Particle size distribution for copper heap leaching operations as established from 3D mineral exposure analysis by X-ray microCT

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ABSTRACT

The particle size distribution (PSD) for copper heap leaching is an important consideration in the design and operation of any copper heap leaching facility. High-resolution 3D X-ray microtomography (XMT) can be used for the direct determination of the percentage of exposed valuable mineral grains in multiphase particles which vary in size from 40 mm down to a few hundred microns. For cone-beam CT, a whole 3D data set is acquired with only one rotation of the sample. Clearly, cone-beam CT has the best prospects for true 3D exposure analysis of packed particle beds and is able to provide the necessary accuracy to quantitatively describe the 3D distribution of micron-sized mineral grains in multiphase particles. Using recently developed software, microCT data can be used to determine the fraction of mineral exposed and thus estimate the extent of recovery. XMT technology consists of examining the degree of mineral exposure for each size fraction in 3D, then, with the use of algebraic calculations, the extent of recovery can be estimated for different particle size distributions. To confirm the usefulness of such mineral exposure analysis, column tests were performed using three PSDs for three samples of ore composites obtained from the copper heap leaching operation at Zaldivar-Chile.

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INTRODUCTION

Considerable advances have been made in the practice of heap leaching. Technical progress was revealed in the recent "International Technical Meeting on the Development of Copper Bioleaching Technology" sponsored by Compañía Minera Zaldívar (CMZ) and held in Antofagasta, Chile, 12-14 March 2001, during which time heap leaching at CMZ was reviewed. Heap leaching is a process extensively used by the mining industry to recover metals from large quantities of submarginal grade materials. Currently, heap leaching finds important applications in the recovery of copper from its ores because of its low cost, short construction time, operational simplicity, good performance, and environmental advantages.

In the heap leaching process, inclusions of the valuable minerals (copper bearing minerals) are to be dissolved from ore particles. The copper bearing minerals have some unknown grain size distribution, texture/exposure, and spatial distribution in the ore particles. In order to build a heap for copper recovery, the mined ore is crushed to an appropriate particle size so that the valuable mineral grains are exposed and can be extracted. Then, the crushed ore is mixed with sulfuric acid solution in an agglomerating device at an optimum moisture content to consolidate the fines with the coarser material and to precondition the ore for bacterial development. Subsequently the material is piled on a lined pad or on top of previously leached ore. Proper aeration is provided to the bacteria through plastic piping with ventilation holes that are distributed along the pad. The heap is irrigated with fresh sulfuric acid solution, recycled leaching solution, or a mixture of both, depending on the circumstances. The flowrate of the leaching solution should allow for nonsaturated flow through the leaching heap. The pregnant leaching solution is discharged at the base of the pad, stored in a pond, and directed to a solvent extraction – electrowinning (SX-EW) facility for copper recovery. The leaching solution, depleted of copper, the raffinate, is recycled to the heap.

Detailed analysis of copper heap leaching systems should involve both the chemistry/biochemistry and the mechanics of the system. Optimum design of the chemistry, utilization of reactants (acid, air, microorganisms, bacteria population, iron), is limited by our current understanding of the mechanics of the system. The mechanics of the copper heap leaching system include such issues as particle breakage/exposure/liberation, particle texture/composition, and fluid flow phenomena inside the packed bed of particles which constitute the heap. Once these issues (such as how particle size distribution influences both mineral exposure/liberation and flow behavior) are resolved more appropriate heap designs and an optimal chemical schedule can be established.

First, if we can determine the relationship between the percentage of exposed valuable mineral with respect to particle size for a given ore type, the extent of recovery in the heap leaching process can be predicted for a specific particle size distribution. Then, the size of the heap is not only related to economic factors of the crushing circuit and its capacity but to the permeability characteristics of the heap. Excessive fines will block flow channels, retaining the pregnant solution inside the heap and reducing the efficiency of the process. This problem can be partially solved by including an agglomeration circuit prior to stacking the ore. An optimum specification of the particle size distribution for the heap should balance mineral exposure and permeability in order to obtain the highest recovery; instead, historic d_{80} and/or d_{10} values are only taken into consideration today for the design of the crushing circuit. The importance of the PSD is evident because first of all it controls solution flow via the permeability of the heap and, second, the PSD establishes the extent of mineral exposure and hence the amount of copper that can be leached in a reasonable time provided the chemistry/biochemistry is in order.

