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**GEO THERMAL ENERGY FOR THE INCREASED
RECOVERY OF COPPER BY
FLOTATION ENHANCEMENT**

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ABSTRACT

The possible use of geothermal energy (a) to speed the recovery of copper from ore flotation and/or leaching of flotation tailings and (b) to utilize geothermal brines to replace valuable fresh water in copper flotation operations were evaluated in this report. Geothermal energy could be used to enhance copper and molybdenum recovery in mineral flotation by increasing the kinetics of the flotation process. In another approach, geothermal energy could be used to heat the leaching solution which might permit greater copper recovery using the same residence time in a tailings leach facility. Since there is no restriction on the temperature of the leaching fluid, revenues generated from the additional copper recovered would be greater for tailings leach operations than for other types of leach operations (for example, dump leaching operation) for which temperature restrictions exist.

The estimated increase in total revenues resulting from a two percent increase copper recovery in a 50,000 tons ore/day plant was estimated to be over \$2,000,000 annually. It would require an estimated geothermal investment of about \$2,130,000 for a geothermal well and pumping system. Thus, the capital investment would be paid out in about one year. Furthermore, considerable savings of fresh waters and process equipment are possible if the geothermal waters can be used directly in the mine-mill operations, which is believed to be practical.

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INTRODUCTION

Much of the copper mined in Arizona is of the sulfide-oxide nature with the sulfide minerals constituting the largest proportion. Typical copper ores, usually from open-pit mines, contain between 0.3 and 1.0 wt. % copper. Presently, the increased demand for copper, coupled with the depletion of high-grade copper ores has resulted in lower and lower grade deposits being mined. The actual cut-off grade of copper below which mining is uneconomical primarily depends on the selling price of copper, the size of the ore deposit and the cost of mining and extraction.

Approximately 90 percent of the world's primary copper originates from sulfide ores (1). These ores are not easily leached with an acidic solution since they are soluble in sulfuric acid only under highly oxidizing conditions such as those provided by high oxygen pressures. Therefore, the majority of the extraction of high- to moderate-grade copper ores is accomplished by conventional techniques starting with copper concentrates.

The extraction process consists of the following major steps:

- (a) concentration by froth flotation;
- (b) matte smelting;
- (c) conversion to blister copper.

A flowsheet for recovering pure copper from sulfide ores is shown in Figure 1; Figure 2 describes the comminution and flotation sequences in more detail. After crushing and grinding the ore, froth flotation is applied to form a separate, high-grade concentrate of copper minerals. The application of geothermal energy for heating the ore slurries used in froth flotation may result in increased mineral recovery. The concentrate is then usually subjected to matte smelting and is converted to blister copper. This process is followed by refining and electrorefining in order to obtain highly pure

Figure 1: Principal Processes for Extracting Copper from Sulfide Ores

Figure 2: Generalized Flowsheet for the Production of Copper from Copper Sulfide - Iron Sulfide Ores

copper cathodes.

The flotation tailings are low in copper content. However, geothermal energy could possibly be used to heat leaching solutions which would result in greater copper recovery from the tailings and faster recovery rates.

Treatment of Copper Ore Prior to Flotation

After grinding, the grains of copper minerals are free (liberated) from the grains of the other minerals. The required degree of grinding for effective liberation varies with the grain size of the minerals in the ore and at present can be reliably determined only by performing grinding and flotation tests (1). Figure 3(a) shows the effect of particle size on extent of copper recovery in concentrate; Figure 3(b) shows the effect of particle size on copper concentration in tailings. There is an optimal particle size for maximum recovery of copper in the concentrate. Larger particles can cause the copper minerals to be trapped in the gangue minerals thus preventing their flotation; very fine particles tend to form a slime which coats the copper minerals and therefore lowers the efficiency with which they are floated. Industrial operations tend to choose the optimal particle size in terms of cost. Since grinding requires a considerable amount of electrical energy and time, the particle size chosen is slightly larger than that for maximum recovery (3).

In particle sizing, large ore pieces are first crushed by applying compressive forces in jaw or eccentric crushers. Then, the crushed particles are wet-ground in rod and ball mills in which abrasive, impactive and compressive forces all contribute to breaking the ore. The ore may be recycled for regrinding in order to obtain a fine enough particle size for efficient flotation.

