 5 m. The depth of the tailings deposit is around 45 m in the specific area in which the test was performed.

## Methods and Procedures of Study

The experimental setup is shown in Figure 1 and was designed to maximize the copper recovery based on a preliminary test. The approximate depth of these wells was 30 m, and they were set up with screened PVC casing 152 mm in diameter and with a sand filter 51 mm thick. The wells were screened from a depth of 1 m to a depth of 29 m. In addition, four observation wells of 50 mm in diameter were constructed at the locations shown in Figure 1.

The physical and mineralogical properties of the tailings were determined through analyses of samples taken during the construction of the four observation wells. From the well OW-4, disturbed (split-dredge bucket) samples were recovered from different depths, whereas, four undisturbed (Shelby tube) samples were taken from wells OW-1, OW-2 and OW-3 (a total of 12 samples, each 8.4 cm in diameter).

The mineralogical characterizations included determinations of mineralogical composition and the contents of total and soluble copper. Soluble copper was determined by leaching 5 g of tailings with 50 mg of 5% (v/v) sulphuric acid solution at ambient temperature with continuous agitation for 30 minutes. The leached copper was measured by atomic absorption spectrophotometry.

The hydraulic conductivity was determined by several types of laboratory and field tests. During construction of the observation wells, Lefranc tests (Schneebeli, 1987) were performed at each 10 m depth in the cavity created by Shelby samples extraction. A Lefranc test consists of injecting a given flow rate at a constant head into a cavity of known dimensions inside the medium. The decline of the water table is then measured as the injection flow rate is reduced to zero (infiltration test). Following the completion of construction of the injection and extraction wells, five variable rate pumping tests were performed.

Additionally, vertical hydraulic conductivity tests were performed by permeating samples that were contained in cut portions of the Shelby tube, and horizontal hydraulic conductivity tests were performed on samples extracted from the Shelby tube (ASTM D2434).

A tritium (3H) tracer test was performed to determine the hydrodispersive parameters of the medium (longitudinal and transversal dispersion coefficients and porosity). The test consisted of establishing a radial flow pattern by injecting flow into well EW-5 and pumping in equally distributed portions through wells IW-6, IW-7, IW-10 and IW-11 (Fig. 1). Once a constant flow regime had been achieved, a pulse of tracer ($2{\cdot}10^{12}$ dpm) was injected all along the screened portion of the well. Samples of solution were then taken from the four extraction wells and at different depths in observation well OW-4 to study the changes in tracer concentration. The injection rate entered was 0.3 L/sec. and the extraction rate at each exit well was 0.075 L/sec. The total duration of this test was four months.

A pilot-scale leaching test was performed to evaluate the leaching technology using solution injection and extraction wells. The test consisted of injecting a leaching solution — a mixture of water and sulphuric acid — through the injection wells (IW) and subsequently recovering the leaching solution through the extraction wells (EW).

Prior to the start of this test, pre-conditioning was carried out by injecting an acidified solution through the extraction wells. The purpose of this pre-conditioning was to acidify the medium in the vicinity of each extraction well to promote the leaching process and to keep the initial pH sufficiently acidic to prevent precipitation of iron in the immediate surroundings of the extraction wells. The natural pH of this tailings material was ~4. The solution was injected at an average rate of 0.5 L/sec. and an acid concentration of 120 g $H_2SO_4$/L (pH = 0.1) over a period of 10 days during this pre-conditioning phase.

The leaching test, which lasted 44 days, commenced three days after the completion of the pre-conditioning phase. The extraction rate was 0.86 L/sec. Acidity in the leaching solution was around 80 g $H_2SO_4$/L (pH = 0.1).

The hydraulic functioning of the test was monitored by measuring, at a frequency of two times per day, the water table level in all wells,

Fig. 1. Well configuration in the Barahona tailings pond.

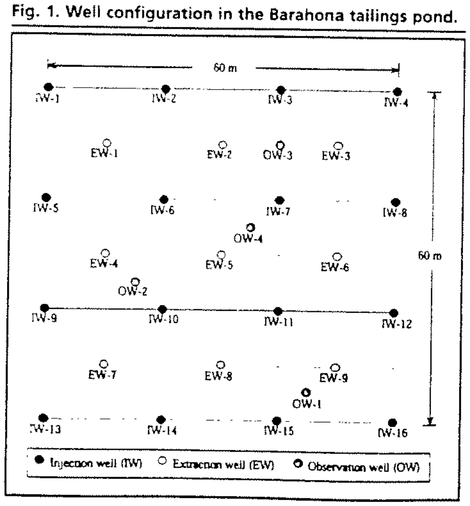



Fig. 2. Average value and 95% confidence interval of representative particle-size distribution of tailings studied.

