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GEOHERMAL ENERGY FOR
COPPER DUMP LEACHING

DOE/RA/50076--9

DE83 005439

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August, 1982

Subcontract 115-80 with
Department of Chemical Engineering
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Work performed under
Contract No. DE-FC03-80RA50076
Modification No. A-001
Evaluation of Geothermal Energy in Arizona
U.S. Department of Energy
San Francisco Operations Office
Oakland, CA

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ACKNOWLEDGEMENTS

Many individuals contributed to this study. Recognition is extended to Dr. David Wolf for his technical contributions. Larry Goldstone was project manager for this study and other functions of the project.

Other contributors included Tom Young, Cherif Balamane, Mohamed Chehab, Gary Kyle and Xavier Suarez. In addition, recognition is extended to the Arizona Bureau of Geology and Mineral Technology - Geothermal Group for its support and advice. We are also grateful for its providing office space for about two years.

ABSTRACT

This report evaluates the possibility of using geothermal energy to heat a sulfuric acid leaching solution for the purpose of faster and more efficient copper recovery from copper-containing minerals. Experimental studies reported in the literature have shown that this technique can be economically feasible for the extraction of copper from low-grade dump ores. Its main advantage appears to be the considerable reduction in long-term leaching periods; it could also be less expensive than other conventional processing operations if an economical geothermal resource were provided. However, this process has some pitfalls which might restrict the extent of geothermal energy use. Nevertheless, the process is still technologically sound, especially if groundwaters are used directly in the leaching operation.

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INTRODUCTION

Arizona is the largest copper-producing state in the nation. The total output of copper in 1978 from all mines in Arizona constituted 65 percent of all domestically produced copper¹. In response to the projected growth of world-wide copper consumption, the state's copper production is expected to continue to increase at an annual rate of approximately 2.5 percent.²

Currently there are 15 operating mines in Arizona. Most of these mines are located in Pima, Pinal, Graham, Greenlee, Cochise and Gila counties, all of which are within a 100-mile radius of Tucson and are collectively called the Arizona Copper Belt. The majority of these mines extract part of their copper by a process called dump leaching. Dump leaching is applied to the low-grade copper wastes from conventional mining methods, usually from conventional open-pit operations. The wastes are deposited in large dumps and an aqueous leaching solution containing sulfuric acid is periodically distributed over the surface and allowed to trickle through the dump. Much of the copper produced from dumps is leached from sulfide minerals, a process for which oxygen is required. The oxygen is supplied by allowing air to rise through the dumps between periodic applications of leaching solution. The approximate amount of low-grade copper ore being extracted in this manner in Arizona ranges from 2.6 to 3 billion tons per year.

Sulfuric acid is by far the most common reagent used nationwide for leaching copper ores. Its principal advantage is its availability: 4,000 tons of sulfuric acid are produced each day by all copper mining companies as a by-product of copper smelting. Additional capacity could be made available if economically desirable. Other advantages of sulfuric acid include its rapid attack on oxidized copper ores and the fact that by bacterial action on sulfide minerals additional sulfuric acid is produced.

The copper content of most if not all dumps is less than 0.3 wt. percent. It is present mainly in the form of sulfide minerals such as chalcopyrite, chalcocite and, to a lesser extent, some minor sulfide minerals. Unlike leaching oxidized copper ores, the process of leaching sulfide ores with sulfuric acid is very slow. The leaching reactions tend to be slow unless the oxidizing conditions are extremely severe, such as those provided by high oxygen pressures.³ As a result, dump leaching of an oxide-sulfide mixture of mine wastes may last up to 30 years depending on the size of the dump. It was reported that 300,000 tons of copper was extracted in 1973 by these long-term leaching techniques.⁴

Factors leading to increased leaching rates of sulfide-oxide ores are high sulfuric acid strengths (up to $150 \text{ kg/m}^3 \text{ H}_2\text{SO}_4$), increased temperatures of the leaching fluid (up to 60°C) and oxidizing conditions provided by aeration.⁵ In addition to improving the efficiency with which copper is recovered from the ore body, the leaching process also avoids the problem of SO_2 emissions from smelters. Furthermore, the application of solvent extraction techniques to dilute, acidic copper leach solutions favors the further expansion of dump leaching because it produces an electrolyte suitable for the direct electrowinning of 99.9 percent pure copper cathodes.

During the late 1920s the heating of leaching solutions was practiced by the Inspiration Mine in Arizona in order to obtain a satisfactory rate of copper extraction. This practice was later discontinued due to the high cost of heating fuels.⁶ Presently, all dump leaching operations in Arizona use acid solutions at ambient temperature. As demonstrated by experimental results, the hotter the leaching fluid, the better the production; however, leaching temperature should be controlled to about 40°C so that beneficial bacterial action will be maintained⁵. It appears that the use of geothermal

water to heat leaching solutions would be extremely feasible and desirable. More efficient recovery of copper could be obtained by using geothermal energy in the leaching process. It is predicted that under conditions of hot, strongly acidic leaching solutions at 40°C and good aeration, nearly 65 percent of the copper in the dumps could be extracted in approximately half the time required by leaching with acidic solutions at ambient temperatures.