Until recently it has not been possible to accomplish mineral exposure analysis by traditional mineralogical techniques due to stereological limitations. It is important to note that exposed copper mineral grains can be identified only through 3D analysis of multiphase particles. Now such analysis is possible using cone beam X-ray (XMT) (1). Using the 3D images obtained from the X-ray tomographic scan, the percentage of exposed valuable mineral grains can be determined and, assuming that all those grains would be accessed by the leaching solution, the recovery predicted for given particle size distributions (PSDs). If the method can be developed to make accurate predictions, crushing circuits can be redesigned and the efficiency of heap leaching operations improved based on mineral exposure analysis. In this study, the new XMT technique has been applied for several different copper ore composites encountered at the Compañía Minera Zaldívar (Antofagasta-Chile). Considering the fact that the current PSD used at Zaldivar provides satisfactory permeability conditions, the same d_{80} and d_{10} were adopted to prepare two new PSDs. Then based on the data obtained from the XMT the ultimate recovery for these composites was predicted for each of three particle size distributions. Column leach testing was carried out, in duplicate, in 1.5-m columns, for each sample (total 18 tests) in order to improve our confidence in the results from the column leach experiments. The recoveries from column leach experiments were then compared to ultimate recovery predictions from mineral exposure analysis by XMT.

METHOD

High-Resolution 3D X-Ray Microtomography (XMT)

The application of the principles of cone-beam computed tomography (CT) at the microscale level (microtomography) allows for the quantitative examination of objects in three dimensions. Practical microtomography systems only recently have been developed. As the resolution and the techniques for 3-D geometric analysis have advanced in the last decade, it is now possible to map in great detail the mineralogical texture of ore particles in three-dimensional digital space. High-resolution 3-D X-ray microtomography (XMT) can be used for the direct determination of the percentage of exposed valuable mineral grain in multiphase particles which vary in size from 100 mm down to a few hundred microns. Spatial resolution on the order of ten micrometers can be achieved with the use of microfocus X-ray generators.

For cone-beam CT, a whole 3-D data set is acquired with only one rotation of the sample. This provides for fast data acquisition and better x-ray utilization. In a cone-beam design, each projection of the object is, in essence, a radiograph. Attenuation measurements are simultaneously made for the entire object rather than for a single slice. Clearly, cone-beam CT has the best prospects for true 3D liberation/exposure analysis and should be able to provide the necessary accuracy to quantitatively describe these micron-sized multiphase systems such as the multiphase particles encountered in heap leaching operations. As shown in Figure 1, a unique, custom designed cone beam x-ray microtomography system installed at the University of Utah (2) was used for this study.

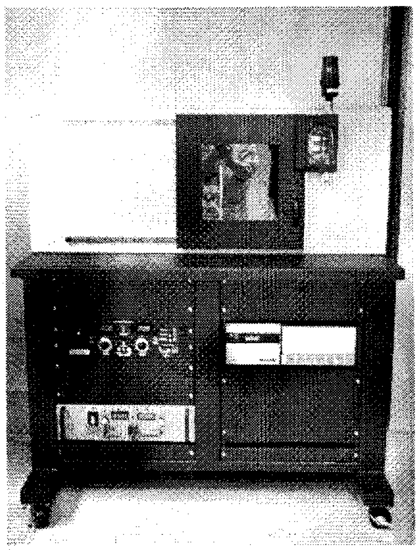

Figure 1 – The Cone-Beam X-Ray MicroCT System

Sample Preparation

The mine site selected for sampling was that of Compañía Minera Zaldívar located about 160 km east of Antofagasta, Chile. Representative samples from three composites were screened into ten size fractions (25.4x19.1, 19.1x12.7, 12.7x9.5, 9.5x6.36, 6.36x3.18, 3.18x1.7, 1.7x0.425, 0.425x0.150, 0.150x0.075 and –0.075 mm). These samples, as much as 10 kg for the coarse particle size classes, were prepared by personnel at Zaldívar and were shipped to the University of Utah after the chemical and mineralogical analyses of the various size fractions had been completed. It is noted that composite 6 contains primarily oxide copper minerals, whereas composites 2 and 4 contains primarily sulfide copper minerals. The chemical and mineralogical analyses of the various size fractions had been completed and reported previously (3).

Mineral Exposure Analysis by 3D XMT

Miller et al. (1) previously detailed the equipment and the principles of the XMT technique. Figure 1 illustrates the procedures and steps for 3D mineral exposure analysis by XMT. First, 2D projections of packed particle beds were scanned using cone beam geometry. Then, the 3D image was reconstructed. Using a 3D image processing technique, we can remove all the host rock mineral phase (middle photo) and reveal only the copper bearing mineral grains as shown in the lower right-hand side of Figure 2. Also included in Figure 2 is a sectioned 2-D image along the cutting plane of z-axis. Finally, the overall, internal and exposed grain size distributions of copper minerals were determined as well as the percent of exposure. Each size fraction was analyzed and the relationships between the mineral exposure and particle size for composites 2, 4 and 6 are presented in the results and discussion section.