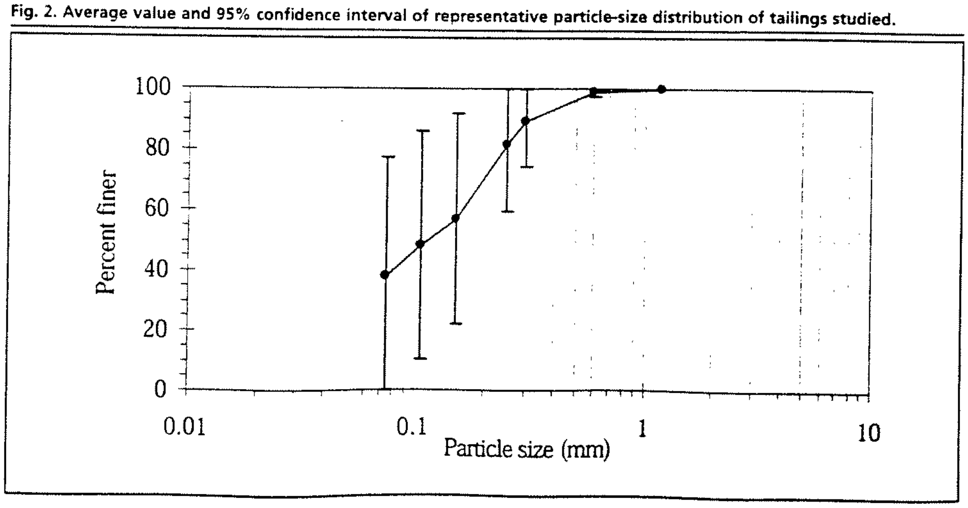


Fig. 3. USGS classification (ASTM D2487) of tailings samples obtained from well OW-4.

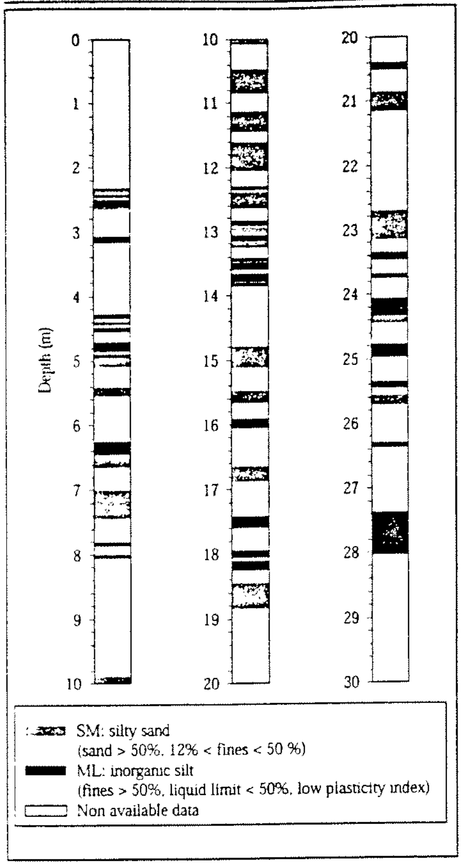
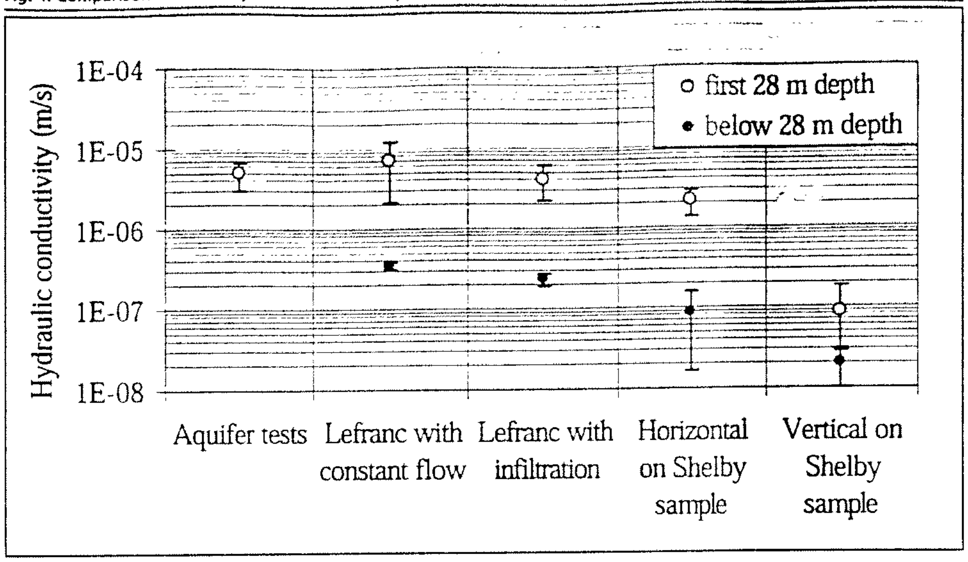



Fig. 4. Comparison between hydraulic conductivity values estimated by different tests and their standard deviation.




the flow rate injected through each injection well (IW), and the flow rate extracted through each extraction well (EW).

