NUCLEAR TECHNOLOGY AND MINERAL RECOVERY

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You will notice as I proceed that the proposed title of my talk, "Nuclear Technology and Mineral Recovery," becomes rather limited in scope. The particular aspect of nuclear technology most applicable to the mineral field, as has been pointed out by various authors, is nuclear blasting. The prime target for this nuclear blasting has usually been a large disseminated deposit of copper mineralization which, because of large dimensions, employs the nuclear devices most effectively.

From the work of the AEC we know that the larger nuclear devices fragment rock for a lower energy cost per unit of ground broken than do smaller nuclear devices or chemical explosives.

A mineralized deposit near the surface is usually not amenable to nuclear fragmentation, nor are the more deeply buried thin deposits. Also, one would not anticipate fragmenting a zone of excessively erratic mineralization with nuclear devices.

Many of our mineralized areas would be eliminated using the above criteria, so at this point you are well aware that my self-imposed limitation is to nuclear blasting and large disseminated copper deposits.

As with most other industries, copper mining faces rising costs and greater demands for its products.

One of the rising cost features peculiar to extractive industries is the reliance placed on production from lower grade deposits as the higher grade deposits are depleted. As the grade or metal content of an orebody decreases more material must be handled to produce a given amount of metal. The increased volume of ore which must be handled as the grade declines requires expansion of facilities and higher capital expenditures. Expansion of facilities for mining, milling, and concentrating of the ore increases the per unit capital cost of the end product--copper. Increased copper consumption will aggravate this situation with demand for more metal, much of which will have to be obtained from lower grade deposits.

As the higher grade deposits are depleted, future production will come from those deposits which cannot be exploited economically today. Therefore, the small, high-grade deposit which presently cannot support the necessary capital expenditures, the lower grade deposits, the deeply buried deposit, and those which have a high ratio of waste to ore will be the probable sources of copper in the future.

We have increased the size of equipment and improved our machine efficiencies to keep up with the demands made by the copper industry. As emphasis is placed on lower grade deposits to meet future demand, new methods offering opportunities for improved costs must be considered.

Most familiar of the proposed new methods is in situ leaching, often mentioned in conjunction with nuclear blasting. The union of the two technologies originated with the initial consideration of Kennecott's Project Sloop in 1958. Nuclear blasting would be used to fragment the orebody, after which the solution will be introduced at the top of the column of broken ore, leaching out copper values on its migration to the bottom of the broken zone, where the solution will be collected and processed through the recovery system.

Although the physical handling of ore and waste and their costs are eliminated, various investigators have raised many questions which affect the economics of an operating system. Questions of total copper recovery, rate of copper recovery, radioactive contamination, fracture healing, precipitation of iron compounds in the leaching zone, reagent consumption, solution collection, and others have to be answered before we know if this new technology is one of the viable solutions to the problems confronting the industry.

Many investigators--Heiss and Morgenstern, Hardwick, Smith and Young, Hansen, Thomas, and others--believe nuclear blasting and in situ leaching are compatible and will compete economically with conventional systems.

Because statistics have not been kept on dump leaching operations for any great length of time and because of the difficulty of sampling a dump during and after leaching, copper recovery figures are not too reliable. At one Western operation, over a five-year period a copper recovery rate of 4-1/2% per year was recorded. The operator assumes that the rate of recovery will fall, but is reluctant to estimate how much and when.

The British Columbia Research Council has run column leaching tests on samples from various locations. From one sulfide dump sample under their test conditions, 34.1% of the copper was extracted in 600 days. Of this percentage, 1.9% was extracted in the last one-half year. In a similar test performed on an oxide dump sample, 45.8% was extracted in 600 days with only 0.9% extracted in the last half year of the test.

Other tests by the B.C. Research Council checked the variation in leachability with depth in copper sulfide mineralization. The microbiological extraction of copper declined with increasing depth from 59.3% for the interval of 45 ft to 145 ft to 26.6% for the interval of 260 ft to 360 ft. Sampling showed that a biologically sterile solution extracted 26.5% of the copper in the uppermost 10 ft and only 12.6% in the lower 10 ft of a gross sample taken between the depths of 60 and 110 ft. (See Figure 1.)

