up

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

MASTER
UCRL - 73284
PREPRINT

CONF-720204--3

LAWRENCE LIVERMORE LABORATORY
University of California/Livermore, California

NUCLEAR CHEMICAL MINING OF PRIMARY COPPER SULFIDES

Arthur E. Lewis

Robert L. Braun

January 27, 1972

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

This paper was prepared under the auspices of the
U. S. Atomic Energy Commission for presentation at the
AIME, 1972 Meeting, San Francisco, California

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

84

NUCLEAR CHEMICAL MINING OF PRIMARY COPPER SULFIDES*

Arthur E. Lewis and Robert L. Braun

Lawrence Livermore Laboratory, University of California
Livermore, California 94550

ABSTRACT

A contained nuclear explosion is proposed to produce a chimney of broken ore well below the water table. After the chimney is filled with water and reaches hydrostatic equilibrium, oxygen, under pressure, is introduced near the bottom of the mass of broken rock. The increase in solubility of oxygen at high hydrostatic pressure is sufficient to initiate the oxidation of the primary sulfides: chalcopryrite and pyrite. The oxidation and dissclution of these sulfides produces enough heat to increase the temperature of the ore and water in the chimney as much as 100° to 150°C. The rate of dissolution of chalcopryrite becomes so rapid under these conditions that the rate of recovery is no longer limited by the rate of chalcopryrite dissolution, but by the degree of exposure and other factors.

Means of solution control and distribution of oxygen in the chimney have been examined in some detail. A calculational model utilizing experimentally determined solubility rates is utilized to estimate the temperature rise in the chimney and the rate of copper recovery as a function of initial temperature, sulfide content of ore, size of sulfide particles, and fraction of sulfide exposed to solution.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

It is concluded that the high pressure and high temperature obtainable in a large ore mass broken by nuclear explosives promise the rapid and economic recovery of minerals not considered soluble by conventional in-situ leaching methods. The method should be broadly applicable to the kinds of deep deposits that must be depended on for future production and with minimum disruption of the environment.

INTRODUCTION

A method for the in-situ chemical mining of primary sulfide ores, which promises to have a major impact on the technology and economics of recovery of some metals from their ores has been proposed.¹⁻⁴ If successful, the process will greatly increase the reserves of metals such as copper and nickel by reducing the cost of production of deep, disseminated deposits and will significantly reduce some of the undesirable effects on the environment that are unavoidable with conventional mining methods.

To leach metal from primary sulfide ores the ore must be broken up to allow solutions capable of dissolving the metal from the ore to come in contact with the ore. The cost of breaking ore by conventional mining techniques and the failure of commonly available sulfuric acid and ferric sulfate solutions to leach primary minerals such as chalcopyrite (CuFeS_2) have prevented the in-situ chemical mining of primary sulfide ores.

In the method proposed, contained nuclear explosives would be used to break the ore. These explosives are capable of breaking large tonnages of ore at depth; the tonnage being dependent on the explosive yield of the nuclear device and the depth for any given rock type (Fig. 1).

The chimney of broken rock is constructed well below the water table and is allowed to fill with water either by natural inflow of groundwater or by diversion of surface water (Fig. 2). Estimated chimney properties⁵ are shown in Table I. Oxygen may be introduced into the bottom of the chimney through drill holes. It will be dissolved in the water as it percolates upward. The solubility of the oxygen is much greater under hydrostatic pressure than it is in water at 1 atm. The dissolved oxygen greatly increases the rate of oxidation and dissolution of the primary sulfide minerals. The oxidation of the sulfide minerals produces a large amount of heat, which is effective in raising the temperature of the chimney contents many tens of degrees centigrade because of the low conductivity of rock surrounding the chimney and the low surface-to-mass ratio of a large chimney.

The net result is a rapid dissolution of primary sulfides under conditions of high temperature and high oxygen solubility at high hydrostatic pressure. The solutions would be withdrawn from the chimney through drill holes, processed in a solvent extraction plant to remove the metal values, and returned to the chimney in a closed circuit.

Undesirable flow of solutions out of or into the chimney through fractures or other permeable paths may be controlled by maintaining the hydrostatic equilibrium between the chimney and the surrounding rocks. The chimney will therefore behave as a suitable container for this process even though the rocks surrounding the chimney may not be entirely impermeable.

SULFIDE DISSOLUTION

The two minerals of interest in this application are chalcopyrite and pyrite.