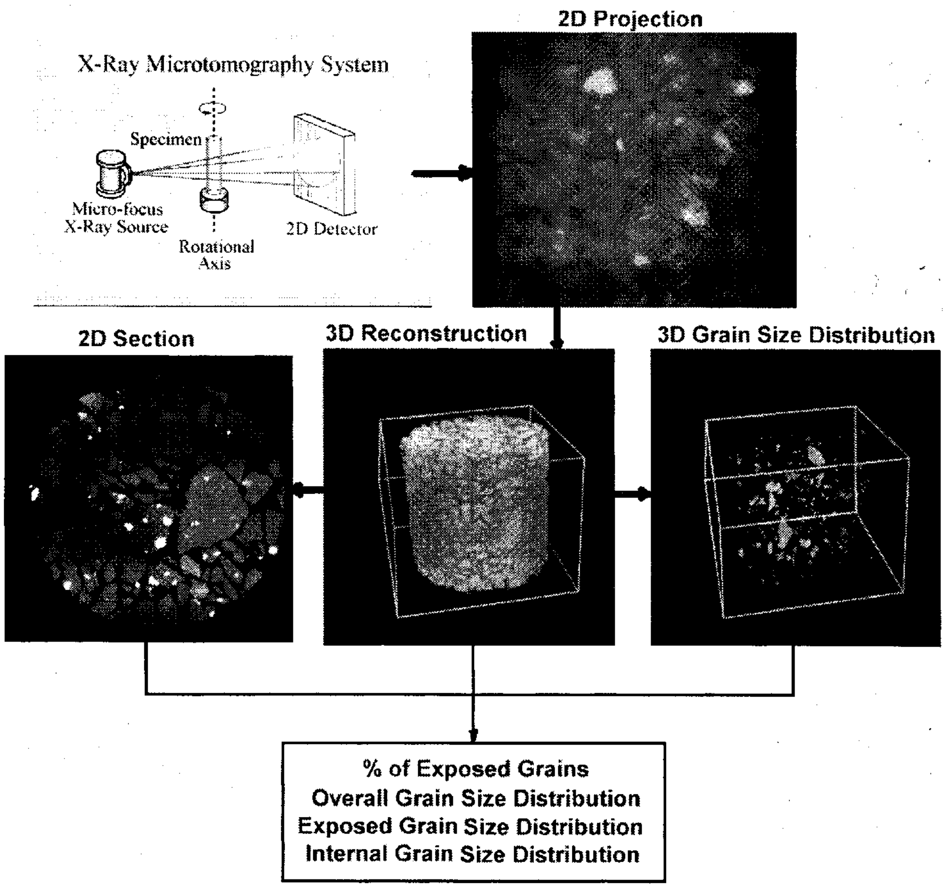

Figure 2 - Steps for Mineral Exposure Analysis by 3D XMT

Exposed grains can be identified only through the analysis of the 3D data set for the particle bed. For instance, four cross sections (from a total of 512 sections) along the Z-direction are extracted and shown in Figure 3. Here the gray scale levels of the images are based on the relative attenuation coefficient and are indicative of different mineral phases present in the sample. The white regions represent sections of the copper mineral grains. Although a specific copper mineral grain, as indicated by the arrows in the middle of the images, looks like an internal grain in the z = 0, 40, and 80 micron images, in reality, this grain is exposed as revealed by the image at 120 microns along the Z-direction. In this fashion, with the use of a special 3D-image analysis algorithm, the internal copper bearing grains can be distinguished from exposed grains during the analysis of packed particle beds.