Other investigators feel that a recovery factor of 30% is about the best that can be expected in a dump leaching operation. Many people in the industry also express views that the recovery associated with dump leaching will be this low.

In dump leaching operations because more copper is ordinarily added to the pile per day than is extracted, the recovery factor is of little importance. The leaching operation is usually a profitable auxiliary to a conventional open pit operation in which the ore is mined and then processed through a concentrator.

In a nuclear in situ application, however, the recovery factor becomes much more important, the copper output from the mineralized zone would have to pay for the cost of the entire operation. Fracture healing, blinding by clays and precipitates, and channeling are all factors which will govern how much of the copper mineralization is actually contacted and hence dissolved. Loss of dissolved copper through contact with clay will decrease the percentage recovered. J. K. Grunig pointed out that he had not arrived at an adequate explanation for copper lost through this mechanism. Compaction of dumps by wheeled vehicles, which adversely affects the distribution of the leaching solution in the normal dump leach operation, will be absent in a nuclear in situ operation. Another factor which affects the copper recovery is solution recovery. Any solution which is lost through the cavity walls or otherwise bypasses the solution collection circuit carries with it contained copper which decreases the overall recovery factor. Smith and Young in their paper, "Nuclear Explosives and Mining Costs," state that "The in situ leaching will recover 40% of the ore (probably the most difficult assumption to justify)."

The consensus is that the copper recovery of the conventional oxide plant is much higher than the recovery projected for a nuclear in situ operation.

In considering an hypothetical mining situation, the present method of production of copper would be used to the lowest economically feasible grade to both conserve resources and return the minimum acceptable profit. Below that lowest feasible grade we have the choice of leaving the mineral values in place in the ground, raising the price of copper, or of using the new technology. With the present production processes and copper prices, we would have a mineralized zone; whereas, with the nuclear in situ technology there would hopefully be an orebody. The difference between the mineralized zone and the orebody is expressed in one word--profitability.

At a recent meeting of the Atomic Industrial Forum (AIF), in the presentation by William L. Oakley on the "Hard Core Costs of Projects Gasbuggy and Rulison," the hard core costs were shown to be on the order of $2.9 million each. A concluding statement in this paper was, "I am optimistic that we can meet the $1 to $1.5 million target which has sometimes been given as the economic test Plowshare must face initially."

Using the $1.5 million figure for all nuclear related costs and assuming that a 50 kiloton device in a fully contained condition will break roughly five million tons (see Figure 2), the nuclear related costs per pound of copper recovered from various grades of material at different copper recoveries will be as