Metallurgical performance was monitored by measuring the acid concentration of the injected solution, and the pH and copper concentration in the extracted solution. The sampling and subsequent chemical analysis was performed daily.

## Results and Discussion

### Properties of the Tailings

Figure 2 shows the average particle-size distribution curve for the samples analyzed from observation well OW-4 along with the 95% confidence interval assuming a normal distribution.

The results, as shown in Figure 3, indicate that the tailings material is composed of heterogeneous layers of muddy sand (SM) and low-plasticity mud (ML), with volumetric moisture contents ranging from 27% to 56%. The characteristic heterogeneity of these profiles is due primarily to the horizontal stratigraphy of the tailings deposit which developed during its formation.

A very fine tailings material (99% less than #200 mesh) with a relatively low permeability ($K < 10^{-7}$ m/sec.) lies below a depth of about 28 m. Sizable lenses of this same material also occur above a depth of about 28 m. In observation well OW-4, this essentially impermeable material constituted ~33% of the material bored for observation well OW-4. Thus, only 18 m of the total 28 m thickness of the tailings in the test area is considered permeable and, hence, amenable to leaching.

The volumetric moisture contents are very close to saturation and always less than the theoretical porosity calculated on the basis of the dry density and the density of the particles.

Fig. 5 presents the estimated hydraulic conductivity of the medium (i.e., representative of the entire profile) based on variable rate pumping (aquifer) tests. The values obtained from these tests were consistent, with an arithmetic mean hydraulic conductivity of $4.90 \cdot 10^{-6}$ m/sec. and a standard deviation of $1.96 \cdot 10^{-6}$ m/sec.

The variations in the hydraulic conductivities within the first 28 m and below 28 m from the surface are compared in Figure 4. The hydraulic conductivities estimated by the Lefranc tests and horizontal hydraulic conductivity tests, for the first 28 m depth, were consistent with those estimated by the aquifer tests performed in the field. Hydraulic conductivities estimated on the basis of Lefranc tests and laboratory tests correspond to point values and indicate the range of variation of hydraulic conductivity existing among the different strata comprising the medium.

The vertical hydraulic conductivities measured in the laboratory were highly variable and almost two orders of magnitude lower than the field-measured values. Field-measured values are considered representative of the numerous horizontal strata of different characteristics in the tailings deposit.

The hydraulic conductivity tests performed deeper than 28 m yielded values that were at least one order of magnitude lower than those performed at shallower depths. This finding is consistent with expectations, given the very fine tailings found at depths greater than 28 m. In several of the Lefranc-type tests performed below a 28 m depth, the medium did not accept any measurable flow indicating that the hydraulic conductivity of the strata involved was either very low or impermeable for all practical purposes.

Table 1a presents the contents of the minerals in the tailings and the grades of copper, iron and sulphur. The major minerals in which copper is present are chalcopyrite and covellite. The copper grades ranged from 0.16% to 0.25%. Soluble copper as determined in the laboratory varied between 5% and 14% of total copper. The mineralogical composition observed is very similar to that of the tailings used by Montero et al. (1994) and Briceño et al. (1993), the results of which are also presented in Table 1a. The principal components of the gangue, which together account for 98% of the material present in the tailings, are shown in Table 1b.

### Tracer Test

Figure 5 shows the concentrations of tracer obtained at different depths in observation well OW-4. The samples are representative of four strata located at different depths: sample A, between 7 m and 9 m; sample B, between 11 m and 13 m; sample C, between 16 m and 20 m; and sample D, between 22 m and 27 m. One dpm/mL is equivalent to 0.1417 tritium unit (TU), which corresponds to the concentration of tritium in the water (1 TU = $^3H_2O/H_2O = 10^{-18}$). The results show a peak in concentrations appearing at around three days, and primarily in the upper strata (i.e., sample A, 750 dpm/mL, and sample B, 430 dpm/mL). This peak cannot be explained on the basis of the average hydraulic conductivity of

**Table 1a. Mineralogical composition and chemical assay of tailings mixtures of the Barahona tailings pond (% total minerals)**

| Mineral | Wells | | | Columns* | Field samples | Field samples[f] |
|---|---|---|---|---|---|---|
| | OW-1 | OW-2 | OW-3 | | | |
| Chalcopyrite | 0.16 | 0.08 | 0.11 | 0.21 | 0.51 | 0.10 |
| Chalcosite | 0.04 | 0.04 | 0.12 | 0.06 | | 0.08 |
| Coveilite | 0.12 | 0.08 | 0.09 | 0.12 | 0.02 | 0.04 |
| Bornite | | | | 0.03 | 0.07 | 0.01 |
| Grey copper | | | 0.01 | | | |
| Native copper | 0.02 | 0.03 | | 0.03 | | |
| Cuprite | 0.01 | 0.01 | | 0.09 | | |
| Oxide copper | | 0.01 | | 0.06 | | |
| Pyrite | | | | | 1.05 | 0.54 |
| Total copper | 0.25 | 0.16 | 0.25 | 0.33 | 0.24 | 0.28 |
| Total iron | | | | | 3.45 | 2.66 |
| Total sulphur | | | | | 0.77 | 0.57 |
| Soluble copper | 0.083 | 0.059 | 0.054 | 0.0140 | | 0.048 |