Chalcopyrite is the chief copper mineral in primary copper deposits; pyrite is

almost always present and affects the dissolution process principally because of the heat generated as it dissolves.

The effect of oxygen pressure on the relative rate at which chalcopyrite is dissolved at 50°C is shown in Fig. 3. By measuring the surface area of the chalcopyrite, the rate of dissolution as a function of surface area and temperature was obtained (Fig. 4). These data were obtained by bubbling O_2 through a pressure vessel containing the chalcopyrite sample and distilled water. Sulfuric acid is produced in the reaction and rapidly stabilizes at a constant pH between 1.5 and 2.5. The products of the decomposition of chalcopyrite are cupric sulfate, sulfuric acid, hematite, and sulfur. Pyrite decomposes to basic iron sulfate, sulfur, sulfuric acid, and iron sulfate. These reactions are shown in Eqs. (1) and (2).

In a mixed system of chalcopyrite and pyrite the products are mixed and the results are further complicated by films of reaction products. Covellite is also observed where local oxygen depletion occurs.

It is easy to show that when exposed to solutions containing oxygen, chalcopyrite will go into solution rapidly enough for in-situ mining if the temperature approaches 100°C. Information on the dissolution rate of chalcopyrite, as it occurs in ore fragments, is crucial for this application.

Recovery of Copper from Large Ore Fragments

The recovery of copper from large ore fragments is being studied in a 1000 gal pressure vessel shown in Figs. 5 and 6. The vessel was charged with 8.4 tons (5.8 metric tons) of primary sulfide ore and 370 gal (1400 l) of distilled water. Operating conditions are 90°C and 400 psi oxygen. Oxygen was introduced into the bottom of the vessel at a flow rate of 50 SCFH (standard cubic feet per hour) during the first 3 mo. of the run, then reduced to 25 SCFH.

The ore used in this experiment is a specially-selected, coarse fraction of block-caved primary porphyry ore from the Magma Copper Company's San Manuel Mine. The particle size distribution of the ore charge is given in Fig. 7. The maximum diameter is 11 in. while approximately 50 wt% of the ore has a diameter of more than 5 in. Chemical analysis of this primary sulfide ore showed an average grade of 0.7 wt% Cu (as chalcopyrite), a pyrite/chalcopyrite mole ratio of 2, and a CO₂ content of 0.5 wt%.

Periodically, samples of solution and effluent gas are taken for chemical analysis. The fraction recovery of copper (Fig. 8) has reached 0.16 in 160 days. This recovery curve follows the basic pattern discussed by Harris⁶ for leaching low porosity particles of ore in which the sulfide is disseminated throughout. The initially high rate of copper extraction from the chalcopyrite exposed at the surface of the ore fragments is followed by a lower, diffusion-limited rate of extraction of copper from the interior of the fragments. A calculational model based on this recovery curve and on other experimental and theoretical considerations will be discussed later for use in predicting the rate of copper recovery in nuclear solution mining.

Additional, interesting analytical results of this pilot plant are shown in Figs. 9 and 10. The pH of the pregnant liquor (Fig. 9) dropped rapidly from an initial

value of 5.3 to 1.75 (at 40 days) because of the production of H_2SO_4 .

Thereafter, the pH has remained in the range of 1.70 to 1.75, where the system is naturally buffered by the $\text{SO}_4^{-2} + \text{H}^+ \rightleftharpoons \text{HSO}_4^-$ equilibrium and by more complex chemical equilibria.

The rate of CO_2 evolution (Fig. 9) from the decomposition of calcite decreased from an initially high value of nearly 600 g/day to a nearly steady rate of less than 50 g/day after 60 days. The net amount of evolved CO_2 at 160 days corresponds to approximately 50% of the initial CO_2 content of the ore charge. No trace of COS , SO_2 , or H_2S has been detected in the effluent gas by either gas chromatographic analysis or microwave spectroscopy.

A summary of the chemical composition of the pregnant liquor is shown in Fig. 10. The Fe^{+3} content rose rapidly and reached a nearly stable concentration slightly in excess of 0.1 g/l as the pH stabilized at 1.7. The $\text{Fe}^{+2}/\text{Fe}^{+3}$ ratio at this pH stabilized at 0.2. The additional iron liberated by dissolution of chalcopyrite and pyrite precipitates as $\text{Fe}_3(\text{SO}_4)_2(\text{OH})_5 \cdot 2\text{H}_2\text{O}$ (carphosiderite), $\alpha\text{-Fe}_2\text{O}_3$ (hematite), and hydrated iron oxides (goethite and limonite). The K^+ and Na^+ decreased from initial concentrations of 0.1 g/l, probably as a result of precipitation first of $\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$ (jarosite) and then of $\text{NaFe}_3(\text{SO}_4)_2(\text{OH})_6$ (natrojarosite), both of which are isomorphous with $\text{Fe}_3(\text{SO}_4)_2(\text{OH})_5 \cdot 2\text{H}_2\text{O}$.