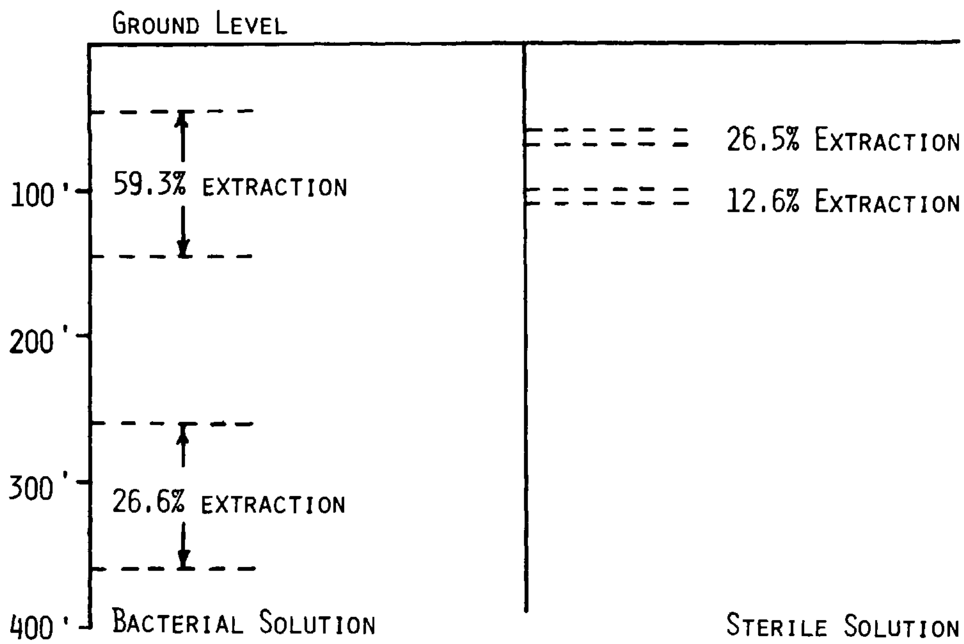

FIGURE 1

VARIATION OF LEACHABILITY WITH DEPTH

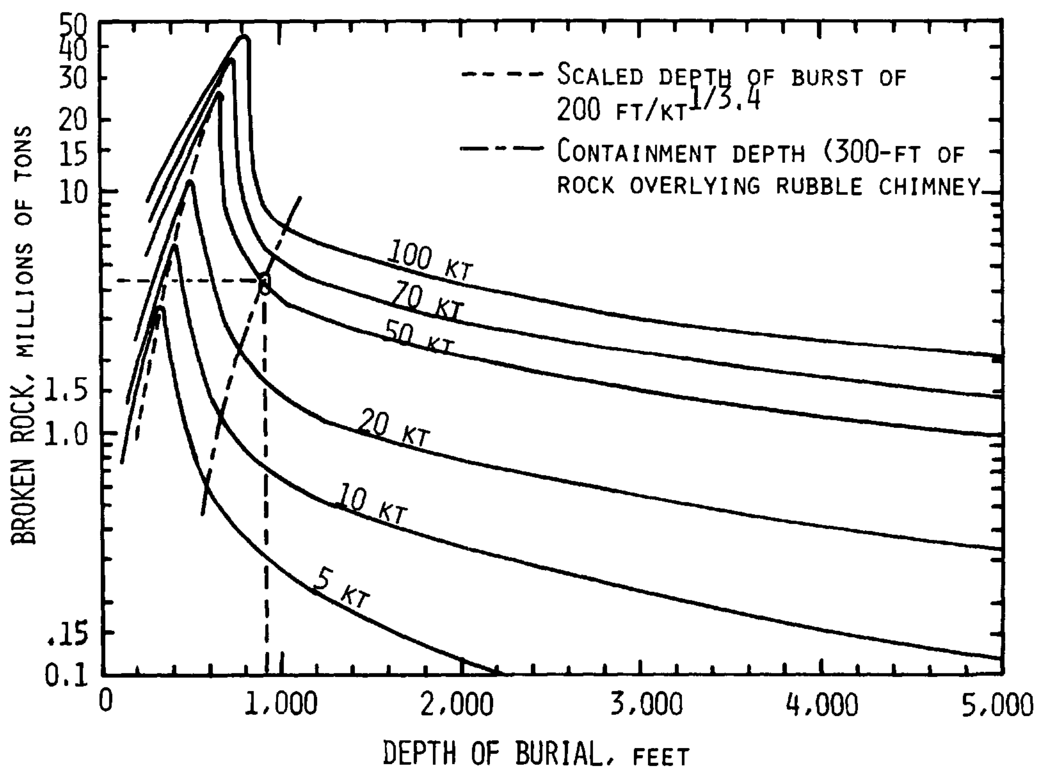

FIGURE 2

TONNAGE CURVES OF ROCK BROKEN BY INTERMEDIATE UNDERGROUND NUCLEAR EXPLOSIONS. (COURTESY, LAWRENCE RADIATION LABORATORY, UCRL 12180.)

shown in Figure 3. If the containment condition is altered to a retarc depth and if all other conditions remain equal, the fracturing cost per pound of copper recovered would be on the order of 1/6 the costs since the volume of rock broken would be six times as large. The retarc depth is that depth of burial at which an explosive produces an inverted cone of fragmented material, the surface elevation of which is greater than the elevation of the original ground. Maximum tonnage is broken with an explosive in this configuration.

At this point, it should be noted that the copper mineralization in the fracture halo which surrounds the cavity is not considered in the following discussion, although if it were recovered the unit fracturing costs would be decreased.