* Montero et al. (1994)

[f] Briceño et al. (1993)

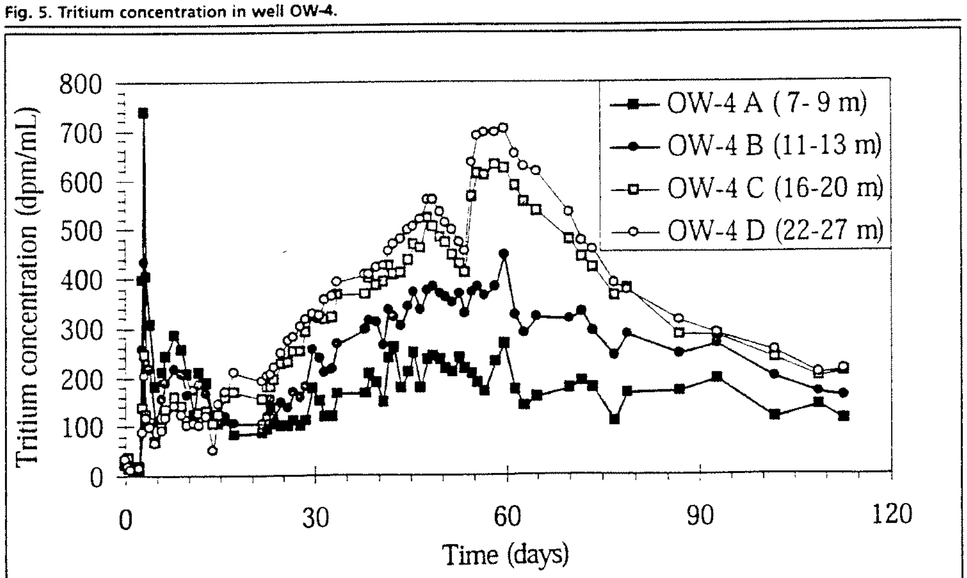
**Table 1b. Principal gangue components found in the Barahona tailings pond**

| Mineral | Weight (% of total mineral) | Mineral | Weight (% of total mineral) |
|---|---|---|---|
| Quartz | 40.93 | Tourmaline | 4.74 |
| Biotite | 16.95 | Clays | 3.47 |
| Feldspar | 10.12 | Chlorite | 2.83 |
| Plagioclase | 6.83 | Jarosite | 0.26 |
| Alunite | 6.43 | Calcite | 0.24 |
| Sericite | 5.19 | Anhydrite | 0.10 |
| | | Total | 98.09% |

the medium and, therefore, implies the existence of preferential flow paths located in these strata. Additionally, a second peak, of lesser magnitude, appeared at around seven days primarily in the upper strata (sample A, 300 dpm/mL, and sample B, 220 dpm/mL). After this second peak, the tracer began to appear in all of the profile (in all four samples) at around day 12, with an average concentration of approximately 100 dpm, which began to increase gradually until achieving the primary peak at day 60. In this case, the peak was significantly greater in the lower strata (i.e., sample C, 630 dpm/mL, and sample D, 700 dpm/mL) than in the upper strata (i.e., sample A, 160 dpm/mL, and sample B, 450 dpm/mL).

The times at which the peaks occurred were found to be identical for all of the strata sampled, with the only differences in the magnitudes of concentrations. This consistency in peak concentration arrival times indicates that these strata contain the same average hydrodispersive characteristics. The occurrence of multiple peaks suggests the existence of a series of interconnected microstrata of different characteristics, such as lenses of silt and clay (Li et al., 1994). The differences observed in concentrations can be explained, in part, due to a possible difference in concentration in the injection well. At the beginning of the test, high concentrations were exhibited in the upper strata, with higher concentrations thereafter being achieved in the lower strata throughout most of the remainder of the test. In spite of these differences, the medium overall essentially can be considered to be relatively homogeneous, but is composed of randomly occurring horizontal microstrata of different characteristics.

**Fig. 5. Tritium concentration in well OW-4.**




The total mass recovered by the end of the 113 days of the test amounted to approximately 7.5% of the total mass injected. The largest peak observed in well OW-4, around day 60, was not observed in the extraction wells although the tracer test was stopped at day 113. This would explain the low tritium recovery in the tracer test.