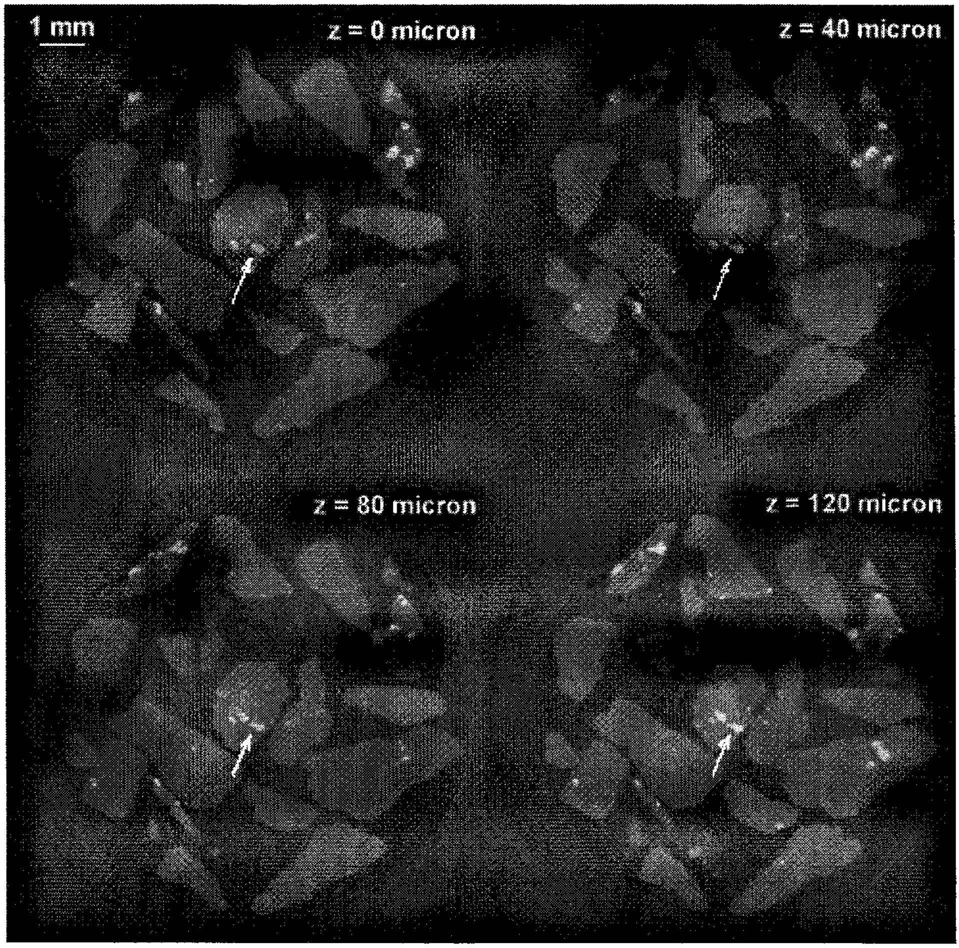

Figure 3 - Cross Sectional Images from the 3D XMT Reconstruction of a Packed Bed of Multiphase Particles. As Indicated by the Arrow, Exposed Grains can be Identified only through the Analysis of the 3D Data Set of Particles

Ultimate Recovery Estimation

The relationship between the percent of copper exposed and particle size, provides the basis for the prediction of copper recovery for a known particle size distribution. In this regard, combining the results of the chemical and the mineral exposure analyses, the ultimate recovery of copper can be estimated for a specific particle size as follows:

$$\begin{pmatrix}\text{Increment Total Copper}\\ \text{in Size Class i}\end{pmatrix}=\begin{pmatrix}\text{Total Copper}\\ \text{in Size Class i}\end{pmatrix}\begin{pmatrix}\text{Weight (\%)}\\ \text{in Size Class i}\end{pmatrix} \tag{1}$$

$$\begin{pmatrix}\text{Increment Exposed}\\ \text{Total Copper}\\ \text{in Size Class i}\end{pmatrix}=\begin{pmatrix}\text{Increment}\\ \text{Total Copper}\\ \text{in Size Class i}\end{pmatrix}\begin{pmatrix}\text{Copper Mineral}\\ \text{Exposure (\%) in}\\ \text{Size Class i}\end{pmatrix} \tag{2}$$

Then the total recovery for a given particle size distribution (PSD) can be estimated as follows:

$$\text{Ultimate Recovery}=\frac{\sum^{n}\text{Increment Exposed Total Copper in Size Class i}}{\sum^{n}\text{Increment Total Copper in Size Class i}}x100 \tag{3}$$

where *i* is the size class and n is the number of size classes.

Column Leaching Tests

Three different particle size distributions (Figure 4) were selected to examine the accuracy of the XMT mineral exposure method. The first PSD is that currently used at Compañía Minera Zaldívar Plant, the second and the third PSDs are designed maintaining the same d_{80} and d_{10} as the current Plant PSD. The differences are in the percentage of the middle sizes and how such variation influences mineral exposure. The two new PSDs are called XMT-1 and XMT-2. The XMT-2 was designed to obtain 80% recovery of copper based on the exposure data of Composite 6. Whereas the XMT-1 particle size distribution was established based on simulation of the current crushing circuit at the Zaldívar Plant site.

The Compañía Minera Zaldívar, based on their experience with these ores, suggested optimum values for the column leach operation (solution composition, solution flow application rate, agglomeration procedure, aeration rate, etc.). See Table I for details. The lixiviant solution was passed through the columns just once with no re-circulation. Due to the low content of copper sulfide minerals, neither bacteria nor air was used for columns containing Composite 6.

