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ECONOMICS AND SAFETY OF NUCLEAR CHEMICAL COPPER MINING

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ECONOMICS AND SAFETY OF NUCLEAR CHEMICAL COPPER MINING*

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INTRODUCTION

The paper by Lewis and Braun¹ presents experimental and calculational evidence that primary chalcopryrite ores are rapidly oxidized by warm oxygen-bearing water. Resulting solutions contained copper sulfate products of the matrix rock decomposition such as magnesium sulfate and sulphuric acid. Iron was oxidized to insoluble hematite and hydrous iron sulfates. Oxygen injection near the base of a broken and permeable flooded ore deposit was calculated to cause circulation of oxidizing solutions to the entire permeable region. The rate of dissolution of copper and degree of oxygen saturation for given oxygen injection rates were presented.

Their work suggests that in-situ recovery of deep, disseminate primary copper deposits is technically feasible. The actual feasibility depends on economics and environmental safety as well, and it is the purpose of this paper to address these two aspects.

THE MINING PROCESS

The mining process would start after identification of the ore body, the local hydrology, approximate ore grade and distribution, laboratory confirmation of

*This work was performed under the auspices of the Atomic Energy Commission.

the rate of solubility, and survey of the nearby environment. It would consist of: (1) progressively shattering the ore in place with nuclear explosives fired at regular intervals, assumed here to be 1 year; (2) drilling four access holes to the base of each chimney* for oxygen injection lines, drilling one hole to the top of the chimney for oxygen and solution exit, and drilling one hole to the base of the chimney for solution return; (3) connecting tubing in these holes to the oxygen injection plant and surface process facilities and flooding the chimney with water from overlying aquifers or surface streams; (4) injecting oxygen until copper concentrations are high enough for processing; and (5) continuing oxygen injection during circulation of the pregnant solutions through a solvent extraction-electrowinning facility until operation becomes unprofitable. It is estimated that it will require 6 months to drill the emplacement hole, emplace, stem, and fire the explosive; 3 months to complete the post-explosion drilling; 2 months to flood the chimney and make surface connections; and 1 month for oxygen injection prior to start of copper recovery. Thus, copper recovery would begin 1 year following each detonation.

The rate of copper dissolution inferred from Lewis and Braun's experiments is shown in Table I. The rates shown are believed to be a reasonable approximation of what might be expected in a nuclear chimney, based on their experiments. After the fourth year, the rate of recovery was assumed to be zero. Therefore, recovery in any chimney is complete at the end of the fifth year following each explosion. It is noteworthy that 46% of the copper is expected to be dissolved in the first year of leaching.

*The term "chimney" is used in this paper to describe the region of broken rock created by a nuclear explosion.

The schematic flow diagram for the process is shown in Figure 1. Except for the nuclear chimney, all components are used in commercial processes. Major elements from a capital and operating cost point of view are the oxygen plant, storage tanks, liquid extraction plant, electrowinning facility, and plumbing.

ECONOMICS

The economics of the process were examined by assuming a series of hypothetical ore bodies of varying grade, depth, and size using various explosion sizes. Each parameter was varied while holding the rest constant. The "standard" from which each was varied was a deposit of 70 million metric tons* extending downward from a 1250 ft depth with an average ore grade of 0.45% copper. This was developed with eleven 100-kt explosions buried at 2460 ft. The pyrite-chalcopyrite ratio was assumed to be 5:1 in all ore bodies. No original cost or royalty is included in the analysis since the value of these factors can vary from site to site. They must be deducted as appropriate in the evaluation of a real case. Costs of environmental studies and proof drilling were capitalized along with the plant facilities and operating reserve. The first detonation and developments prior to first production could also have been capitalized but were not. Instead, all detonation and production costs were treated as operating expenses. This lowers profitability by increasing the discount term by 2 years and reducing depreciation.