The Ca^{+2} content, after rising rapidly to 0.5 g/l as a result of dissolution of calcite, remained at 0.5 to 0.6 g/l because of the low solubility of calcium sulfate. The Mg^{+2} and Al^{+3} contents have steadily increased as a result of dissolution of various other minerals in the rock.

Examination of the leached ore and the solid reaction products at the termination of the experiment will enable a more extensive interpretation of the chemical composition changes in the pregnant liquor.

EXTRACTION OF METAL VALUES FROM BROKEN ORE

In the extraction of copper from an ore fragment, the rate of recovery of copper is initially limited by the rate of oxidation of the chalcopyrite particles located at or near the surface. As this outer, accessible chalcopyrite becomes depleted, however, the rate of recovery is increasingly limited by diffusion processes. The following model, based on these two limiting steps and the transition between them, is proposed for quantitatively describing the overall extraction kinetics. The model is consistent with the removal of copper from an ore fragment by diffusion processes along liquid-filled pores and fractures.

Consider an idealized "spherical" rock fragment of a specified diameter. For calculational purposes we divide this fragment into spherical shells, where ΔR_0 is the thickness of the outermost shell, which contains the readily oxidizable chalcopyrite located at or near the surface of the ore fragment, and ΔR is the thickness of each of the concentric inner shells. For each of the inner shells we define two reaction suppression factors, ϵ_i and δ_i .

Factor ϵ_i is related to the exponential decrease of oxygen concentration as a function of distance into the interior of a rock fragment due to diffusion limitations. That is, $\epsilon_i = e^{-iB}$, where parameter B is related to the shell thickness (ΔR) and to the effective diffusion coefficient for diffusion in a porous solid. The effective diffusion coefficient is a function of the molecular diffusivity of the reactants and products in the liquid phase, the porosity and permeability of the solid phase, and the tortuosity factor for diffusion in pores.

Factor δ_i is related to the suppression of the oxygen concentration in shell i as a result of consumption of oxygen in the adjacent outer shell $i-1$. That is, $\delta_i = 1 - \frac{S_{i-1}}{S_i}$, where S_{i-1} is the total initial surface area of all chalcopyrite

particles in shell $i-1$ and S_{i-1} is the surface area of the partially dissolved chalcopyrite particles in shell $i-1$ at a given time during the course of the extraction. The value of S_{i-1}^0 is calculated from the grade of ore and the initial, spherical-chalcopyrite-particle diameter.

The net rate (g/sec) of oxidation of all chalcopyrite particles in the rock fragment is then given by:

$$\text{Rate} = k \cdot D_s \cdot \sum_{i=0}^n S_i \epsilon_i \delta_i \quad (3)$$

The specific rate (k , g/cm²-sec) of oxidation of chalcopyrite has been experimentally measured for pure chalcopyrite. For the temperature range of interest in this application (50 to 200°C), the temperature dependence of k is adequately described by the Arrhenius equation:

$$k = A e^{-\Delta E/RT},$$

where $A = 6.1 \times 10^2$ frequency factor at an oxygen partial pressure of 400 psi and $\Delta E = 17.5$ kcal/mole activation energy.

The degree of saturation (D_s) of the bulk solution with dissolved oxygen can be maintained at some desired value by adjusting the rate of oxygen flow through the system. This extraction model is extended to the entire mass of broken ore being leached by including the contributions from all rock fragments in the summation of Eq. (3).

To calibrate this extraction model for San Manuel primary sulfide ore, data from the 1000-gal pressure vessel (pilot plant run 1) was used. The measured rate of copper recovery is in good agreement with the calculated rate, as shown in Fig. 8, using values $\Delta R_0 = 0.07$ cm, $\Delta R = 0.02$ cm, $B = 0.045$, and an effective

spherical-chalcopyrite-particle radius of 0.025 cm. These parameters will be taken as the best calibration of the extraction model until they can be refined by additional data from the pilot plant and by recovery data for other conditions of temperature, pressure, and ore size.