Status of Copper Leaching in Pima County

Pima County, the largest copper-producing county in Arizona, provides 40 percent of the copper produced in the state and is known to contain about 2,200 million tons of proven copper ore reserves. There are eight operating mines in the county, as shown in Table 1, and some form of leaching is practiced in all of them. Geothermal energy could be used to heat leaching fluids in some of these mines to enhance copper recovery. Arizona copper deposits and potential geothermal areas are shown in Figure 1. As can be seen, there are a number of areas in the state where geothermal resources overlap mining locations, notably in Pima, Pinal, Graham and Greenlee counties.

Usually, copper dump leaching is used to extract copper from low-grade ores consisting of tailings or overburden from open-pit mines. However, several mines do not classify their ores but leach dumps containing a mixture of ores of lower and higher grades. Leaching operations are not solely restricted to lower grade ores; in fact, they may produce a good portion of the copper mined. Copper extraction by the leaching process can be as high as 100 percent of the total production in a mine depending on the individual operation. Examples would be Blue Bird Ranchers and Johnson Camp dump leaching operations totaling more than 5,000 tons of ore per day. In addition, Anamax leaches 10,000 tons of ore per day using the agitated leach

Figure 1: Copper Mining Locations and Potential Geothermal Locations in Southern Arizona

Table 1. COPPER MINES IN PIMA COUNTY WITH POTENTIAL DUMPS*

Name of Property or Location	Size of Ore Deposit (10 ⁶ tons)
Ajo (New Cornilia)	126
Sierrita	259
San Xavier	167
Mission	104
Pima	146
Esperanza	22
Twin Buttes	174
Silver Bell	26
TOTAL	1,024

*Potential dumps include an estimation of ore (over the life of each mine) to be dumped upon each existing dump.

procedure. Kennecott uses both the vat and agitated operations to leach 15,000 tons of ore per day. Also, Lakeshore is vat-leaching about 5,000 tons of ore per day. Geothermal energy could be used in all of these processes, but this study concentrates upon dump leaching (the most important).

Potential and Active Copper Dumps

Table 2 lists the existing dump leaching operations along with the estimated size of the deposits. Most leaching operations follow the process shown in Figure 2. The major differences are the methods used to extract the copper from the pregnant liquor. As indicated in Table 2, about half of the

Table 2. EXISTING AND OPERATING DUMPS IN ARIZONA

Name of Property or Location	Size of Ore Deposit (10 ⁶ tons)	Type of Leaching	Type of Copper Recovery
Ray	650	Dump-Vat-Agit	Solvent Extraction
Inspiration	180	Dump-Heap	Solvent Extraction
Bagdad	290	Dump	Solvent Extraction
Ox-hide	31	Heap	Precipitation
Silver Bell	26	Dump	Precipitation
Mineral Park	49	Dump	Precipitation
Cyprus Johnson	20	Dump	Solvent Extraction
Esperanza	21	Dump	Precipitation
Blue Bird	75	Heap	Solvent Extraction
Copper Queen	250	Dump	Precipitation
Morenci	662	Dump	Precipitation
Twin Buttes	329	Agit	Solvent Extraction
San Juan	500	Dump	Precipitation
Mission	104	Dump	Precipitation
Pinto Valley	290	Dump	Solvent Extraction
TOTAL	3,477

state's copper recovery is by means of precipitation by metallic iron. The newest recovery method is solvent extraction which is continuing to grow in importance.

Table 3 lists the names of the potential dump sites in Arizona. It includes inactive mines, still considered copper reserves, abandoned mines, active mines that have a potential for dump leaching, and copper deposits which may be future dump sites.

Table 3. OTHER POTENTIAL COPPER DUMPS IN ARIZONA*

Name of Property or Location	Size of Ore Deposit (10 ⁶ tons)
Ajo (New Cornilia)	126
Bisbee	47
Copper Basin	175
Castle Dome	48
Safford (Kennecott)	2,000
Safford (Phelps Dodge)	400
Sanches	79
Lakeshore	201
Christmas	33
Poston Butte	500
Sacaton	36
TOTAL	3,645

*Potential dumps include an estimation of ore (over the life of each mine) to be dumped upon each existing dump.