Cost of environmental studies was estimated from prior nuclear applications such as the Rulison and Gasbuggy gas stimulation experiments but additional drilling was assumed for more detailed hydrologic studies and later monitoring. Capital

* 1000 kg = 2204 lb.

and operating cost of the oxygen plant was taken from U.S. Bureau of Mines estimates²; those of the storage tanks, plumbing, casing, etc. were taken from Peters and Timmerhaus³; those of the liquid extraction plant from Gardner and Warwick⁴; and those of the electrowinning facility from a Metalges review article.⁵ Site facilities such as roads, offices, telephones, and power lines were held constant. The nuclear explosive, its emplacement and firing, seismic insurance, and incremental operational safety was estimated at \$600,000. Estimates for continual radioactivity monitoring, plant control, sales, and management were included. All costs were inflated from the date of the published estimate to 1970. A copper sales price of 43¢ per lb was assumed. No future inflation of costs or copper price was included on the assumption that they would inflate at the same average rate.

A total capital cost, annual and unit operating cost, and an annual profit, earnings, and return balance sheet was prepared for each assumed ore body. Depreciation was calculated over the life of the particular ore body, depletion at 15% of sales (with the 50% limitation), and income taxes at 50% of profit. Years to return the investment and internal rate of return^{*} were computed. The results are shown in Figures 2 through 5 where the economic parameters are plotted against each of the varied ore body parameters.

^{*}"Internal rate of return" is identical to: (1) investors' rate of return; (2) discounted cash flow rate of return; (3) interest rate of return; (4) interest rate which makes present worth equal to capital investment; and (5) profitability index.

While these ore bodies are hypothetical and each real ore body will differ, it appears that this process can be quite competitive with present methods of copper production, even though the ore bodies are deeper and the grades lower than in most operating mines. The profitability appears limited to ore bodies (1) larger than 30 million tons; (2) less than 3500 to 4000 ft deep; (3) richer than 0.25% copper; and (4) using single explosives larger than 60 kt. There are other dependencies not shown in these figures. For instance, higher ore grades would be profitable at greater depths and in smaller ore bodies. Also, different pyrite-chalcopyrite ratios would influence the ultimate recovery and oxygen consumption and thus affect the economics. The development schedule and equipment sizes were not optimized for maximum economic return because the purpose of the study was to get a general idea of the relative worth of this method compared to others. It was not designed to discover the best way to develop nuclear solution mining.

HAZARDS EVALUATION

Any operation involving explosions as large as 100 kt of TNT equivalent, whether nuclear or conventional explosives are used, is accompanied by risks. In the present instance, nuclear explosives are used because rock can be broken in place much more cheaply (ca. 20¢ per ton) at depths below 1000 ft. However, these explosives also produce a risk from radioactivity, which does not accompany conventional explosives. In addition, the ground shock is usually greater because all the explosive is fired at once instead of at time intervals.

A detailed analysis of all of the risks has been performed on the same hypothetical ore bodies assumed for the economic studies. Most significant risks were found to arise from the ground shock and low-level radiation exposure to laborers in the

extraction plant and electrowinning facility. Experience with other nuclear explosions shows there is very little chance of prompt release of radioactivity for the explosive yield and depth of burst used in these studies. Also, no chance of copper product contamination was found, providing the process described previously were used for copper recovery.

There has been considerable experience with ground shock effects from nuclear explosions conducted by the USAEC.⁶⁻⁹ From this experience, shock effects on any given structure at any distance from an explosion can be predicted quite accurately. Table II shows the limits of range of extent of several effects from a 100-kt explosion in hard rock. Each of the ranges beyond 1 mile represents the outer limit of the possible effect and defines the area in which assessment of shock damage costs should be made. Within the indicated range, both the frequency and the severity of damage decrease at greater distances. Actual structural damage, that is, permanent alteration of the basic structure, does not extend beyond about 4 miles. All damage beyond that range is of an architectural nature such as plaster cracking. Architectural damage may cause temporary disruption of utility of a structure; for example, a crack in a concrete tank may cause a leak; however, such damage is generally easily and inexpensively repaired.