Figure 3: Examples of the Effects of Grind (Particle Size) on: (a) Copper Recovery and (b) Concentration of Copper in Flotation Tailings. (Taggart, 1954)

Froth Flotation

Flotation is undoubtedly the most important and versatile mineral processing technique, and both the use and the application of this technique over the years has been expanded to treat greater tonnages of ore. Sulfide minerals are first conditioned with a special reagent which causes them to become hydrophobic, i.e., water-repellent. This hydrophobicity can be created for specific minerals within a water-ore pulp. Secondly, bubbles of air which are passed through the flotation cell collide with the water-repellent copper minerals and entrain them to the surface of the cell; the wetted non-copper mineral particles do not attach themselves to air bubbles and settle to the bottom of the cell.

The same procedure is applied to copper ores: the ore pulp is conditioned with the proper reagent so as to make the copper minerals hydrophobic without affecting the other minerals. A stream of air bubbles is then passed through the pulp. The air bubbles attach themselves to the copper minerals and carry them to the top of the flotation cell. The froth is gathered in a network of troughs adjacent to the flotation cells where it collapses and flows into a collection tank. The products from flotation contain about 70 weight percent water, most of which must be removed before the copper concentrate can be smelted.

Copper sulfide minerals are usually associated to some degree with pyrite in a gangue which may contain silica, calcite and various silicates. In this case, the purpose of flotation is to separate the sulfide minerals from the gangue and pyrite. Copper is one of the most floatable of the sulfide minerals and responds readily to sulphydryl reagents (collectors), with potassium ethyl xanthate being the most commonly used reagent. Reagent consumption is generally in the range 0.02-0.3 kg xanthate and 0.02-0.15 kg frother per ton

of ore (4). Usually, either pine oil or a higher alcohol is used as a frother (4). Since flotation involves surface chemical reactions, these reaction rates can be increased by raising the temperature; these increased reaction rates could produce increased mineral recovery.

When a sulfide-oxide ore mixture is treated by flotation, the recovery of oxide minerals by the flotation process is not efficient because the mineral surfaces do not respond to xanthate collectors and most nonsulfide collectors function well only at temperatures above ambient. This is the primary reason for the loss of copper minerals in tailings. However, the oxides can be made floatable by adding NaHS or Na_2S (0.5-5 kg per ton of ore) to the pulp (5) or by the use of nonsulfide collectors. Due to the small percentage of oxides in the ore, the above step is generally neglected. Typical froth flotation produces concentrates containing 20 to 30 percent copper and tailings containing 0.10 to 0.20 percent copper. However, the concentrate stream is much smaller than the tailings stream so that some 20 weight percent of copper is not recovered at this point.

Copper Extraction from Flotation Outputs

The copper concentrates constitute the main product from the flotation process. After the concentrates are dewatered the sulfides of flotation are subjected to roasting. This process consists of partially oxidizing the sulfides of flotation concentrates and eliminating the sulfur as SO_2 . This is done by reacting the concentrates with air at temperatures between 500° and 700°C (1) in hearth or fluid bed roasters under well-controlled conditions. The roaster product, calcine, is a mixture of oxides, sulfates and sulfides; its composition can be varied by controlling the temperature of the roasting process and the ratio of air to concentrate. Roasting produces a gas composition of 5 to 15 percent SO_2 which is then recovered as sulfuric acid.

Roasting is used prior to reverberatory and electric furnace smelting. The principal purposes of roasting are to utilize the heat of roasting to dry and heat the charge before it is added to the smelting furnace and to increase the concentration of copper in the smelting liquid matte. Roasting is an optional step. A number of copper mining operations such as those of Ajo, San Manuel, and Morenci do not roast the sulfides of flotation concentrates; a "green smelter" does both functions.

Smelting is the next step in the procedure. In Arizona, only Inspiration Copper uses an electric furnace for matte smelting; the other companies use conventional reverberatory furnaces. In smelting, a liquid sulfide phase which contains almost 90 percent of the copper in the charge and a liquid slag almost free of copper are formed. The slag consists of silica, aluminum, iron oxides, lime and other oxides and is lighter than and almost immiscible with the matte. As a result, the slag is easily separated from the matte. The slag is either discarded immediately or is passed through a copper recovery step. The matte is oxidized with air to remove the iron and sulfur which results in the production of a 99 percent "blister" copper. This process is universally carried out in the horizontal basic refractory-lined cylindrical Pierce-Smith converter (6). The resulting blister copper contains less than one weight percent iron and 0.02 to 0.1 weight percent sulfur.