Methods of Applying Leach Solutions

Flooding and spraying are the two methods for applying leach solutions on copper dumps in Arizona. Spraying is the more common method of application.¹⁰ Perforated plastic pipes are placed over the dumps and the leach solution is sprayed under pressure. Sprinkler heads are generally used. This system provides a uniform distribution of water with minimal evaporation loss. In the flooding method, the leach solution is introduced to the surface of the dumps in ponds formed by furrows, ditches or channels. The surface of the dump is sectioned with some areas being flooded while others dry out. The efficiency of this method of alternate wetting and drying is discussed by Van Arsdale.¹¹

A leach solution of sulfuric acid and varying amounts of ferrous sulfate and ferric sulfate are used.¹² The end product or pregnant liquor is collected in reservoirs and contains copper in the form of copper sulfate.¹³ This solution is then pumped to either a copper precipitation plant or a solvent extraction plant where the metallic copper is extracted. Referring back to Table 2, it is seen that of the 15 operating dumps in Arizona seven use the solvent extraction method to extract their copper; the others use the more common precipitation method. A schematic of the solvent extraction process is shown in Figure 3.¹⁴

After extraction, the barren solution from the copper recovery plants is replenished by adding sulfuric acid and water which may have been lost through evaporation and seepage. This solution is recycled to the dumps as the leach solution. Generally, 80 percent of the leach solution is recovered. Dump leaching requires about three gallons of make-up water for every pound of copper recovered after the initial flooding of the dumps.

Figure 3: Schematic Flowsheet for Extracting Copper from Dilute Leach Solutions into an Organic Phase and for Producing Copper Electrowinning Electrolytes

Effect of Bacteria on the Leaching of Sulfides

The use of geothermal energy to heat leaching solutions could remarkably increase the efficiency of copper recovery in dump leach operations. However, several bacteria which live in the absence of organic matter are known to accelerate the leaching reactions as shown in Figure 4. A leaching temperature above 40°C to 50°C would harm the bacteria and prevent the sulfides from being leached. The bacteria believed to enhance the leaching of sulfide minerals is *Thiobacillus ferrooxidans*.¹⁵

Most sulfide mine waters contain active *Thiobacillus ferrooxidans*. The use of these mine waters as leach solutions automatically provides the initial cultures of bacteria for the leach system. Malouf and Prater stated that for optimum bacterial action, the leaching should be carried out under conditions in which the bacteria will flourish.¹⁶ These conditions are:

- (a) a pH between 1.5 and 3.5;
- (b) temperatures between 25°C and 40°C;
- (c) an adequate oxygen supply obtained by aerating the solutions and by periodically draining the ore pile;
- (d) Avoidance of exposing the solutions to sunlight.

The dissolved solids in geothermal brines should not harm these bacteria.

Sulfuric acid builds up and offsets acid losses in gangue materials and is thus useful. However, the leach solutions tend to become saturated in ferric sulfate which tends to precipitate as basic ferric sulfate or jarosite in the leach dumps.¹⁷ In some cases the precipitate may inhibit the trickling of leaching solution through the ore pile. This problem can be partially overcome by occasionally passing a reducing solution, such as sodium bisulfite, through the dumps.¹⁸

Figure 4: Laboratory Results Showing the Effect of Bacteria on the Rate of Copper Extraction from Chalcopyrite

GEOHERMAL RESOURCES

Essentially all of the copper production in Arizona (except for one mine near Kingman and some work at Douglas) is in Pima, Pinal, Graham and Greenlee counties. Therefore, this report concentrated it's efforts upon the geothermal energy resources of those four counties.

Pima County

Pima County lies entirely within the basin and range physiographic province which is characterized by numerous mountain ranges rising abruptly from broad valleys. Four areas believed to store thermal water at depths less than 1200 m (3937 ft) have been identified within the county. Pima County is shown in Figure 5 and labeled areas identify the four suspected areas.

Three of the areas highlighted in Figure 5 have been assessed for geothermal resource potential. There are several large copper production mines near the geothermal area extending south of Tucson through Green Valley. There is no known copper near the other two geothermal resource area, so this section will concentrate on the area south of Tucson.

Based on studies conducted in the basin and range province, certain general characteristics have been identified that help recognize low temperature geothermal occurrences. First, USGS defines a possible geothermal resource area as having water temperatures 10°C (18°F) greater than the mean annual air temperature and temperature gradients (i.e. temperature changes with depth) greater than $25^{\circ}\text{C}/\text{km}$ ($1.4^{\circ}\text{F}/100\text{ ft}$). Each of the areas identified on the map (Figure 5) meet these criteria. Second, in Nevada, Utah and Arizona major range bounding faults act as conduits for warm to hot water to rise from depth toward the surface. The heat source can be either shallow magmatic intrusion or deep circulation in a normal temperature gradient regime. In Arizona, most geothermal occurrences are related to deep

circulation which does not usually reproduce the high temperatures that result from a magmatic heat source. However, most valleys in southern Arizona are basin-range grabens bound by deep faults (see Glossary of Geological Terms). Thus, low temperature ($<90^{\circ}\text{C}$, 194°F) geothermal resources might reasonably be expected to occur in most deep basins.