A leachable ore of copper is commonly one which contains the oxide and simple sulfide minerals of copper. If the mineralized zone is deficient in iron pyrite which breaks down in the presence of water and oxygen to form sulfuric acid, then all of the acid for a leaching operation must be added. The acid is consumed by either the oxides or simple sulfides of copper in the ore to form copper sulfate as follows:

$$CuO + H_2SO_4 \rightarrow CuSO_4 + H_2O$$

$$CuS + Fe_2(SO_4)_3 \rightarrow CuSO_4 + 2\ FeSO_4 + S$$

$$4\ FeSO_4 + 2\ H_2SO_4 + O_2 \rightarrow 2\ Fe_2(SO_4)_3 + 2\ H_2O$$

In the cementation portion of the circuit, free sulfuric acid reacts with iron to form ferrous sulfate. Other consumers of acid are the clay and carbonate constituents of the rock itself. A typical clay reaction would be

$$Na_2\ Ca\ Al_4\ Si_8\ O_{24} + 4H^+ + 2\ H_2O \rightarrow 2\ Al_2\ Si_2O_5\ (OH)_4 +$$

$$4\ SiO_2 + 2\ Na^+ + Ca^{++}$$

Since the acid consumption is primarily dependent upon factors other than the amount and kind of copper mineral present, it appears more realistic to assume a feed rate of acid per ton of material rather than on the basis of pounds of acid per pound of copper produced.

In Figure 4 the acid cost per pound of recovered copper is indicated at different recoveries for various grades of ore when the acid cost is $20 per ton. The acid consumption of 50 lbs per ton of material presupposes an orebody which is low in acid-consuming constituents.

Iron consumption, as has been pointed out previously, is dependent upon the hydrogen ion and also the ferric ion concentration in the leaching solution. Table 1 shows some typical iron consumption figures for various operating cementation plants. At a cost of $50 per ton for iron, the iron cost per lb of recovered copper ranges from 3-1/4¢ to 7-1/4¢.

The next consideration is the cost of a solution recovery system and a copper recovery system. The nuclear device previously mentioned had a 50-kton yield. For containment, this device