In the economic study it was assumed there were 250 single-family residences distributed uniformly in the first 30 miles from the site and that there were no high rise structures such as stacks. Experience at the Nevada Test Site indicates that the operations plant can be designed to withstand the ground shock if simple protective actions (which would require shutdown for a few days) are taken. These protective measures include disconnecting all pipes, draining storage tanks, removing light bulbs, and like measures. The drill holes in any given chimney will withstand the ground shock, provided they are located on the opposite side from the next explosion. Occasionally casing breaks requiring repair may occur.

Radioactivity can potentially create hazards in three ways: (1) uncontrolled venting or seepage at the time of detonation; (2) atmospheric contamination with gaseous radioactivity carried with the off-gas oxygen and CO_2 during leaching; and (3) through loss of or exposure to contaminated leach solutions. The hydro-logic conditions required for process solution control prevent contamination of ground water and, during the first two or more years, the void produced by the nuclear explosion prevents outflow of contaminated water. There is then no chance of ground water contamination except by the leach solution.

Nuclear testing experience indicates that the chance of prompt venting or seepage is less than one-in-a-thousand for the energy range, depths of burst, and rock types associated with nuclear chemical mining. How much less is not known since no venting has accompanied the 80 test explosions that are of comparable yield but are generally buried at shallower depths in much weaker rock. The worst consequence, if venting were to occur, is that residents in the downwind sector would have to evacuate to 15 miles from the site for a period of about 2 weeks. This would prevent any radiation exposure in excess of 0.5 R, which is about 1/20 as much radioactivity as one would get from a fluoroscopic examination.

The second kind of radiation exposure is caused by release of radioactive krypton and tritium, which will be released with the off-gases. These will lead to very small downwind radiation exposures, calculated to be less than 1/100 of the natural radioactive background 1 mile downwind from the release stack. The background is mostly due to natural potassium in one's body and to cosmic rays, and does not include fallout radioactivity from past weapons testing.

The pregnant solution will be contaminated with radioactivity leached from the rocks melted by the explosion. This then causes the third kind of possible danger. Results of leaching studies with the appropriate solutions and radioactive fused

rocks from underground tests at the Nevada Test Site show that the copper-pregnant solutions will contain a number of radioactive substances.¹⁰⁻¹¹ The amounts contained, according to these studies, will produce radiation fields in the plant comparable to or a little less than those observed in uranium mills. In addition, the residual tritium can produce an inhalation hazard. The degree of hazard is insignificant unless workers breathe the undiluted vapor over the extraction units. Good solvent control practice minimizes chance of such vapor exposure. Operating costs must include estimates for continual monitoring of air levels and personnel exposures to assure safety. At the completion of recovery operations, all holes must be sealed with acid-resistant cement to prevent slow diffusion of the acid and radioactive solutions into ground water. Monitoring of hydrologic test wells will have to continue on a periodic basis for some years following shutdown of a site. Costs for these activities are included in the economic analysis.

ENVIRONMENTAL CONSIDERATIONS

On balance, there are very favorable environmental aspects of this copper recovery method. Most important is the fact that no SO_2 is produced during leaching or any other part of the process. This feature alone probably offsets the potential detrimental effects of radiation exposure to plant personnel and certainly offsets the very slight risk of general environmental contamination with radioactivity. In addition to the complete absence of SO_2 there will be no residual wastes such as tailings and dumps. Except for surface construction such as ground leveling, access road construction, and power lines, there would be no alteration of the landscape. If proper operating, shutdown, and salvage procedures are followed there need be no long-term detrimental aesthetic effects.

BENEFIT-RISK ANALYSIS

An attempt was made to assign monetary values to all the risks such as radiation exposure and the psychological discomfort created by ground shock. It should be emphasized that these values are not estimates for compensation, but rather are estimates of the value of the intangibles such as inconvenience and fear. Actual costs of any ground shock damage (and evacuation in the unlikely case it should be required) are borne as project costs.