In addition to expected low temperature ($<90^{\circ}\text{C}$, 194°F) resources within Pima County, one area has been inferred to contain an intermediate (90° - 150°C , 194°F - 300°F) temperature resource. The inference is based on a deep oil test well near the center of the Tucson basin, which had a bottom hole temperature of 147°C (297°F) at a depth of 3600 m (11,810 ft). Figure 5 also shows the location of this deep oil test well. USGS has estimated the reservoir volume to be 2.5 km^3 . Although the bottom hole temperature is known, a producible resource has not been confirmed. This oil well with a bottom-hole temperature of 147°C (297°F) is about five miles east of the nearest copper mine. No geothermal resource data is available on this intermediate region.

A state geothermal map compiled by the Arizona Bureau of Geology and Mineral Technology - Geothermal Group and published by the National Oceanographic and Atmospheric Administration provides a complete and updated listing of data concerning thermal well and spring locations in Arizona as well as temperature and depth estimates, flow rates and total dissolved solids. The map can be obtained free of charge by writing to the Arizona Bureau of Geology, 845 N. Park Avenue, Tucson, Arizona 85719.

Summary of Pima County Geothermal Resource Areas

Over a five year period, geologists from the Arizona Bureau of Geology and Mineral Technology have performed preliminary geothermal exploration and assessment of a number of locations around Arizona. Though the work performed

was preliminary, the results of one area within Pima County is summarized below, because it is reasonably close to several copper mines and concentrating plants using flotation technology.

This preliminary investigation of the geothermal potential of the Tucson basin was initiated in 1979 by the Arizona Bureau of Geology - Geothermal Group. The area is bounded by the Santa Catalina mountains on the north, the Rincon Mountains on the east, the Tucson Mountains on the west and the Santa Cruz county line on the south. Principal cities in the study area are Tucson, South Tucson, Continental and Green Valley. The Tucson basin area extending south through Green Valley is shown in Figure 5.

According to the study, this area has excellent potential for low-temperature ($<90^{\circ}\text{C}$, 194°F) geothermal resources. Hot water, 50°C (122°F), is within drilling depths of 762 m (2,500 ft) to 1,524 m (5,000 ft) in areas with anomalous temperature gradients. In addition, large volumes of low-temperature water are probably stored in the Tucson basin. Based on wells drilled below 800 m (2,625 ft), thermal water is expected to contain less than 1000 mg/l total dissolved solids and 4 to 10 mg/l of fluoride.

More current, and as yet unpublished, work by the Geothermal Group provides further evidence of geothermal occurrences. Zones of warm water 60°C (140°F) can be expected at depths of 760 m (2,500 ft). Further, the chemical quality of the water is excellent, containing less than 600 mg/l total dissolved solids. Reservoir lifetimes have been preliminarily estimated to be at least 100 years with proper management.

Pinal County

Pinal County lies entirely within the basin and range physiographic province which is characterized by numerous mountain ranges rising abruptly from broad valleys. Three areas believed to store thermal water at depths of

Figure 6: Locations of Potential Geothermal Resources in Pima County

less than 1200 m (3,937 ft) have been identified within the county, as shown on Figure 6. Extensive copper production and reserves being considered for future production overlap two of these areas. These are the geothermal resources in the Casa Grande and San Manuel areas. To date, most of the areas highlighted in Figure 6 remain relatively unexplored for geothermal resources. The three areas presented on the map were identified as probable areas based on water well data.

Eight thermal wells have been identified in the San Manuel - Mammoth area ranging in temperature from 31°C (87°F) to 42°C (108°F). The depths of these wells range from 16 m (53 ft) to 453 m (1486 ft). From the information available, it appears that the warmest water is flowing from confined aquifers beneath gypsiferous clay at a depth below 396 m (1300 ft). The thermal gradient for the area was calculated to be 48°C/km (2.6°F/100 ft). The thermal water contain sodium sulfate and sodium bicarbonate with a much lower level of total chlorides. Fluoride content exceeds 5 mg/l and total dissolved solids average 450 mg/l. Chemical geothermometry suggest subsurface temperatures of 70°C (158°F) at depths less than 1 km (3181 ft).

Twenty-seven irrigation wells in the Coolidge - Casa Grande area have been identified as having temperatures between 35°C (95°F) and 60°C (140°F) ranging in depth from 366 m (1,200 ft) to 914 m (3,000 ft). Many of these wells have discharge rates greater than 50 l/sec (790 gpm) and contain dissolved solids between 500 mg/l and 3,000 mg/l.