The average concentration for the four samples from well OW-4 was used to estimate the hydrodispersive parameters of the medium (longitudinal and transversal dispersion coefficients and effective porosity), i.e., excluding from consideration the first two peaks observed. The analysis was performed through use of the MT3D solute transport model (Zheng, 1990) and the MODFLOW flow model (McDonald and Harbaugh, 1988). The following assumptions were made in the MODFLOW and MT3D models to interpret the tracer test: a homogeneous medium 28 m thick; a water table located at 5 m depth; an average hydraulic conductivity of the tailings equal to $4.9 \cdot 10^{-6}$ m/sec.; an injection rate of 0.28 L/sec.; and an extraction rate equal to 0.28 L/sec. The medium was made discrete through the use of a grid consisting of 59 rows and 59 columns, with cells of 1 m by 1 m each and with a constant head boundary at 5 m depth.

The similarity between the Lefranc tests, the horizontal hydraulic conductivity tests, and the aquifer tests results allows us to assign an equivalent horizontal hydraulic conductivity to the whole medium. Due to the hydraulic conductivities below a depth of 28 m being significantly lower than those values in the upper strata, the uppermost 28 m was only modelled in the simulation.

Calibration was performed under a constant flow regime. The small difference between the modelled flow and that actually injected (0.3 L/sec.) may have resulted in a preferential subsurface flow pattern resulting in the first two peaks that were observed with the tracer test.

The fit obtained is presented in Figure 6, and the values of the associated hydrodispersive parameters are shown in Table 2. Also included in this table are the hydrodispersive parameters estimated by Muñoz et al. (1997) on the basis of laboratory experiments and the average distance travelled by the tracer in both cases. A porosity of 0.40 ± 0.04, a longitudinal dispersivity of 0.6 m, and a transversal dispersivity of 0.21 m, were obtained in this study. The calibrated porosity was similar to the average saturated volumetric moisture content measured on samples obtained from the observation wells and is slightly less than the estimated total porosity, which for the uppermost 28 m of soil was estimated at 0.47.

As shown in Table 2, the ratio between the longitudinal dispersivity and the distance

Fig. 6. Comparison between simulated and average observed values for tritium concentration in well OW-4 in tracer test.

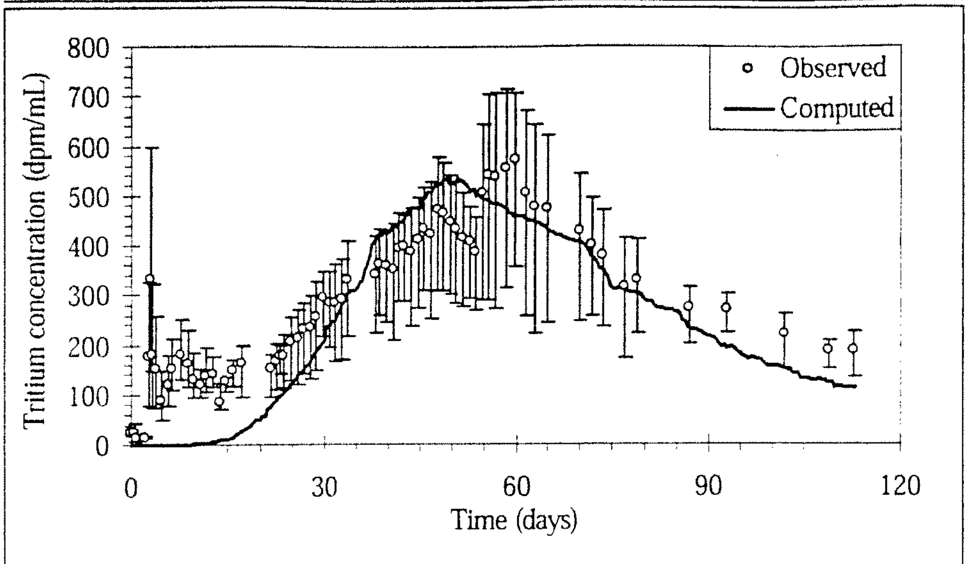



Fig. 7. Injected and extracted flow rates as a function of time.