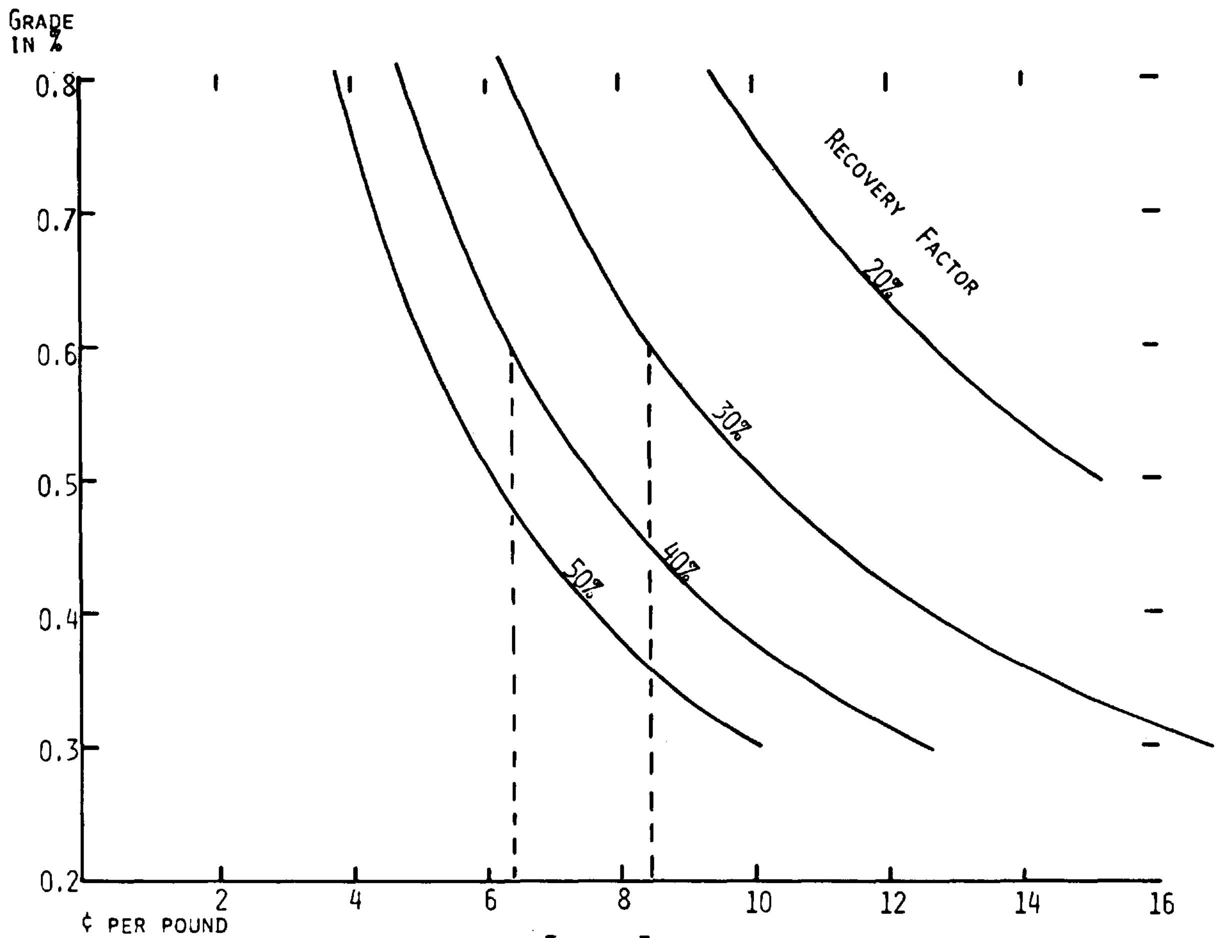

FIGURE 3
FRACTURING COST IN CENTS PER POUND OF RECOVERED COPPER

$$CuO + H_2SO_4 \rightarrow CuSO_4 + H_2O$$

$$CuS + Fe_2(SO_4)_3 \rightarrow CuSO_4 + 2\,FeSO_4 + S$$

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Typical Copper Mineral Reactions