The final step is the electrorefining of copper which consists of the electrochemical dissolution of copper from the impure anodes and the plating of pure copper onto copper cathodes. The electrolyte is an aqueous solution of H_2SO_4 (200 kg m^{-3}) and CuSO_4 (50 kg m^{-3}) usually with a trace amount of chlorine (1). Many of the anode impurities are insoluble in this electrolyte. The electrolyte is continuously circulated as a side stream through a purification circuit to maintain its proper composition.

The tailings are the other output from the flotation process. These tailings generally contain 20 percent of the copper present in the original ore. In the past, these tailings, considered too low in copper content to extract or too uneconomical to regrind and recycle, were directly discarded. With the depletion of high-grade copper ores in Arizona, the extraction of copper from these tailings is often economic. The tailings are mostly oxide minerals that were not floated by the xanthate reagent. These oxides are soluble in dilute sulfuric acid (1). Therefore, sulfuric acid leaching solutions can be used to extract the copper from the tailings. The advantages of using sulfuric acid are its availability as a by-product from smelting operations and its rapid attack on oxidized ores.

An important factor affecting leaching rates is the temperature of the leaching fluid. Experimental studies have shown that increasing the temperature from the ambient level to 60°C increases the leaching rate considerably (1). Unlike dump leaching operations, in which a leach temperature of 40°C cannot be exceeded without harming the beneficial bacteria responsible for sulfide leaching, tailing leaching operations have no restriction as to how hot the leaching solution can be introduced. The hotter the leaching solution, the greater the amount of copper extracted and the faster the extraction rate. As a result, additional revenues can be generated from tailing leaching operations.

POTENTIAL USES OF GEOTHERMAL WATER FOR HEATING SOLUTIONS USED IN LEACHING FLOTATION TAILINGS

Copper processing operations can use geothermal energy to heat flotation slurries or leaching fluids. From the economic point, hot springs are probably the best available evidence of geothermal waters. Minimum exploration is necessary to site production wells for utilization of these

resources. The Clifton Hot Spring system may be the most strategically located and economical (7) low- to moderate-temperature geothermal resource in Arizona from the standpoint of a potential user. The hot springs discharge along the San Francisco River at observed temperatures ranging from 30°C to 70°C.

Unfortunately, hot springs are not always readily useful for copper mining. Mining companies usually do not have direct access to them. In most cases, drilling production wells would become necessary. The completion of a geothermal well involves making a capital investment. The initial investment costs would depend upon the degree to which preliminary studies are made, the depth to the resource and the extent to which precautions are required to avoid contamination of underground water resources. Nevertheless, this can still prove to be economical depending on total revenues generated from the increased copper recovery. Furthermore, these waters might be used directly as the make-up water in the flotation and leaching processes. Considerable savings could result due to the fact that potable water would be available for other uses, reinjection wells would not be needed and a heat exchanger would not be required to heat the leaching solution. Also, fresh and hot geothermal waters could be mixed to result in water at a temperature around 43°C which can be safely used in crushing and grinding operations. In addition, mixing fresh and hot geothermal water prevents steaming.

Mining operations consume considerable amounts of fresh water. Table 1 shows a typical mill water balance (8) in which make-up water represents 18.9 percent of mill water and 21.7 percent of total mine mill water usage. Figure 4 presents a flowsheet for the information presented in Table 1. Total make-up water for an open-pit mill complex is about 175 gallons per ton of ore milled or treated (8). Thus, a mine-mill complex processing 100,000 tons per

day would consume approximately 19 million gallons or 59 acre-feet of make-up water per operating day. This amount of water approximates the amount used daily by a community of 100,000 people. A tailings leach operation would use

Table 1. Copper Concentrating Mill Water Balance

Waters In	(Gpt)	Waters Out	(Gpt)
New Make-up water	110	Evaporation loss in concentrator	4.4
Ore moisture	6	Loss in concentrate to dryers	0.6
Concentrate thickness	31	Tailings slurry to dams	<u>315</u>
Tailings thickeners	230	Subtotal out streams	320
Tailings dam water	135	Concentrate	31
Reclamation wells	69	Tailings thickeners	<u>230</u>
		Subtotal thickener streams	261
Total in streams	581	Total out streams	581

about 45 gallons of make-up water per ton of tailings treated. The dissolved solids in geothermal brines should not be harmful in the proposed copper processing; in fact, some are beneficial, especially any dissolved hydrogen sulfide.