OXYGEN DISTRIBUTION IN CHIMNEY

A key requirement in the successful application of this mining method is that a relatively high dissolved oxygen content must be achieved in as much of the chimney solution as possible. This is important, because regions of the chimney having a low content of dissolved oxygen not only will have a low rate of dissolution of chalcopyrite, but also may have undesirable side effects such as depletion of the copper already in solution by precipitation of covellite. Although the maximum achievable oxygen content (i. e., the solubility limit of oxygen) will be dictated by the temperature and hydrostatic pressure within the chimney, the degree of oxygen saturation (i. e., the fractional part of the solubility limit which is actually reached) will be determined by factors related to the flow of oxygen gas and oxygenated solution through a fixed bed of solid particles. These factors are: (1) the geometric dispersion of the input oxygen gas; (2) the rate of dissolution of oxygen; and (3) the rate of internal circulation of the chimney solution.

We have investigated these factors in detail both experimentally and theoretically. The results of this study indicate that adequate dissolution of oxygen and circulation of the oxygenated solution can be obtained even if only one perforated oxygen line across the bottom of the chimney is used. This is accomplished, however, at the expense of venting a considerable fraction of the input oxygen as undissolved gas passing out of the chimney. The use of more input gas lines

not only decreases this vent fraction, but gives added assurance that, if solution circulation problems arise, a large fraction of the chimney solution will still be adequately oxygenated.

When three input oxygen lines are used, 35% of the chimney solution is directly supplied with oxygen by contact with rising gas bubbles. The remaining 65% can be supplied with oxygen by the circulation induced by the column of rising gas bubbles. The faster the gas is introduced into the chimney the faster the circulation, but at the expense of a lower utilization of oxygen. Enough circulation to provide a saturation level of 61% throughout the chimney can be induced by a gas flow rate that utilizes 50% of the gas. At this rate, 50% of the oxygen is thrown away unless it is collected at the top of the chimney and recirculated.

MODEL OF RECOVERY OF METAL VALUES IN A NUCLEAR CHIMNEY

To apply the preceding extraction model in predicting the rate of copper recovery in a nuclear chimney, it is necessary to utilize many different properties of the chimney and the broken ore contained in it. For present purposes, the values summarized in Table 1 for a 100-kt chimney will be used.

In addition, the main factors influencing both the rate of recovery and the ultimate limit of recovery of copper are: (1) the size distribution of the broken ore and (2) various thermal considerations such as the temperature of the flooded chimney at the start of the leaching operation, the heat generated by oxidation of sulfide minerals, and the heat lost by thermal conductivity.

The rock-size distribution for a given nuclear chimney will be grossly dependent upon the type of rock and its pre-existing fracture pattern. The most accurate

measurement of chimney rubble size was done for the Piledriver nuclear explosion (61 kt in granitic rock). The Piledriver rock-size distribution⁷ is shown in Fig. 11. The more extensive pre-existing fractures in a copper ore deposit should favor the fragmentation of the ore into smaller sizes, which in turn would allow a higher fraction of copper recovery before the extraction process becomes seriously diffusion-limited. The rock-size for monzonite-type open pit mine waste⁸, for example, is indeed much smaller than for the Piledriver event, as shown in Fig. 11.

Unless otherwise specified, the size distribution curve shown in Fig. 11 between the Piledriver curve and the mine waste curve was used in the calculations which follow.

The temperature within a flooded chimney will have a profound influence on the rate of copper recovery, because the specific rate constant for the oxidation of chalcopyrite approximately doubles for each 10°C rise in temperature. A valid model for the in-situ mining of primary sulfide ore must, therefore, take into account the initial chimney temperature, the heat generated within the chimney by the exothermic oxidation reactions, and the heat lost from the chimney to the surrounding rock by thermal conductivity.

The initial chimney temperature will be determined primarily from the ambient temperature of the earth at the particular depth of interest and from the energy deposited within or near the chimney by the nuclear explosion. For a 100-kt explosion, approximately 2×10^{13} cal (20% of the device energy) is deposited within the chimney. Assuming that the preshot ambient temperature is 50°C and that water at 25°C is used in flooding the chimney, the resultant temperature of the chimney contents would be 61°C upon equilibrium. Although additional study is needed to determine the rate of this equilibration, it is expected that convection currents in the chimney solution will give a high rate of heat transfer out of the

hot rock at the base of the chimney. In addition, part of the remaining 80% of the device energy is deposited close enough to the chimney so that, even if it may not immediately contribute to heating the chimney contents, it will at least increase the ambient temperature around the chimney and thereby decrease the conductive heat loss from the chimney. In any event, if a higher chimney temperature is desired at the start of the oxygen injection (~ 9 mo after detonation), then the chimney can be further heated by injecting high pressure steam.