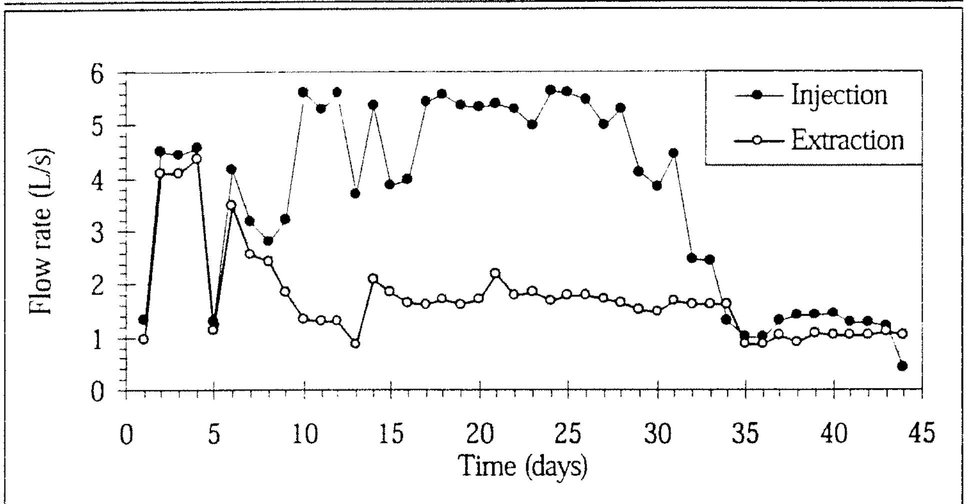



Table 2. Hydrodispersive parameters calibrated in tracer tests

| Parameter | Muñoz et al. (1997) | This study |
|---|---|---|
| Longitudinal dispersivity (m) | 0.0170 | 0.60 |
| Transversal dispersivity (m) | 0.0064 | 0.21 |
| Porosity ($m^3/m^3$) | 0.26 | 0.40 |
| Hydraulic conductivity (m/sec.) | $2.1 \cdot 10^{-5}$ | $4.9 \cdot 10^{-6}$ |
| Distance (m) | 0.19 | 7.07 |
| Longitudinal/transversal dispersivity ratio | 2.675 | 2.857 |
| Longitudinal dispersivity/ distance ratio | 0.090 | 0.085 |

traveled by the tracer in the field (0.09) is similar to that estimated on the basis of laboratory experiments performed by Muñoz et al. (1997). This result is consistent with the effect of travel distance on the dispersivity of the medium reported in the literature, especially in heterogeneous soils having considerable variability in properties (Gelhar et al., 1992; Vauclin, 1994). The higher hydraulic conductivity of Muñoz et al. (1997) is explained because they use a homogenized sandy tailings from the same tailings pond but with particle diameters greater than those used in this study.

## Leaching Test

The injected and extracted flow rates during the test are shown in Figure 7. A total of 13 838 $m^3$ of solution was injected during 44 days whereas only 6456 $m^3$ was recovered, i.e., 54% of the flow injected was not recovered. The extraction capacity of the wells was limited possibly by the existence of the silt and clay lenses. The low injection and extraction flows observed on days one and five were due to an unintentional interruption of the flow. Starting from the eighth day, the extraction flow began to decrease despite injection flows remaining high, indicating an obstruction occurring in the extraction wells and/or their surroundings from the entrainment of finer material, thus causing the excess of injected flow to run off outside of the wellfield. After detection of the obstruction on day nine, the maximum capacity of all of the extraction wells decreased to around 1.5 L/sec. The injected flow rate remained high (5.5 L/sec.) until day 30 (Fig. 8), when the flow rate was reduced to 1.5 L/sec.

When viewed from a metallurgical standpoint, copper enriched solution was obtained from the nine extraction wells. Figure 8 shows the minimum, maximum and average concentrations of copper measured from the nine extraction wells. The average copper concentration increased rapidly until reaching a peak of 1241 mg/L on day six, gradually descending thereafter to values on the order of 500 mg/L on day 43. The pH obtained at the extraction well outlet remained around 2.5.

On the basis of the measured copper concentrations and flows, total copper extraction during 44 days of operation was estimated at 5160 kg. Considering that the area subject to leaching corresponded to a box of 3600 $m^2$ on its base by 23 m high, and that the average dry density of the tailings was 1470 $kg/m^3$ with an average copper grade of tailings of 0.22%, the copper recovery was estimated at 1.9%. However, since the only material participating in the leaching process was the saturated permeable portion, which was only approximately 15 m thick, the recovery thus obtained was 3.0% of the total copper contents in the tailings.

## Model Simulation

The model developed by Muñoz et al. (1997) was used to simulate the leaching test performed in the present study. It is a two-dimensional macroscopic model that simultaneously takes into account acid convection, dispersion and consumption along with copper convection, dispersion, solubilization, and adsorption-desorption. The chemical parameters used in the model govern acid consumption and copper solubilization, adsorption, and desorption. The physical, hydraulic, and hydrodispersive values determined on the basis of the field experiments were used as input for these simulations.

Two applications were made with the model. The first of these (calibration A) was run with the same chemical parameters as those obtained in the laboratory testing (Muñoz et al., 1997) while the leachable fraction was used as the only fitting parameter, in order to analyze the predictive power of the model. The second application (calibration B) included the calibration of the acid consumption coefficients, the copper extraction coefficient and the coefficient for the leachable fraction. For both calibrations, the hydrodispersive parameters determined from the tracer test and a copper grade of 0.25% were used. A summary of all parameters taken into consideration for the two simulations is shown in Table 3. The preconditioning period

Fig. 8. Comparison between experimental (average along with minimum and maximum) and simulated values for copper concentration in this study.