During the fall of 1974, Amax Exploration, Inc., Denver, Colorado drilled a geothermal test well in the Coolidge area to a total depth of 2440 m (8,006 ft). Optimum reservoir flow characteristics were displayed in fractured

AREAS FAVORABLE FOR DISCOVERY OF GEOTHERMAL RESOURCES

* AMAX GEOTHERMAL TEST WELL

0 16
 miles

Figure 6: Locations of Potential Geothermal Resource Areas in Pinal County

precambrian schist below 2000 m (6,560 ft). Fluid temperatures and chemistry were monitored through 193 hours of pumping. Stabilization occurred after 16 hours. The maximum outlet temperature was 82°C (180°F) and the well was pumped at a rate of 18.3 l/sec (290 gpm) for the duration of the test. Chemically, the water had a distinct sodium chloride content with low concentrations of dissolved gases. A maximum bottom hole temperature of 120°C (248°F) was observed after pumping. A normal gradient (35°C/km, 1.9°F/100 ft) heat source is implied. The well has since been plugged and abandoned.

The Amax test well provided documented evidence of the existence of a deep geothermal resource in the Coolidge area. It should also be noted that other deep drilling tests west of Casa Grande have also encountered similar temperatures at depths below 1500 m (4,920 ft). Although the area has not been carefully explored for geothermal resource extent, it would appear that a significantly large geothermal resource can be found beneath the entire Coolidge - Casa Grande area.

Graham/Greenlee Counties

The majority of land within Graham and Greenlee counties lies within the basin and range physiographic province, which is characterized by numerous mountain ranges rising abruptly from broad valleys. Five general areas believed to store thermal water at depths of less than 1200 m (3937 ft) have been identified within the two counties, shown on Figure 7. Extensive copper reserves overlap the geothermal resources (which includes the only two designed known Geothermal Resource Areas (KGRA's in Arizona) in the Morenci/Clifton area. A more general outline of potential geothermal resources is shown in Figure 8.

Of all possible geothermal resource locations in Arizona, The Graham and Greelee county areas are best understood. The five areas presented in Figure

7 have been studied in some detail by the Arizona Bureau of Geology and Mineral Technology - Geothermal Group.

In addition to expected low temperature ($<90^{\circ}\text{C}$, 194°F) resources within Graham and Greenlee counties, seven areas have been inferred to contain intermediate ($90^{\circ}\text{C} - 150^{\circ}\text{C}$, $194^{\circ}\text{F} - 300^{\circ}\text{F}$) to high ($<150^{\circ}\text{C}$, 300°F) temperature resources. Figure 9 also shows the locations of these seven inferred areas. Although some of the seven areas have been confirmed by drilling, each area has been inferred to contain intermediate ($90^{\circ} - 150^{\circ}\text{C}$, $194^{\circ} - 300^{\circ}\text{F}$) temperature geothermal water based on geologic structure and chemical geothermometry. (Geothermometry is a method whereby temperature dependent constituents in gases and water are used to predict or estimate reservoir temperatures at depth (see Glossary of Geological Terms). Geothermometers have been shown to be generally reliable for high-temperature systems and much less reliable for low-temperature systems. Further, the Cactus Flat - Artesia area of Graham County was the location of a heat-flow drilling study during late 1981. Results of the drilling have not yet been released by the Arizona Bureau of Geology - Geothermal Group.

The Clifton - Morenci region is located in central Greenlee county, as shown in Figure 8. This region is situated between the Colorado Plateau and Basin and Range physiographic province. The Clifton - Morenci region is characterized by rugged canyons cut by the San Francisco River, Gila River, Eagle Creek, Blue River and Chase Creek. Elevations range from 3000 ft. to over 8000 ft. above mean sea level.

Arizona's highest temperature thermal springs, Gillard hot Spring, 84°C (183°F) and Clifton Hot Springs, $30 - 72^{\circ}\text{C}$ ($86^{\circ} - 162^{\circ}\text{F}$) occur in the Clifton - Morenci Region. Lands adjacent to the springs are designated by the U.S. Geological Survey as Known Geothermal Resource Areas (KGRA's) and are awaiting

- AREAS FAVORABLE FOR DISCOVERY OF GEOTHERMAL RESOURCES
- * HOT SPRINGS
- ① MARY MACK WELL
- ② MOUNT GRAHAM MINERAL BATH WELL

Figure 7: Locations of Potential Geothermal Resource Areas in Graham and Greenlee Counties

Figure 8: Location of Potential Geothermal Resource Areas in Lower San Francisco Area

GRAHAM and GREENLEE

- ▲ - POTENTIAL DUMP LEACH LOCATIONS
- - EXISTING DUMP LEACH OPERATIONS
- ▨ - REGION OF HIGH CHEMICAL GEOTHERMOMETERS
- 82 - HOT SPRINGS, WITH TEMPERATURE IN °C
- - THICKNESS OF SEDIMENTS >365 METERS

Figure 9. Potential for Integration of Geothermal Energy and Copper Dump Leaching.

competitive lease sale.