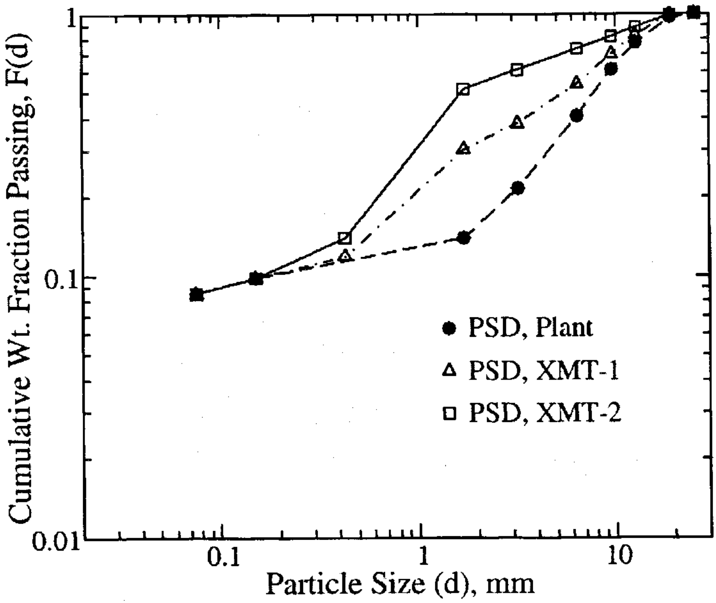

Figure 4 - Particle Size Distributions used in the Column Leaching Tests

Table I - Operating Parameters for 1.5 m Column Leaching Tests

Parameters	Composite 2	Composite 4	Composite 6
Height (m)	1.5	1.5	1.5
Diameter (cm)	20.32	20.32	20.32
Optimum agglomeration moisture (%)	4.8	7.1	7.3
Acid content (kg H_2SO_4/ton)	8.0	8.0	8.0
Solution flow rate ($m^3\ h^{-1}\ m^{-2}$)	0.008	0.008	0.008
Air flow rate ($m^3\ h^{-1}\ m^{-2}$)	0.15	0.15	None
[Fe^{+2}] inlet solution (kg/m^3)	1.2	1.2	1.2
[Fe^{+3}] inlet solution (kg/m^3)	1.0	1.0	1.0
pH inlet solution	1.5	1.5	1.5
E^o inlet solution (V) vs SHE	0.66	0.66	0.66
Bacteria inoculation	Yes	Yes	None
Feed grade (%Cu)	1.02-1.67	0.66-1.49	0.59-0.74

RESULTS AND DISCUSSION

Mineral Exposure and Ultimate Recovery Estimation

As mentioned previously, the ultimate recovery in the heap leaching process can be predicted for a specific particle size distribution, if we can determine the relationship between the mineral exposure and particle size for different ore types. In this regard, representative samples of particles from different size intervals were taken and put into a cylindrical container for XMT analysis. Scanning time was varied depending on the resolution and the number of views. For example, for 20-micron resolution and a 512x512x512 data set, the scanning time is about one hour and full three-dimensional reconstruction requires approximately 2.5 hours.

Relationships between copper exposure and particle size for all three composites are illustrated in Figure 5. It is noted that two size fractions (25.4x19.1 and 19.1x12.7 mm) are under-sampled. It is important to note that these exposure curves have a common shape which is related to the grain size distribution of the copper minerals and in the cases for this study, a critical particle size can be identified. Particles exceeding this critical size have a significant reduction in the extent of exposure. For example, in the case of Composite 4 the critical particle size is 6.35 mm whereas in the case of Composites 2 and 6 the critical particle size is 3.18 mm as shown in Figure 5. For Composite 4, it is found that more than 98% of the copper mineral grains are exposed for particle sizes less than 0.425 mm. Many large, almost completely liberated, copper mineral grains (clusters of grains) were found in particle size classes of 3.18x1.7 mm, and 1.7x0.425 mm.