The result of the analysis suggests that the total value of external detriments is a hundred-fold less than the value of the copper recovered, or about \$10 per ton of copper produced. This arises almost equally from inconvenience caused by the seismic ground shock and potential radiation to plant workers. A similar assessment of an open pit-flotation-smelter-refinery combination suggests its external environmental detriment is about 1/10 the value of the copper produced. Most of this comes from the SO_2 and mine and mill wastes. The nature of these estimates is so uncertain that these values are hardly different. The conclusion one should draw is that hazards that might arise from the nuclear chemical method are certainly no worse than from conventional copper recovery methods, although they are of a different kind. Conventional dump and heap leaching are probably less detrimental than either method, providing adequate solution control is achieved.

CONCLUSIONS

Nuclear solution mining of copper appears economically competitive with other copper production methods, providing suitable ore bodies are found. Such bodies should not be too close to large population centers and extensively developed mines or industrial facilities because explosions larger than about 60 kt are required. The deposits must be deeper than about 1200 ft to assure containment.

of the nuclear explosion products and to provide sufficient hydrostatic head to maintain adequate oxygen concentrations. Grades as low as 0.3% copper are sufficient for reasonable return of the investment if the deposit contains 30 million tons or more of ore.

This copper production method does not generate volatile oxides of sulfur, the copper product will not be contaminated, and while there are safety problems that come from radioactivity and ground shock, the consequences are quite manageable and inexpensive. If applied, this method would clearly extend domestic copper reserves and deeper, more disseminate domestic deposits should be recovered competitively with politically uncertain foreign copper.

Finally, the gross capital requirements (about \$16 million) of this kind of copper production facility should be less by ten-fold than more conventional facilities. This should make financing a considerably less difficult problem and provide smaller operators a competitive opportunity in copper production.

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TABLE I
RATE OF COPPER RECOVERY ASSUMED

<u>Year</u>	<u>Fraction Recovered at End of Year</u>	<u>Average Rate of Dissolution of Copper, % per day</u>
0 [*]	—	0.5
1	0.46	0.125
2	0.55	0.025
3	0.59	0.016
4	0.62	0.005
5	0.64	0.005

^{*}The zero rate is the rate at the start of oxygen injection and is used to compute the maximum size of the oxygen supply plant.

TABLE II
GROUND SHOCK EFFECTS FROM 100 kt
DETONATED 2500 ft DEEP IN HARD ROCK

	Effect	Range	
		<u>km</u>	<u>s mi</u>
1.	Storage tanks buckled unless empty, long pipes bent or broken at support points, concrete motor supports cracked, concrete block walls severely cracked. Some windows and glass fixtures broken, metal frame buildings wracked occasionally, mine shafts hoist guides misaligned, slabbing and minor damage to mines, tall stacks and towers probably collapse.	1.6	1
2.	No damage to working mines in good repair beyond this distance.	3.2	2
3.	No damage to tanks, pipes, metal buildings, motor or equipment supports, general plant facilities, and no structural damage beyond this range.	6.4	4
4.	No architectural damage to plaster, concrete blocks, windows, glass fixtures, or residential facilities beyond this range.	48	30
5.	No damage or cracking of very tall stacks or multistory structures beyond this range.	56	35

Figure 1. Schematic flow diagram of nuclear chemical copper mine and process facilities.

Figure 2. Influence of grade of ore on the economics of nuclear chemical mining of copper. Explosive yield is held constant at 100 kt, the depth of burst at 750 m (2460 ft), and ore body size is fixed at 70 million tons.

Figure 3. Influence of size of explosive on the economics of nuclear chemical mining of copper. Ore body size is held constant at 70 million tons, ore grade at 0.45% copper, and depth of burst at 750 m (2460 ft).

Figure 4. Influence of depth of burst on the economics of nuclear chemical mining. Ore body size is held constant at 70 million tons, the explosive energy at 100 kt, and the ore grade at 0.45%.

Figure 5. Influence of ore body size on the economics of nuclear chemical mining of copper. Explosive energy is held constant at 100 kt, ore grade at 0.45% copper and depth of burst at 750 m (2460 ft).