The Clifton Hot Springs consist of numerous thermal springs and seeps which discharge along the San Francisco River, in and north of Clifton. The discharge from individual springs is less than .3 l/sec (5 gpm). The composite flow rate is estimated to be 75.6 l/sec (1,198 gpm). These thermal springs have a sodium-chloride chemistry with total dissolved solids between 7,000 and 14,000 mg/l. Variations in chemistry suggest that thermal waters mix with non-thermal water as they flow to the surface. The natural heat loss of the system is estimated to be 18 to 27 megawatts of thermal energy per annum.

Available chemical and geothermometer information for Clifton Hot Springs indicate a chemically and thermal nonhomogeneous, fracture controlled 90°C (194°F) to 150°C (300°F) geothermal system at depths less than 2500 m (8,200 ft). At depths greater than 2500 m (8,200 ft), temperatures up to 180°C (356°F) may exist.

Gillard Hot Springs discharge 80° to 84°C (176° to 183°F) water along the banks of the Gila River. These springs discharge sodium chloride bearing water with equal concentrations of sulfate and bicarbonate. Total dissolved solids range between 1200 and 1500 mg/l. Chemical geothermometers predict subsurface temperatures of 130° to 139°C (266° to 282°F) at depths less than 2500 m (8,200 ft). The natural surface discharge along the river banks is estimated to be 29.9 l/s (475 gpm) and convective heat loss into the Gila River is 7.8 megawatts.

Eight miles northwest of Gillard Hot Springs and east of the Gillard fault zone are the Eagle Creek Hot Springs. These springs discharge 42°C (108°F) sodium bicarbonate-chloride bearing water, with less than 1000 mg/l total dissolved solids.

In summary, the Clifton - Morenci region has excellent potential for discovery of 90° to 150°C (194° to 300°F) geothermal resources. Some estimates of well-head thermal energy and beneficial heat available from the Clifton - Morenci region are summarized as follows:

	Wellhead Thermal Energy (10 ¹³ Btu)	Beneficial Heat (10 ¹³ Btu)
Clifton Hot Springs	27.5	6.6
Gillard Hot Springs	25.6	6.2
Eagle Creek	17.0	4.1

ECONOMIC EVALUATION

As compared to conventional copper extraction methods, the inexpensive practice of dump leaching coupled with geothermal energy can be used to increase the rate of copper extraction. Experimental studies have shown that the rate of copper extraction increases while the extraction time decreases considerably if the leaching solution is heated to temperatures higher than the ambient temperature. This implies that the traditionally long-term dump leaching operations could be reduced to much shorter periods of time.

The relationship between the rate of copper extraction and the temperature of leaching fluids is illustrated in Figure 10.¹⁹ As noticed, leach fluid heating does not require high geothermal temperatures, but low to moderate temperatures. Consequently, this application could use the potentially abundant geothermal energy resources known to exist in Greenlee County, Graham County and Pima County. Unfortunately, one cannot always take full advantage of the higher geothermal temperatures which may be available since in some cases the oxidizing bacteria ceases its activity if the leach

solution is introduced at a temperature above 40°C.

As an example of the benefits which may be available from using geothermal energy to heat leaching solutions for dump leaching operations, consider the following analysis. Begin by assuming that a representative leach dump contains 200 million tons of ore at an average grade of 0.15 percent copper. The total amount of copper in the dump equals 300,000 tons. However, only a percentage of this total can be economically recovered.

When leaching with ambient-temperature (25°C) leaching solutions, approximately 55 percent of the available copper should be recovered over the life of the dump. For this example, 165,000 tons of copper would be recovered. It is estimated that copper recovered from a dump leaching operation is valued at \$0.48 per pound, as additional refining steps would be required to bring it up to 99.9 percent pure. Therefore, using ambient-temperature leaching solutions, the dump would generate \$158,400,000 over its total life.

By increasing the temperature of the leaching solution, it has been experimentally demonstrated that copper extraction rates would increase.¹⁹ Although the experimental results presented in Figure 10 are based on laboratory results obtained in a stirred reactor, it is assumed that the percent of copper precipitated using leaching solutions of 40°C would increase to approximately 70 percent. Total recovery over the life of the dump would increase to 210,000 tons. Valued at \$0.48 per pound, the total recoverable value of the dump would increase to \$201,600,000. The net effect of using geothermally heated water in the leaching solution is \$43,200,000 over the useful life of a dump containing 200 million tons of ore.