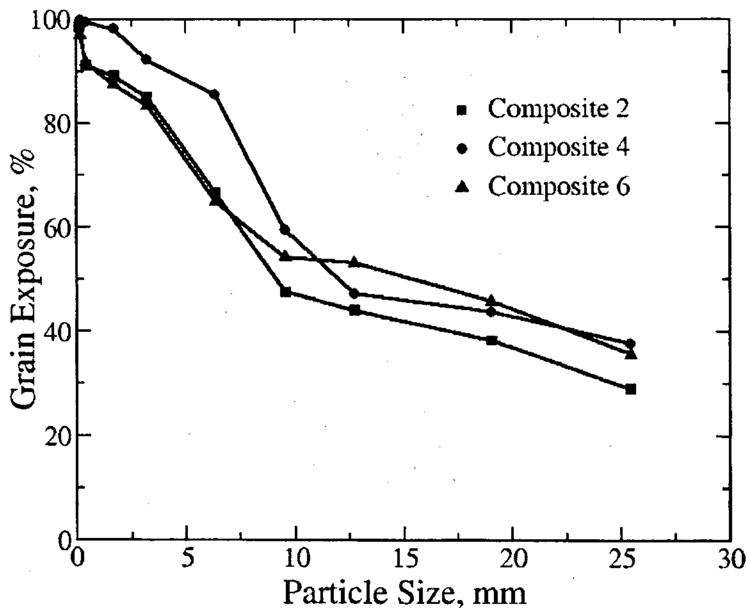

Figure 5 – Copper Mineral Exposure with Respect to Particle Size
for Composites 2, 4 and 6

Of course, copper mineral inclusions have a certain size distribution (grain size distribution). The heap leaching process should be designed to crush the ore so that the copper mineral grains are exposed and can be leached. Figure 6 presents the overall grain size distribution for various particle size classes for the Composite 4 sample. A 3D connected components labelling technique was used to label and classify each individual grain volume (number of voxels). In this way, then, the grain size is defined as the cube root of the grain volume. It is noted that the copper mineral grain size distribution is bimodal for Composite 4. Of course the exposure curve, as shown in Figure 5, is influenced by this bimodal grain size distribution. In any event, the exposure analysis can be used to establish an appropriate particle size distribution for any heap leach operation.

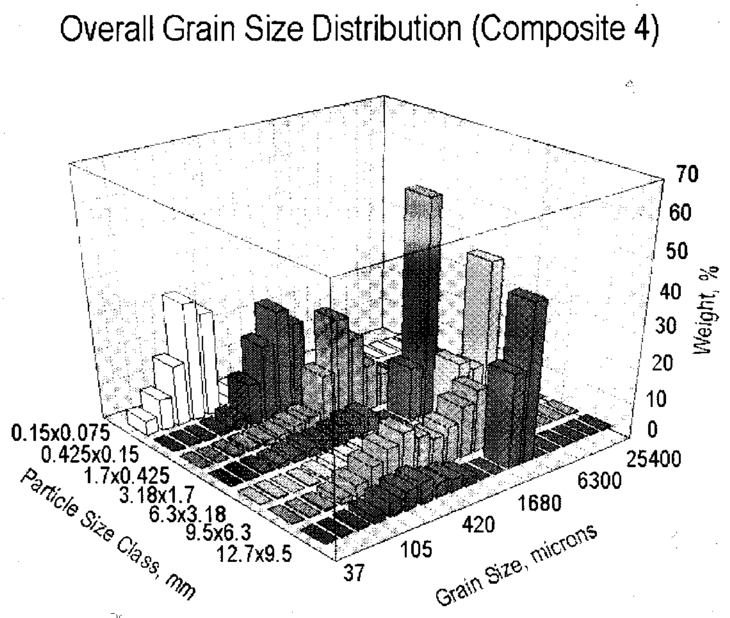

Figure 6 - Overall Grain Size Distributions of Composite 4 for Different Particle Size Classes

As expected from Figure 5 the exposure decreases with an increase in particle size. The slope of the curve is much more pronounced below 10 mm indicating that the exposure can be increased significantly by increasing the amount of material in the middle size classes. Composite 4 shows a better exposure than Composites 2 and 6; for coarse sizes the exposure is very similar. A better recovery should be expected from Composite 4, for an equivalent PSD and appropriate chemical conditions.

Table II shows the calculated ultimate recovery for Composites 2, 4 and 6; these values were obtained using equations 1 to 3 for the three different PSDs. Results show that the predicted recovery for the Composite 4 is greater than for Composites 2 and 6.

Furthermore the ultimate recovery for Composite 4 could be increased by 10% using PSD XMT-1 and up to 18% using PSD XMT-2. For Composite 6 the ultimate recovery is improved up to 8% using the XMT-1 particle size distribution and up to 13% with XMT-2 PSD. For Composite 2 the ultimate recovery is improved up to 6% using the XMT-1 particle size distribution and up to 15% with XMT-2 PSD.