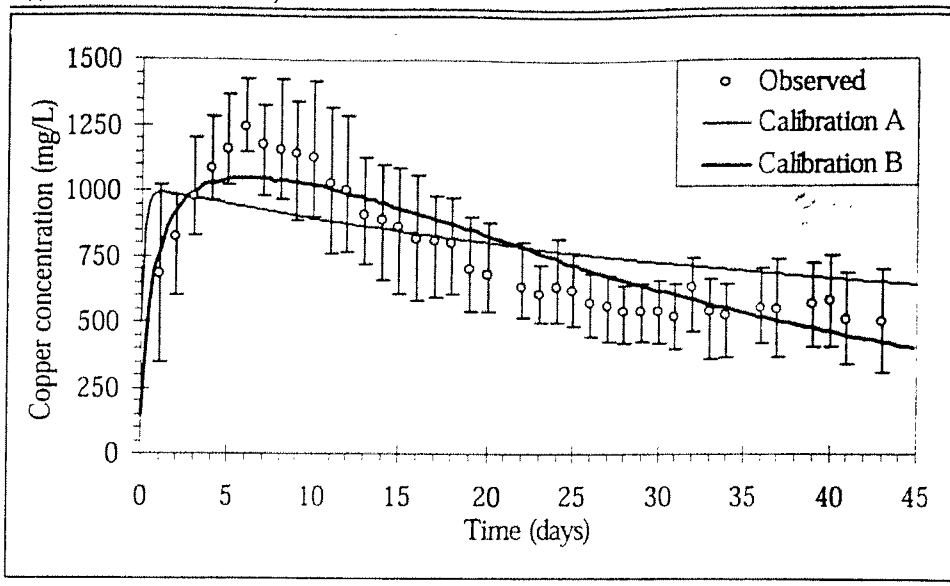



Table 3. Values of parameters used in modelling

| Parameter | Batch tests | Calibration A | Calibration B |
|---|---|---|---|
| **Physical parameters** | | | |
| Saturated thickness (m) | | 23.0 | 23.0 |
| Density (kg/m$^3$) | | 1470 | 1470 |
| Copper ore grade (g/kg) | | 2.5 | 2.5 |
| **Hydraulic parameters** | | | |
| Horizontal hydraulic conductivity (m/sec.) | | $4.9 \cdot 10^{-6}$ $^f$ | $4.9 \cdot 10^{-6}$ |
| **Dispersive parameters** | | | |
| Longitudinal dispersivity (m) | | 0.60 $^f$ | 0.60 |
| Transversal dispersivity (m) | | 0.21 $^f$ | 0.21 |
| Medium porosity (m$^3$/m$^3$) | | 0.40 $^f$ | 0.40 |
| **Chemical parameters** | | | |
| Adsorption coefficient (m$^3$/kg) | $1.0 \cdot 10^{-4}$-$3.0 \cdot 10^{-4}$ | $8.67 \cdot 10^{-5}$ * | $8.67 \cdot 10^{-5}$ |
| Extraction coefficient (s$^{-1}$) | $3.0 \cdot 10^{-2}$-$1.9 \cdot 10^{-1}$ | $5.75 \cdot 10^{-3}$ * | $4.00 \cdot 10^{-3}$ |
| First decay coefficient (s$^{-1}$) | $8.6 \cdot 10^{-5}$-$7.5 \cdot 10^{-4}$ | $4.02 \cdot 10^{-5}$ * | $0.80 \cdot 10^{-5}$ |
| Second decay coefficient (s$^{-1}$) | $0$-$1.2 \cdot 10^{-5}$ | $2.60 \cdot 10^{-5}$ * | $0.80 \cdot 10^{-5}$ |
| Leaching fraction (%) | 37-86 | 30 | 26 |

* Muñoz et al. (1997)
$^f$ from tracer test of this study

as actually performed also was included in the two simulations.

Upon comparing the values for the calibrated chemical parameters with the values determined in the batch experiments (Table 3), the leachable fraction was found to be greater in the laboratory. This difference was expected since better contact between the particles and the solution occurred in the laboratory, and the impermeable strata encountered in the field were not considered in the model. However, the absorption coefficient was similar, and the coefficient of initial acid decay and the coefficient of copper extraction were found to be at least one order of magnitude less in the field than in the laboratory. The second acid decay coefficient was within the same range of calibrated variation as the values determined in the laboratory.

The results obtained with the model are also shown in Figure 8. These results are based on considering the beginning of the leaching test as occurring immediately after completion of the conditioning phase.

Calibration B had a residence time equal to that measured in the field and yielded a greater degree of correlation than calibration A (0.91 and 0.79, respectively). The amounts of copper recovered in 44 days when calculated with the two calibrations (3900 kg with A and 3980 kg with B) were less than the actual amount in the field (5160 kg) because these models assumed a constant flow rate throughout all of the test (1.4 L/sec.), and also neglected the greater initial flow extracted during the first eight days of the test. The amount of copper that would have been recovered in the field, i.e., if the flow had been constant and equal to that used in the models, and if the same copper concentrations had been involved, would have been only 3840 kg, an amount that is similar to that obtained with calibration B.