In order to compare this expected benefit with an estimated geothermal development cost, it is first necessary to estimate water requirements for the

Figure 10. Effect of Temperature on Copper Precipitated and Reaction Time

leaching operation. It is estimated that a copper dump leaching operation would require 3 gallons of makeup water for each pound of copper extracted. It is also assumed that 80 percent of the water distributed over a dump is recovered and used again. Lastly, it is assumed that a leached dump has a useful life of 20 years. Given these assumptions and under ambient-temperature conditions, 16,500,000 pounds of copper would be recovered each year. A total of 247,500,000 gallons of leaching solution would be required each year, of which 198,000,000 gallons (80 percent) would be recycled solution and 49,500,000 gallons would be makeup solution. Assuming a batch leaching operation in which the leaching solution is applied on the dump six times each year with intervals between applications for the dump to rest, 41,250,000 gallons of solution would be required for each batch. Eighty percent of the 41,250,000 gallons would be recovered and used again.

If the temperature of the leaching fluid were increased to 40°C, additional leaching fluid would be required to accomodate the additional copper extracted. Using the assumptions stated above, leaching solutions with a temperature of 40°C would recover 21,000,000 pounds of copper each year, requiring a total of 315,000,000 gallons of leaching solution. Of this amount, 252,000,000 gallons (80%) would be recycled and 63,000,000 gallons would be makeup solution. Assuming six applications per year, 52,500,000 gallons of leaching solution would be required for each application. Of this total, 42,000,000 gallons (80%) would be recycled solution and 10,500,000 gallons would be makeup solution.

For this analysis, the 52,500,000 gallons of leaching solution should have a temperature of 40°C upon application. Assuming that the 42,000,000 gallons of recycled solution is at 25°C, the addition of 10,500,000 gallons of 100°C geothermal water would create the desired leaching solution temperature.

Several mining locations, particularly those located in Pima, Graham and Greenlee Counties, are favorably situated on or near prospective geothermal resources. In the worst situation, a temperature gradient of $40^{\circ}\text{C}/\text{km}$ can be expected in the Basin and Range province of Arizona. This being the case, 100°C temperatures would be encountered at 7000 feet. For the more favorable locations, gradients of $50^{\circ}\text{C}/\text{km}$ or greater would not be unreasonable. In estimating drilling costs, it is assumed that the temperature gradient is $40^{\circ}\text{C}/\text{km}$, implying a drilling depth of 7000 feet for the desired temperature.

From previous drilling experience, a completed geothermal well to 7000 feet would cost approximately \$1,600,000. In addition, pumps and a piping network would be required to transport the geothermal water to the desired location. It is estimated that a wellhead pump capable of producing 1000 gpm of 100°C water plus circulation pumps would cost \$100,000. A piping network consisting of two miles of insulated 10-inch pipe would cost \$40 per installed foot, or about \$430,000. Therefore, a general estimated investment cost for the geothermal system is \$2,130,000.

Assuming equal returns in each year from the copper dump leaching operation, an additional 4,500,000 pounds of copper would be recovered each year as a result of heating the leaching solution. At \$0.48 per pound, the total value added per year by the geothermal system is \$2,160,000. For each successive year in which the dump is operated, similar results would also be obtained. In comparing the annual cash flow with the investment cost, a payout of slightly over one year is attained.

In addition to the extra revenue generated by the geothermal system, two other benefits are also available. First, the use of geothermal water in place of fresh makeup water represents a 20 percent fresh-water savings. Second, by investing in a geothermal system, a mining operation would qualify

for significant tax advantages. The mine would be able to claim a depletion allowance for geothermal production equal to 27.5 percent of revenue for state tax purposes and 20 percent of revenues for federal taxes. In addition, the mine could claim a 25 percent tax credit for the capitalized costs of the geothermal system. Although the water savings and tax incentives have not been added to the calculation, it is obvious that the system payout would decline to less than one year.

Limitations and Alternative Routes for Geothermal Application

In general, the use of a geothermal resource has some limitations which are summarized as follows:

- (1) The cost of drilling wells and completion of the geothermal system might require a high capital investment. The initial investment costs depend upon the degree to which preliminary studies are made, the depth to the resource and the extent to which precautions are taken to avoid contamination of underground water resources.
- (2) A geothermal brine with a relatively high salinity may cause corrosion problems, thereby increasing the operating cost of the project. It should not reduce leaching rates.
- (3) A limit on the temperature of the geothermal water used is imposed because of the possible harm to beneficial bacteria in the leaching of copper sulfide ores.

If a nearby geothermal resource were used, all the above restrictions would have alternative routes making the process economically sound. It is estimated that geothermal resources in Arizona have between 700 and 1400 milligrams per liter of dissolved solids, which is considered to be a low solids content. As a result, these waters could be used directly as the make-up water for the leaching fluid. Considerable savings would result due to the

following reasons:

- (a) a heat exchanger would not be needed since the hot water would be used directly to heat up the leach solution;
- (b) reinjection wells would not be needed since the used geothermal water would be collected in holding ponds and recycled for reuse; and
- (c) Potable water would be available for other uses such as domestic and irrigation purposes.