Heat is generated within the chimney primarily by the oxidation of sulfide minerals. The principal reactions occurring in the oxidation of chalcopyrite and pyrite are shown in Eqs. (1) and (2). The heats of reaction, calculated from standard heats of formation, are -262 kcal/mole and -231 kcal/mole, respectively. For the present calculations, we use the more conservative value of -262 kcal/mole for both minerals.

Heat loss from the chimney to the surrounding rock by thermal conductivity is calculated by the standard one-dimensional heat flow equation.⁹ The present model uses the following spatial zoning to calculate an interzonal heat transfer rate: zone 1 is the nuclear chimney idealized as a hemispherical cylinder and zones 2 to 50 are concentric shells of 1-meter thickness around zone 1.

Summary of Computer Model

A finite-difference computer code, based on the preceding kinetic and thermal considerations, has been developed to calculate the temperature in the chimney and the fraction of copper recovered as a function of time. In summary, the calculation takes into account the following factors:

- Dimensions of chimney
- Amount of broken ore
- Particle size distribution of broken ore

- Grade of ore
- Mole ratio of pyrite to chalcopyrite
- Initial temperature of flooded chimney
- Degree of oxygen saturation
- Heat generated in chimney by oxidation of sulfide minerals
- Heat lost from chimney by thermal conductivity
- Dissolution of chalcopyrite particles within ore fragments
- Change in rate of dissolution of chalcopyrite with temperature

Calculational Results

The following calculational results were obtained for the nuclear chimney described in Table 1 by using a degree of oxygen saturation of 0.5 and an estimate (see Fig. 11) for the rock-size distribution to be expected for a 100-kt nuclear explosion in copper ore. Figure 12 shows the chimney temperature as a function of time for three ore grades for an initial temperature of 60°C and a pyrite/chalcopyrite mole ratio of 1. Figure 13 shows the fraction of copper recovered for the same set of conditions. These two figures illustrate that an appreciably greater fraction of copper can be recovered from the higher grade ore as a result of the higher temperatures produced when more sulfide fuel is available.

For a given ore grade, the fraction of copper recovery can be increased by preheating the chimney with high-pressure steam. The effects of preheating the chimney to initial temperatures of 60, 80, and 100°C are shown in Fig. 14 (temperature vs time) and Fig. 15 (fraction recovery vs time).

For a given ore grade, the fraction of copper recovery is higher for ores containing more pyrite. The increase results from the additional temperature rise produced by the oxidation of pyrite. The effects of varying the pyrite/chalcopyrite ratio in

0.50 wt% Cu ore are shown in Fig. 16 (temperature vs time) and Fig. 17 (fraction recovery vs time).

Although the ultimate economic limit of copper recovery is appreciably influenced by the thermal considerations presented in the preceding examples, it is influenced to an even greater extent by the particle size of the broken ore. For example, if the particle size were actually as small as that of the monzonite-type open pit mine waste (from Fig. 11, with extrapolation parallel to the Piledriver distribution), then the fraction of copper recovery would be as depicted in Fig. 18. For comparison, the recovery curve for the particle size used in the preceding examples is shown, as well as the recovery curve for the Piledriver particle size. In this example, the grade of ore is 0.5 wt% copper, the pyrite/chalcopyrite mole ratio is 1, and the initial chimney temperature is 60°C.

The poor rate of recovery for the Piledriver particle size distribution, reaching only 0.25 recovery in 5 years, can again be considerably improved by preheating the chimney, as shown in Fig. 19 for initial chimney temperatures of 60, 80, and 100°C. Thus, even for a coarse ore size, a satisfactory rate of recovery can be obtained.

CONCLUSIONS

We believe that the mining method proposed is technically feasible. Understanding of the chemistry of the sulfide minerals and of various ores will improve with further experimental work and will allow more accurate prediction of the recovery of copper from an in-situ mining operation. The particle size distribution of the broken ore is very important but, for the most part, will remain unknown and in practice will be inferred from copper recovery data obtained in the field.