Table II - Predicted Ultimate Recovery for Three Different Particle Size Distributions

PSD	d_{50} (mm)	Ultimate Recovery (%)		
		Composite 2	Composite 4	Composite 6
Plant	8.0	63.2	73.8	67.0
XMT-1	5.2	69.6	83.2	73.9
XMT-2	0.8	78.0	91.1	80.8

Column Leaching Tests

Ultimate recovery values from column leaching tests for composites 2, 4 and 6 are shown in Tables III, IV and V and are compared with predicted recovery values as determined by mineral exposure analysis. Also, included in these tables is total leaching time and acid consumption. Estimated values of recovery from mineral exposure analysis for Composite 4 using XMT-1 and XMT-2 PSDs agree with those obtained in the columns leaching tests. For the Plant PSD the experimental results show an underestimation, the difference between the estimated value and the experimental value is around 10%. The Composite 6 shows a different behaviour, the experimental recoveries for the coarse (PSD Plant) and the fine size distributions (PSD XMT-2) agree with the prediction, however the recovery for the intermediate size (PSD XMT-1) was underestimated by about 10%. For Composite 2, in general, recoveries for three PSD were underestimated in the range of 7 to 10%.

It is noted that the predicted recoveries from XMT exposure analysis are, in general, underestimated compared with the actual recoveries from column leaching tests. Several reasons can account for this discrepancy. First, particles are broken and cracks are extended during the leaching tests, which will generate new exposed grains. This difference can be corrected by particle size analysis before and after column leaching tests. Second, resolution for the XMT analysis is limited to 5 microns. If the fracture crack networks inside the particles are less than 5 microns, the internal grains can still react. Finally, the internal grains embedded near the particle surface may have a chance to be leached. It is expected that even better agreement will be realized when these factors are incorporated into the data analysis. In any case the XMT-2 PSD shows the highest ultimate recoveries. These results agree with the prediction made by the XMT mineral exposure analysis, XMT-2 PSD has the greatest amount of intermediate sizes, which means, according to Figure 5, a greater percentage of copper mineral exposed.

Table III - Column Leaching Test Results for Composite 2

	PSD Plant (d_{50} = 8.0mm)		PSD XMT-1 (d_{50} = 5.2mm)		PSD XMT-2 (d_{50} = 0.8mm)	
Column Test No.	1	4	3	6	2	5
Recovery Predicted (%)	63.2		69.6		78.0	
Recovery Obtained (%)	75.1	73.9	75.5	77.5	85.7	84.1
Leaching Time (days)	81	76	94.0	91.2	91	82
Acid Consumption (kg/ton)	6.61	6.25	5.66	5.50	4.93	6.78

Table IV - Column Leaching Test Results for Composite 4

	PSD Plant (d_{50} = 8.0mm)		PSD XMT-1 (d_{50} = 5.2mm)		PSD XMT-2 (d_{50} = 0.8mm)	
Column Test No.	7	10	9	12	8	11
Recovery Predicted (%)	73.8		83.2		91.1	
Recovery Obtained (%)	83.7	86.7	85.5	84.7	90.0	93.3
Leaching Time (days)	85	83	82	84	80	83
Acid Consumption (kg/ton)	6.23	6.04	6.91	6.82	6.64	6.86

Table V - Column Leaching Test Results for Composite 6

	PSD Plant (d_{50} = 8.0mm)		PSD XMT-1 (d_{50} = 5.2mm)		PSD XMT-2 (d_{50} = 0.8mm)	
Column Test No.	13	16	15	18	14	17
Recovery Predicted (%)	67.0		73.9		80.8	
Recovery Obtained (%)	74.3	68.3	81.8	82.4	84.5	83.8
Leaching Time (days)	71	73	70	76	72	73
Acid Consumption (kg/ton)	9.88	10.65	7.78	7.60	8.04	80.4

Figures 7, 8 and 9 illustrate the kinetics for the recovery of copper from Composites 2, 4 and 6, respectively. Again XMT-2 PSD provides for the best recovery rate. For both composites the rate of recovery is greater for XMT-2 PSD; it is evident that smaller sizes with greater exposure allow for better contact between the leaching solution and the copper mineral grains. Finally comparing the column leach kinetics, the rate of recovery for Composite 6 is faster than Composites 2 and 4 even thought the ultimate recovery is greater for Composite 4. These results demonstrate the significance of the chemical reaction rate since Composite 6 contains primarily oxide copper minerals, whereas Composites 2 and 4 contain primarily sulfide copper minerals.

SUMMARY

In summary, ultimate recovery can be directly predicted from mineral exposure analysis by XMT as demonstrated for three different particle size distributions (PSDs) and three different ore composites. No other factors, such as solution flow rate, porosity, permeability or erosion were considered. Although good agreement with copper recovery predicted by mineral exposure analysis was achieved further research is in progress. This research will involve modification of the mineral exposure analysis procedure to account for secondary factors and in this way it is expected that even better predictions can be made in the future. Already improved recovery from heap leaching operations has been achieved by using the PSD recommended from mineral exposure analysis.