EXPERIMENTAL DATA ON FLOTATION AT HIGHER TEMPERATURES

The application of geothermal brines to enhance copper flotation, as suggested during this study, motivated the Arizona Bureau of Geology and Mineral Technology, University of Arizona, to make a few

* U.S. Gallons per dry short ton of ore treated.

Figure 4: Descriptive Flowsheet for Table 1

experimental tests in its laboratories at its expense in late 1981.

In an effort to assess this potential of using geothermal brines directly, exploratory laboratory flotation tests were conducted to determine the effects of heating flotation slurries to the approximate temperature that could be achieved by using geothermal water as makeup water. Using 70°C geothermal water, the resulting temperature of the slurry was estimated to be 43°C. Results of these laboratory tests on very low grade chalcopyrite ore are given in Table 2.

TABLE 2 - EXPERIMENTAL DATA ON HOT SLURRY ROUGHER FLOTATION

Variable Series	Unheated Slurry First Series	Heated Slurry Second Series	Heated Slurry
Number of Tests in Mean	10	3	3
Slurry Temperature	23.5°C	42.4°C	45.4°C
Frother Dosage (MJBC in kg/t)	0.098	0.098	0.196
Concentrate Recoveries			
% of Total wt.	4.11	2.31	2.81
% of Cu	91.23	91.19	92.91
% of Mo	89.14	85.99	87.47
Concentrate Grade			
% Cu	6.46	11.13	9.30
% Mo	0.644	1.120	0.808

General Test Conditions

1,000 gram charge; ground to give 66.8% passing 150 μ m ; Flotation agents other than frother: Lime to pH 11.4 (approximately 4.3 kg/t), Phillips Orfom MCO (0.0772 kg/t), American Cyanamid 3302 (0.0152 kg/t) and American Cyanamid Aero 355 (0.010 kg/t); Flotation Time 5 minutes; Grinding Time 6.5 minutes; all reagents were added to the ball mill.

These data indicate the rougher concentrate grades can be improved when the flotation slurry is heated, about 1.7 wt.% increased recovery. Although

the selectivity of the flotation process is improved, slightly lower molybdenum recoveries may be experienced. The slight decreases in molybdenum recoveries probably result from the volatilization of the methyl isobutyl carbinol (MIBC) surfactant used as the frother. Molybdenite recoveries are very sensitive to insufficient frothing. Actual increases in recoveries would be expected if a less volatile frother such as Dowfroth 250 were used. The recovery economics would require evaluation of an ore from a specific deposit using the appropriate geothermal brine. Since actual brine was not used in the reported experiments, only the effects of slurry temperature can be shown.

The bulk of the world's molybdenum is produced by flotation either as a product from primary mines or as a by-product recovered from mineral concentrates originating in the flotation of copper. The heating of slurries for the improved selectivity of molybdenum is currently practiced in some molybdenum by-product plants.

Additional investigations of the use of geothermal brines in the froth flotation of copper and molybdenum minerals appears warranted. The use of geothermal brines may increase either mineral selectivities or mineral recoveries. The use of geothermal brines as process water make-up may result in decreased consumption of the potable water resources of the arid areas of the western United States.

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 temperature 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 resource 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° -

Figure 5: Locations of Potential Geothermal Resources in Pima County

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 km³. 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 in 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 contains 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.

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 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.

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

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 contents all exceed 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 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, as 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 Greenlee 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

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.

Figure 7: Location of Potential Geothermal Resources Areas in Lower San Francisco Area

■ AREAS FAVORABLE FOR DISCOVERY OF GEOTHERMAL RESOURCES

* HOT SPRINGS

① MARY MACK WELL

② MOUNT GRAHAM MINERAL BATH WELL

Figure 8: Location of Potential Geothermal Resource in Areas in Graham and Greenlee Counties

G R A H A M a n d G R E E N L E E

- ▲ - 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

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 competitive lease sale.