The difference between the results obtained with calibration B and the field results was due, in part, to the difference between the constant flow rate of 1.4 L/sec. assumed in the model and the actual flow rates in the field which varied from 4.3 L/sec. during the initial period to 1.4 L/sec. afterwards. This situation caused the peak observed concentration to be greater and narrower than that modelled. In addition, the coefficients for calibrated acid consumption and copper extraction were lower than those determined in the laboratory, possibly resulting from a lower leaching efficiency in the field due to the considerable medium heterogeneity that likely gave rise to preferrential flow paths.

The measured acid concentration decayed rapidly during the first four days, and thereafter remained at values less than 1 g/L. The model simulation, based on the laboratory parameters (calibration A), exhibits an extremely rapid decay that does not adequately simulate the measured acid behaviour. Calibration B, based on fitted decay parameters, shows better results. However, the fitted decay coefficients were less than those calibrated in the laboratory indicating that the acid reactions in the field proceeded more slowly, probably due to the presence of the microstrata with relatively low permeability.

## Conclusions

The tailings impoundment in this study consisted of highly permeable horizontal lenses resulting in principally horizontal flow patterns that significantly affected the efficiency of the in situ leaching of copper.

The average hydraulic conductivity of the medium estimated on the basis of pumping tests ($4.9 \cdot 10^{-6}$ m/sec.) was similar to the values estimated by both the Lefranc tests (between $1.8 \cdot 10^{-6}$ and $16 \cdot 10^{-6}$ m/sec.) and the laboratory tests performed on Shelby tube samples (between $1.16 \cdot 10^{-6}$ and $3.15 \cdot 10^{-6}$ m/sec.). Hydraulic conductivities estimated from the Lefranc type tests and the laboratory tests carried out on Shelby tube samples, unlike that estimated on the basis of pumping tests, corresponded to point values and were indicative of the approximate range of variation of hydraulic conductivity between the different strata making up the profile of the medium.

Below a 28 m depth, the hydraulic conductivities were an order of magnitude lower than at shallower depths. As a result, only the tailings between the water table (depth 5 m) and a low-permeability tailings at 28 m depth are amenable to leaching.

Vertical hydraulic conductivity was found to be much lower than horizontal hydraulic conductivity, amounting in some cases to as much as two orders of magnitude lower. However, the results obtained from the pumping tests and the tracer test showed a relatively homogeneous behavior of the medium despite the existing local heterogeneity.

The leaching test did not yield satisfactory results, with approximately 50% of the injected flow escaping the wellfield. A portion of this diverted flow may have resulted from clogging of the extraction wells with fine-grained material during the initial days of operation and/or to the presence of two very permeable strata located in the upper part of the medium.

From an economic viewpoint, the copper recovery from this tailings pond would not be profitable based on the application of the in situ leaching technology in this study, because the copper recovery was slow, and with a maximum recovery in the long term, estimated to be only 26% of the total copper content in this tailings deposit.

Simulations performed using the model developed by Muñoz et al. (1997) adequately reproduced the trends of total copper concentration during the leaching of copper ore tailings deposits by means of injection and extraction wells. In particular, the model simulations adequately reproduced the quantity of total copper obtained and the approximate fate of its concentration. The model simulations can be improved substantially if the chemical parameters are appropriately calibrated on the basis of field experiments that take into account any heterogeneity in the medium.

Applications of in situ leaching technology employing solution injection and extraction wells for use on copper ore tailings deposits require having appropriate knowledge of the medium in each case. The most important aspect that should be known is the stratigraphy of the deposit, including the hydraulic conductivity and thickness of each stratum. This information along with the application of predictive models for flow and transport allow for the possibility to evaluate economically the convenience of exploiting a given tailings deposit using the in situ leaching technology.

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NEWS IN BRIEF

# International Seminar on the Review of the Environmental Agenda

The Comisión Chilena del Cobre, the Consejo Minero a.g. and the Universidad de Concepción are inviting the mining community to participate in the International Seminar on Review of the Environmental Agenda: New Initiatives in the Mining Sector, that will be held in conjunction with EXPOMIN 2002, on **May 8-9, 2002 in Santiago, Chile.**

The objective of this seminar is to invite government officers, delegates from mining companies and academia, and other associations, to expose, analyze, and discuss the main aspects of mining and the environment, such as; public policies and regulatory trends; mining and sustainable development; the trends in the metals market; mining and public health; technological innovation for the efficient use of the natural resources and environmental management of the mining industry.

Authors are invited to submit an abstract of their paper in English or Spanish by **November 30, 2001.** Sufficient details to permit a thorough review and evaluation of the paper's eligibility must be provided.

Final acceptance of papers will be confirmed by **January 15, 2002.** Final versions of the papers are due **March 15, 2002.** Send paper title, 200-word or less abstract, authors name, brief CV, telephone number, fax number, e-mail and complete address to one of the following:

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Registration fees for the seminar are General attendee: US$200; Student: US$50. Cheques must be made payable to "Comisión Chilena del Cobre."

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