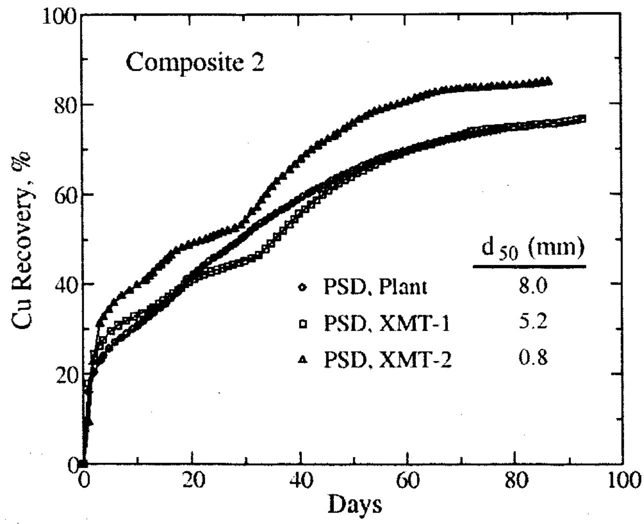

Figure 7 - Copper Recovery versus Time for Composite 2

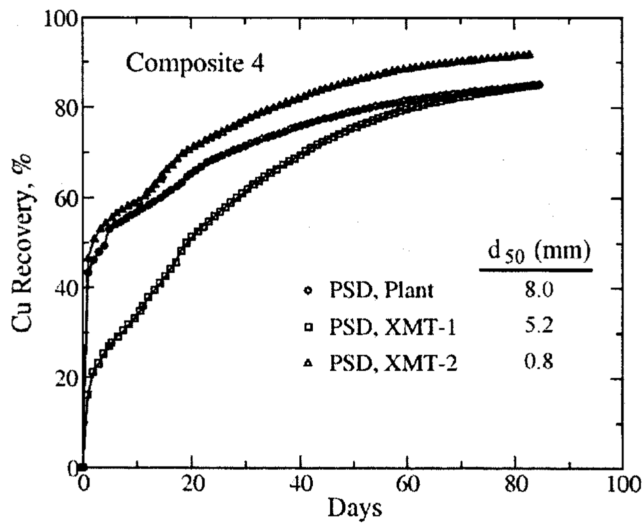

Figure 8 - Copper Recovery versus Time for Composite 4.

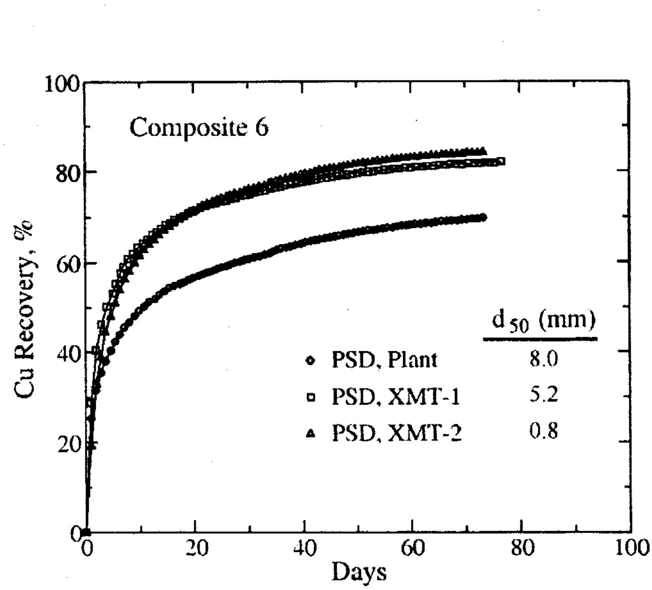

Figure 9 - Copper Recovery versus Time for Composite 6.

The predicted recoveries from XMT exposure analysis are slightly underestimated compared with the actual recoveries from column leaching tests. Several reasons can account for this discrepancy. First, particles are broken during the leaching tests, which will generate new exposed grains. This difference can be corrected by particle size analysis before and after column leaching tests. Second, the resolution for the XMT analysis is limited to 5 microns. If the fracture crack networks inside the particles are less than 5 microns, the internal grains can still react. Finally, the internal grains embedded near the particle surface may have a chance to be leached. It is expected that even better agreement will be realized when these factors are incorporated into the data analysis procedure. In any case the XMT-2 PSD shows the highest ultimate recoveries. These results agree with the prediction made by mineral exposure analysis; XMT-2 PSD has the greatest amount of intermediate sizes, which means a greater percentage of copper minerals are exposed. It is evident that mineral exposure analysis is a most powerful technique to determine the ultimate recovery in heap leaching operations, and research is in progress to establish its full potential.

ACKNOWLEDGEMEMTS

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