The Clifton Hot Springs consists 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 2.5 km (8,200 ft). At depths greater than 2.5 km (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 2.5 km (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 megwatts.

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	Beneficial Heat
	<u>(10¹³ Btu</u>	<u>(10¹³ Btu</u>
Clifton Hot Springs	27.5	6.6
Gillard Hot Springs	25.6	6.2
Eagle Creek	17.0	4.1

ECONOMIC EVALUATION

Due to the extensive geothermal resources in the Clifton-Morenci area, it is believed that only a modest capital investment would be required. The majority of the investment cost is drilling, though other capital equipment, such as pumps and piping would be required. Since the well cost is significant, its cost is estimated for a general case and compared to the

expected increase in revenue. It is assumed that suitable temperature geothermal water at Arizona mining locations can be discovered at a depth of 2.5 kilometers. According to local drillers, the average fixed cost of drilling a 28-inch diameter top hole, 16-inch casing well is \$192,250:

Drilling cost	\$124,250
Casing cost	\$ 42,000
Equipment set up	\$ 20,000
Mud cost	<u>\$ 6,000</u>
	\$192,250

In addition, a rate of \$1,000 per hour for an estimated work period of 27.5 weeks (50 hours/week) must be added. The total drilling costs are:

$$\$192,250 + \$1,375,000 = \$1,567,250, \text{ or about } \$1,600,000.$$

A pumping and insulated piping system of, say, two miles would add an estimated \$530,000. Therefore, the net earnings for the two-percent increase in copper recovery in the first year are:

$$\$2,210,000 - \$2,130,000 = \$80,000/\text{year}.$$

Thus, the system would be paid out in about one year. Increases in copper recovery of greater than two percent are quite plausible, and net savings would be even higher.

CONCLUSIONS

Depletion of high-grade copper ores has led to the extraction of ores of lower and lower grades. Increased copper recoveries of about 2.0 wt.% achieved by either geothermal heating of flotation slurries or tailings leach solutions would result in increased revenues from the processing of low grade

ores. It would appear that a capital investment of about \$2,130,000 would pay back over \$2,000,000 during the first year of operation. If a solvent extraction method would then be used to extract the copper from the pregnant leach liquors, geothermal heating of these solutions would also be beneficial. From an economical standpoint, geothermal water appears to be a good heating medium. Even though capital investment must be made, expected revenues are promising and an the overall increase in copper recovery should result. Increased supply of water for the copper operations resulting from the direct use of geothermal waters also is an important factor.

Expected Net Revenues from Increased Copper Recovery

The experimental tests indicated that geothermal-heated flotation might increase the copper recovery by about 1.7 percent. It is the opinion of technologists experienced in flotation that more extensive studies would lead to an overall increase recovery of 2 percent copper. It is assumed that an open-pit ore containing 0.7 percent copper is used for the extraction process. The normal recovery of copper in flotation concentrates is about 75 percent. Because of the impurities contained in this copper its current selling price at this stage would amount to \$0.48 per pound of copper in concentrate. One ton of ore contains:

$$(2000 \text{ lbs/ton})(0.007) \frac{\text{lbs Cu}}{\text{lb ore}} = 14 \text{ (lbs copper/ton ore)}$$

Even if geothermal heating only increased copper recovery from 75 to 77 percent, the amount of copper recovered would be quite significant:

$$(14 \text{ lbs Cu/ton ore}) (0.02) = 0.28 \text{ lb Cu/ton ore.}$$

This is equivalent to a gain of:

$$(0.28 \text{ lb Cu/ton}) (\$0.48/\text{lb Cu ore}) = \$0.13/\text{ton ore}.$$

For the case of the mining operation where about 50,000 tons of ore per day are treated, the total revenue would be:

$$(50,000 \text{ tons ore/day}) (\$0.13/\text{ton ore}) = \$6,500/\text{day}.$$

For 340 operating days in a year, the annual revenue would be:

$$(\$6,500/\text{day})(340 \text{ days/year}) = \$2,210,000/\text{year}.$$

In addition to the above, if a solvent extraction method were used to extract the copper from the pregnant leach liquors, geothermal heating of these solutions would also be beneficial. From an economical standpoint, geothermal water appears to be a good heating medium. Capital investments for geothermal energy are modest, considering the potential savings by increased recovery of copper. Increased supply of water for the copper operations resulting from the direct use of geothermal water is an equally important factor.