REFERENCES

1. Lewis, A. E., "Chemical Mining of Primary Copper Ores by Use of Nuclear Technology," in Proceedings of Symposium on Engineering with Nuclear Explosives, Vol. II, American Nuclear Society, CONF-700101, 1970.
2. Lewis, A. E., Chemical Mining of Primary Copper Sulfide Ore Using High-Pressure Oxygen in a Flooded Nuclear Chimney, presented at the 1971 Idea Conference New Mexico Institute of Mining and Technology, Socorro, New Mexico. Lawrence Livermore Laboratory Report UCRL-73110 (1971).
3. Braun, R. L., and A. E. Lewis, Chemical Mining of Primary Copper Sulfide Ores - O₂ Distribution, Fluid Circulation, and Rate of Copper Recovery, presented at the 1971 Idea Conference, New Mexico Institute of Mining and Technology, Socorro, New Mexico. Lawrence Livermore Laboratory Report UCRL-73110 (1971).
4. Lewis, A. E., Nuclear Chimneys: Underground Containers for Chemical and Metallurgical Processing. Presented at the G. S. A. Symposium on the Underground Environment, Washington, D. C., November 3, 1971. Lawrence Livermore Laboratory Report UCRL-73130 (1971).
5. Butkovich, T. R., and A. E. Lewis, Aids for Estimating Effects of Underground Nuclear Explosions, Lawrence Livermore Laboratory Report UCRL-50929 (1970).
6. Harris, J. A., "Development of a Theoretical Approach to the Heap Leaching of Copper Sulfide Ores," Proc. Aust. Inst. Min. Met., Vol. 230, No. 81, 1969.

7. Rabb, D. D., Particle-Size Distribution Study: Piledriver Event, Lawrence Livermore Laboratory, Report UCRL-72078 (1969).
8. Potter, G. M., U. S. Bureau of Mines, Salt Lake City, private communication (October 6, 1971).
9. Kittel, C., Thermal Physics, John Wiley and Sons, New York, 1969, p. 213.

TABLE I
CHIMNEY PROPERTIES

YIELD OF NUCLEAR DEVICE	100 kt
DEPTH OF BURIAL	750 m
DEPTH OF WATER TABLE	50 m
WATER CONTENT OF ROCK	3 wt%
IN-SITU DENSITY OF ROCK	2.7 g/cm^3
BULKING POROSITY	0.17
RADIUS OF CAVITY	41 m
HEIGHT OF CHIMNEY	300 m
VOLUME OF WATER IN CHIMNEY	$2.9 \times 10^5 \text{ m}^3$
VOLUME OF ROCK IN CHIMNEY	$1.4 \times 10^6 \text{ m}^3$
MASS OF ROCK IN CHIMNEY	$3.8 \times 10^{12} \text{ g}$
HYDROSTATIC PRESSURE AT DEPTH OF BURIAL	1000 psi
HYDROSTATIC PRESSURE AT TOP OF CHIMNEY	570 psi

Fig. 1. Mass of rock broken as a function of explosive yield and depth of burst.

LOCATED PRIMARY SULFIDE ORE

Fig. 2. Chemical mining

Fig. 3. Copper concentration in solution vs time of 50°C for different O_2 pressures.

Fig. 4. Dissolution rate of chalcopyrite in dilute H_2SO_4 solution containing dissolved O_2 .

Fig. 5. Photo of pilot plant pressure vessel.

PRESSURE VESSEL FOR EXPERIMENTAL LEACHING OF PRIMARY SULFIDE ORE

Fig. 6. Diagram of pilot plant pressure vessel.

Fig. 7. Particle size distribution of San Manuel ore sample, pilot plant run 1.

Fig. 8. Fraction recover of copper from San Manuel ore sample vs time, pilot plant run 1.

Fig. 9. CO₂ evolution and pH vs time.

Fig. 10. Chemical composition of pregnant liquor vs time.

Fig. 11. Rock size distribution in Piledriver chimney.

Fig. 12. Chimney temperature vs time for various grades of copper ore.

Fig. 13. Fraction recovery vs time for various grades of copper ore.

Fig. 14. Chimney temperature vs time for various initial chimney temperatures.

Fig. 15. Fraction recovery vs time for various initial chimney temperatures.

Fig. 16. Chimney temperature vs time for various ratios of pyrite to chalcopyrite.

Fig. 17. Fraction recovery vs time for various ratios of pyrite to chalcopyrite.

Fig. 18. Fraction recovery vs time for ore of different size distributions.

Fig. 19. Fraction recovery vs time for various initial chimney temperatures for Piledriver particle size distribution.