CONCLUSIONS

The rate of copper extraction is enhanced at higher leaching fluid temperatures. Currently, all copper leaching operations in Arizona are performed at an ambient leach fluid temperature. However, the use of geothermal waters as a heating medium could prove to be very useful since the water is already hot. The Morenci, Safford, and Pima County areas are ideal sites for geothermally assisted copper leaching because of the proximity of geothermal resources to the mining locations. Leach fluid heating does not require high geothermal temperatures, as does geothermal power generation. Furthermore, experimental results indicate that beneficial bacteria needed for the leaching of sulfides limit the extent to which solution temperatures can be increased. The low to moderate water temperatures, low salinity and relatively easy and inexpensive production can make geothermal-incorporated leach systems a highly desirable alternative for increasing copper production.

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ADDITIONAL RELATED REPORTS

The following fifteen reports were prepared by the Evaluation of geothermal Utilization group:

1. Goldstone, L.A. and White, D.H., 1982, Geothermal Development Plan: Maricopa County, prepared for the U.S. Department of Energy, Contract No. DE-FC03-80RA50076 and the Arizona Solar Energy Commission: State of Arizona Bureau of Geology and Mineral Technology Open-File Report 79-8.
2. Goldstone, L.A. and White, D.H., 1982, Geothermal Development Plan: Pima County, prepared for the U.S. Department of Energy, Contract No. DE-FC03-80RA50076 and the Arizona Solar Energy Commission: State of Arizona Bureau of Geology and Mineral Technology Open-File Report 79-9.
3. Goldstone, L.A. and White, D.H., 1982, Geothermal Development Plan: Graham/Greenlee Counties, prepared for the U.S. Department of Energy, Contract No. DE-FC03-80RA50076 and the Arizona Solar Energy Commission: State of Arizona Bureau of Geology and Mineral Technology Open-File Report 79-10.
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5. Goldstone, L.A. and White, D.H., 1982, Geothermal Development Plan: Yuma County, prepared for the U.S. Department of Energy, Contract No. DE-FC03-80RA50076 and the Arizona Solar Energy Commission: State of Arizona Bureau of Geology and Mineral Technology Open-File Report 81-18.
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Other related reports include the following:

1. Acorn Engineering Associates, 1982, Geothermal Feasibility Study for Decker Land Development, Tucson, Arizona: Unpub. Report for Oregon Institute of Technology, Contract No. TA 1-82: State of Arizona Bureau of Geology and Mineral Technology Open-File Report.
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Open-File reports can be obtained by writing to:

State of Arizona Bureau of Geology
845 N. Park Avenue
Tucson, Arizona 85719

or to

Arizona Solar Energy Commission
1700 W. Washington, Room 502
Phoenix, AZ 85007

In addition, reports prepared for the U.S. Department of Energy can be obtained by contract number from

U.S. Department of Energy
Technical Information Center
P.O. Box 62
Oak Ridge, TN 37830

GLOSSARY OF GEOLOGICAL TERMS

Anomalously shallow depth - unusually or unexpectedly shallow depth.

Basin-range graben bound by deep faults - an area usually ten to hundreds of km² in area that has been down dropped along deep faults relative to the surrounding mountains; the grabens become filled with sediments to become valleys.

Curie-depth - the depth at which rocks become hot enough to lose their magnetic properties, ~ 525°C. Curie temperature within 5-10 km of the surface are an indicator of geothermal resource potential.

Deep circulation - the natural movement or flow of ground water, as a result of convection, whereby it descends and becomes heated at depth and then rises toward the surface.

Deep sediment-filled, faulted basin - see basin - range graben.

Depth of Curie-isotherm analysis - technique used to estimate depth to the Curie temperature.

Hot dry rock production - a method for extracting useful heat in a deep dry hole; accomplished by fracturing the hot rock between two deep holes, and pumping cold fluid into one and bringing hot fluid out of the other.

Geothermometer - an empirical formula, based on the temperature-dependent solubility of certain minerals, used for estimating deep fluid temperatures in a geothermal reservoir.

Magnetotelluric survey - an electromagnetic method in which natural electric and magnetic fields are measured. Models of the crust can then be constructed and resistivities at great depth can be predicted.

Major range bounding faults - fractures or fracture zones along which mountains have risen relative to down dropped grabens.

Shallow magmatic intrusion - a body of magma that has intruded its way upward into shallower crust.

Na-K-Ca geothermometer -- (also, quartz geothermometer, chalcedony geothermometer) - see geothermometer.

Tectonic history - the cycle that relates the larger structural features of the Earth's crust to gross crustal movements and to the kinds of rocks that form in the various stages of developments of these features.