REFERENCES

1. Biswas, A.K. and Davenport, W.G., "Extractive Metallurgy of Copper", 2nd Ed., Pergamon Press, Inc., 1980.
2. Taggart, A.F., "Handbook of Mineral Dressing", John Wiley and Sons, Inc., New York, 1954.
3. Steane, H.A., "Developing and Implementing Mineral Processing Flowsheets for New Mining Ventures", Lecture Notes in Mineral Processing Systems Course, McGill University, November 25 to December 6, 1974.
4. Wills, B.A., "Mineral Processing Technology", Pergamon Press, Inc., New York, 1979.
5. Ser, F., et al, "Sulfidric Flotation of Previously Sulfidized Oxide Copper Minerals of Nchanga Consolidated Mines Limited", Rudy (Prague), 5(18), 169-174, 1970.
6. Boldt, J.R. and Queneau, P., "The Winning of Nickel", Longmans Canada Ltd., Toronto, Section 3, 1967.
7. Witcher, J.C., "Geothermal Energy Potential of the Lower San Francisco River Region, Arizona", Open-File Report No. 3, U.S. Department of Energy, 1981.
8. Young, T., Ex-Chief of Metallurgy Staff of two concentrators for three years, Phelps Dodge, Morenci.

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.
4. Goldstone, L.A. and White, D.H., 1982, Geothermal Development Plan: Pinal 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 79-11.
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.
6. Goldstone, L.A. and White, D.H., 1982, Geothermal Development Plan: Cochise - Santa Cruz 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 80-9.
7. Goldstone, L.A. and White, D.H., 1982, Geothermal Development Plan: Northern Arizona 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 80-10.
8. Goldstone, L.A. and White, D.H., 1982, Maryvale Terrace: Geothermal Residential District Space Heating and Cooling, 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 81-11.

9. Goldstone, L.A. and White, D.H., 1982, Geothermal Heating for the Arizona Environmental Research Laboratory Greenhouses, 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 81-12.
10. White, D.H. and Goldstone, L.A., 1982, Evaluation of Geothermal Cooling Systems in Arizona, 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 81-13.
11. White, D.H. and Goldstone, L.A., 1982, Irrigation Pumping Using Geothermal Energy, 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 81-15.
12. White, D.H. and Goldstone, L.A., 1982, Geothermal Energy for Copper Dump Leaching, 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 81-15.
13. White, D.H. and Goldstone, L.A., 1982, The Potential of Hybrid Geothermal/Coal Fired Power Plants in Arizona, 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 81-8.
14. Malysa, L.M. and White, D.H., Hahman, W.R., Mancini, F., and Goldstone, L.A., 1980, Arizona Geothermal Institutional Handbook, prepared for the U.S. Department of Energy, Contract No. DE-FC07-79ID12015, and the Arizona Solar Energy Commission: State of Arizona Bureau of Geology and Mineral Technology Open-File Report 80-7.
15. White, D.H. and L.A. Goldstone, 1982, Executive Summary: The Potential of Utilization of Geothermal Energy in Arizona, 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 82-1.

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.
2. Frank, Helmut J., ed., 1982, Arizona's Energy Future: Making the Transition to a New Mix, Tucson: University of Arizona Press.
3. Johannessen and Girand Consulting Engineers, Inc., 1981, Feasibility Study for Geothermal Water Space Heating for the Safford Federal Prison Camp, Safford, Arizona: Unpub. Report for the Oregon Institute of Technology, Contract No. TA 18-80: State of Arizona Bureau of Geology and Mineral Technology Open-File Report 81-30.
4. Pasqualetti, M.J., Goldstone, L.A. and Stone, Claudia, 1981, Land Use Planning for Geothermal Development-Scottsdale, Arizona, partially funded by the U.S. Department of Energy, Contract No. DE-FC03-80RA50076 and the City of Scottsdale Planning Department: State of Arizona Bureau of Geology and Mineral Technology Open-File Report 81-8.

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^oC. 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.