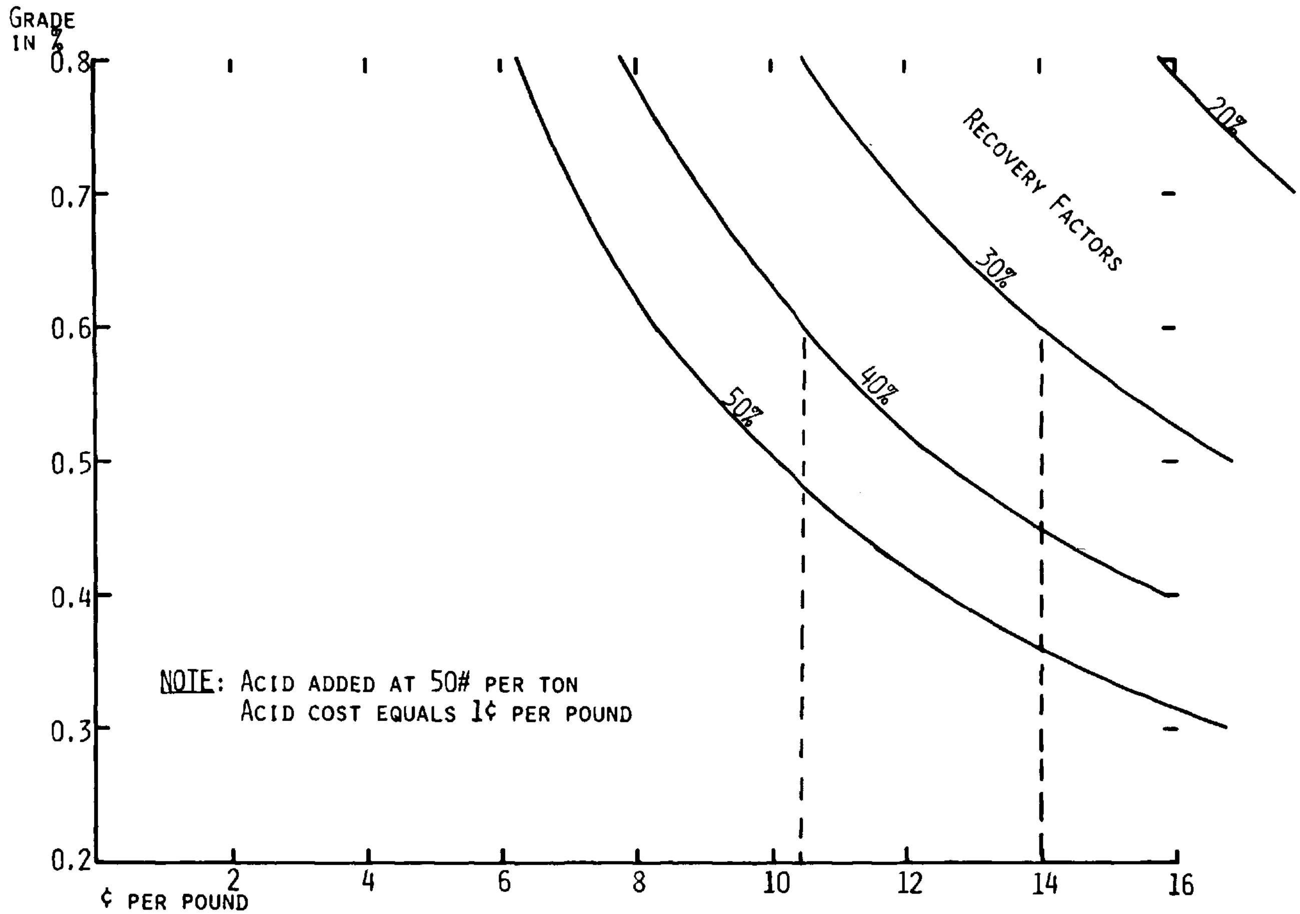


FIGURE 4
ACID COST IN CENTS PER POUND OF RECOVERED COPPER

Andesine — Kaolinite

$$Na_2\,Ca\,Al_4\,Si_8\,O_{24} + 4H^+ + 2H_2O \rightarrow 2Al_2\,Si_2\,O_5\,(OH)_4 + 4SiO_2 + 2Na^+ + Ca^{++}$$

Typical Clay Reaction

would be buried at a depth of roughly 900 ft and would form a chimney 600 ft high which should approximate the thickness of the mineralized zone. Lawrence Radiation Laboratory (LRL) information shows that minor damage to mine workings is sustained at a distance of roughly 3800 ft. (See Figure 5.)

From a 0.6% Cu ore and using a 40% recovery factor, 24 million lbs of copper would be produced from the 5 million tons broken by a contained 50-kton device. This amount of copper could be produced in two years from a pregnant solution with a concentration of one gram per liter flowing at the rate of 2500 gpm.

Let us assume then that each 50-kiloton blast will fragment sufficient copper-bearing rock to sustain a recovery plant for two years. Let us also assume that the recovery plant is written off in a period of ten years.

An underground recovery system is based on sinking a shaft and driving access drifts from which solution collector holes would be drilled upward into the chimney. The shaft would be located outside the damage range (3800 ft) of subsequent nuclear shots. The $2.5 million cost shown in Table 2 distributed over 120 million lbs of copper, ten years production, amounts to 2¢ per lb of copper produced.

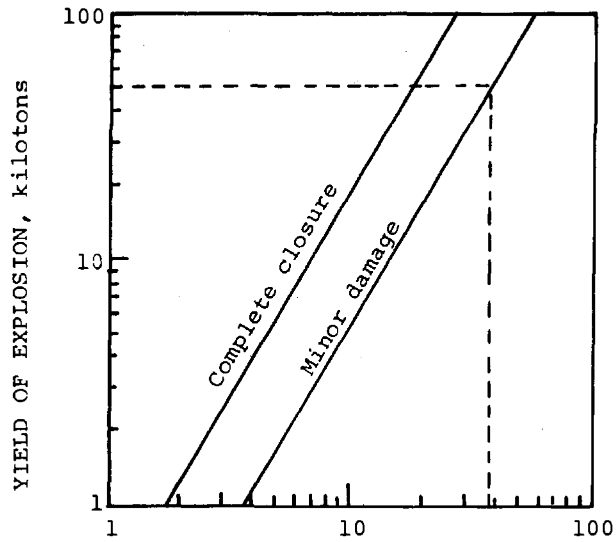
The plant capital cost for a flow of 2500 gpm is $1.25 million when the cost for each 1000 gpm of capacity is $0.5 million. Therefore, over a ten-year plant life the capital cost is 1¢ per lb of copper produced.

Table 3 shows the pound cost figure for a 0.6% grade ore at different recoveries. The total cost of labor has been taken as 2¢ per lb, and the marketing cost, including smelting, refining, and transportation, is 8¢.

An alternate method of recovery of copper from a pregnant solution should also be considered, although the benefits derived are not limited to a nuclear in situ operation. In a solvent extraction-electrowinning system, the copper-laden solution is placed in contact with an organic compound which has an affinity for the copper ion. This copper-rich compound is then processed in an aqueous phase and the copper ions are stripped from it. The organic material is then recirculated to continue its function of concentration of the copper ion. The copper-rich aqueous solution is then introduced into electrolytic cells where the copper is electroplated on cathodes. The product is a high purity copper which requires no smelting or refining.

This technique eliminates the need for iron scrap, and also produces sulfuric acid in the electrolytic cell which can be put into the leaching circuit. Typical plant capital costs for this type of installation per daily ton of copper produced are $200,000, which includes both the solvent extraction and the electrowinning sections.

Table 4 shows a comparison of estimated costs for a cementation circuit and a solvent extraction-electrowinning circuit. The possible savings of 5¢ per lb of copper recovered warrants serious consideration of this process.



DISTANCE FROM SHOT CENTER, hundreds of feet

Figure 5
Damage to Mine Workings from Nuclear Explosions in Granite Rock. (Courtesy, Lawrence Radiation Laboratory UCRL 14201.)

Table 1

Iron Consumption at Various Properties

Plant	Pounds of Iron per lb of Copper*	Iron Cost per lb of Recovered Copper**
Rio Tinto, Spain	1.4	
Silver Bell, Arizona	1.5	
Ray, Arizona	1.8	
Esperanza, Arizona	1.35	
Bagdad, Arizona	1.7	
Miami, Arizona	1.3	3.25¢
Cananea, Mexico	2.9	7.25¢

* Fracturing a Deposit with Nuclear Explosives and Recovering Copper by the In-Situ Leaching Method by William R. Hardwick.

** Calculated by author, using iron cost of $50 per ton.

Table 2

Capital Costs - Underground Recovery System

Shaft	1000 ft @ $700/ft	=	$ 700,000
Drifts	8000 ft @ $ 75/ft	=	600,000
Drill Holes	40,000 ft @ $20/ft	=	800,000
Miscellaneous and Contingency		=	400,000
Total			$2,500,000

Table 3

Production Cost per Pound of Copper

Recovery	40%	30%
Grade	0.6%	0.6%
Capital	3¢	4¢ *
Labor	2¢	2¢
Fracturing **	6.3¢	8.3¢
Acid **	10.5¢	14¢
Iron ***	3.5¢	3.5¢
Smelting, Refining, etc.	8¢	8¢
Total	33.3¢	39.8¢

* Capital cost calculated as being inversely proportional to the % recovered.

** From Figures 3 and 6.

*** The iron consumption is minimal at 1.4 per lb of copper.

Table 4

Cementation vs. Solvent Extraction and Electrowinning

in Cents per Pound of Copper Produced

		Leach and Precipitation		SX EW
Capital	Recovery	1.0¢ 2.0¢		2.0¢ 2.0¢
Labor		2.0¢		4.0¢
Supplies	(included in iron, acid, etc.)			3.0¢
Fracturing		6.3¢		6.3¢
Acid		10.5¢		9.0¢ *
Iron		3.5¢		-
Smelting, Refining, etc.		8.0¢	Transportation	2.0¢
Total		33.3¢		28.3¢

* The acid generated valued at 1½¢ is fed back into the leaching circuit.

In situ leaching has been practiced for years in underground copper mines throughout the world. Ground which has been fragmented due to subsidence over old mined-out areas and low-grade mineralization, which has remained after block caving operations, has been leached successfully. In a nuclear in situ operation we intentionally fragment the rock and then leach it to extract the values. Most of the development work for a solution collection system in old mine areas and block caved areas had been done during the original mining operations, which paid for driving these openings. In virgin ground, the cost of this development work must be borne by the in situ leaching operation. We know that in situ leaching as a method for the extraction of copper values is physically feasible. We need to know if the nuclear in situ method is economically feasible. The answers to questions of total recovery, rate of recovery, contamination, etc., must be found so that we know if we are talking of mineralized zones or orebodies.

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