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GEOTHERMAL PRODUCTION AND UTILIZATION
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NON-ELECTRIC UTILIZATION OF GEOTHERMAL ENERGY IN THE SAN LUIS VALLEY, COLORADO

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MASTER

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ABSTRACT

The objectives of this project are to develop an initial quantification of the magnitude of low-temperature geothermal resources in the San Luis Valley area of south-central Colorado, and to analyze the engineering and economic factors pertinent to the non-electric utilization of these resources. The industrial applications being evaluated are the supply of heat and process water from the geothermal source for the malting of barley for beer production, and for the refining of sugar from beets. Also under consideration is the augmentation of municipal water supplies in some cities in the southern region of Colorado, with the possibility that some space heating may be accomplished before consumption of the water, itself.

A review of the potential size of the resource in the San Luis Valley has been completed and is included in this report. Several process flow options for using low-temperature brine to supply heat to a beet sugar refinery are being studied. One option is presented here in detail, and calculations for more efficient processes are underway.

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I. Project Review--Status and Summary

The geological and hydrological review of the San Luis Valley has been essentially completed, and a preliminary assessment of the geothermal resources in the San Luis Valley has been made. It is estimated that large reserves of good quality water exist in the project area, with temperatures estimated at 250°F at a depth of 8,000 feet. Extrapolations indicate that the 300°F level can be reached between 9,000 and 10,000 feet. Total reserves are estimated at 30 million acre-feet of brine with a salinity of less than 5,000 ppm of total dissolved salts. A detailed report on the basin characteristics is included as Appendix A, and Chapter II provides a summary of those factors most pertinent to industrial use of low-temperature waters.

The energy consumption patterns of a beet sugar refinery have been studied in great depth, to provide a basis for the effective utilization of geothermal heat to replace fossil fuel. Our analysis has emphasized the relationships among quantity of energy utilized, temperature of utilization, equipment design, process factors, and physical properties of the sugar solutions. The methodology used for this analysis was to make a preliminary but complete design of a non-optimized refinery consuming geothermal heat. The material and energy balances associated with this preliminary design are included in Chapter III.

On the basis of this first design, we have identified the critical factors governing energy conservation in a sugar factory using a low-temperature heat source. Accordingly, we have been led to the investi-

gation of two other process systems that will tend to optimize energy consumption, and calculations for these two systems are underway. The first of the final designs will provide a four-effect evaporation system operating at lower temperatures than the two-effect system presented here, for which the energy consumption will be reduced by about one-third. The second of the final designs will provide for a vapor recompression cycle around the thin juice evaporators to further reduce the energy consumption, but the capital cost will be increased because of the turbine-compressor set. All of these design cases are based on operating conditions within the range of normal refinery practice. On this point, we have been assisted by the engineering staff of a local major producer.

A major fraction of the heat load in a sugar beet refinery is consumed in the pulp dryers. The pulp slurry entering the dryer contains about 20% solids. Over 90% of this water is removed in a rotary kiln where the heat supply is normally provided by combustion gases from a fossil-fuel fired burner. This is an extreme service for low-temperature geothermal brines and has not yet been studied as part of this project. With this exception, the process designs under development are completely independent of fossil fuels.

II. Hydrology of the San Luis Valley, Colorado

Various studies have been made of the ground water systems in the San Luis Valley. These include the drilling of an exploratory geothermal well near Alamosa to a 9,500-foot depth. Data from this well and from numerous oil wells, as well as data from geophysical studies have been analyzed and are summarized here. The text of the full hydrological report, which was prepared by consultant Dr. Richard Davis, is included as Appendix A.

The data have been interpreted to indicate the existence of a major aquifer in the northern and eastern portion of the Valley. This is shown as the cross-hatched area in Figure 1, which approximately underlies the Sand Dunes National Park. The aquifer changes considerably in physical characteristics with depth. The most promising zone begins at a depth of 8,600 feet and extends to at least 9,500 feet. This information was acquired from logs of well #1-32, Mapco-State, located near the eastern periphery of the Valley and slightly north of Alamosa (see Figure 1).

In this depth zone the porosity is about 25%. Bouguer gravity data yielded an estimated 225 square-mile surface area for the aquifer. On these bases, it is calculated that the aquifer contains 30 million acre-feet of water.

Extrapolation of geothermal gradient data from other sources indicate a temperature of at least 250°F at about the 8,000-foot depth. This is supported by the logs and drill stem test of the Mapco well and is also within the range of the numerous geochemical temperature estimates that have been made. The permeability in this zone appears to be high enough to enable production and reinjection rates exceeding

FIGURE 1
GEOTHERMAL STUDY
San Luis Valley, Colorado
BOUGUER GRAVITY MAP
(GACA AND KARIG, 1965)

by
Richard W. Davis
Consulting Hydrogeologist
July, 1977

0 5 Miles 0 5 10 Kilometers

LEGEND

GRAVITY CONTOURS,
5 MILLIGAL INTERVAL

ANOMALIES
(-) NEGATIVE (+) POSITIVE

POTENTIAL
GEOTHERMAL
RESOURCE

500 gallons per minute (250,000 lb. per hour). Potentiometric data further indicate the total dissolved solids content is about 2,000 parts per million. This salinity value suggests that substantial circulation of the contained water prevents chemical degradation by dissolution of minerals, and it also supports the conclusion of porosity and permeability values for the aquifer. The available data points to the area just discussed as the most attractive for further exploration and possible development. The same area also contains shallower zones of less favorable, water-bearing strata having lower temperatures, higher salinities, and lower permeabilities. On the other hand, the overall body of data points to another aquifer in the extreme northern portion of the Valley with temperatures near 220°F. This aquifer lies at depths between 5,000 and 10,000 feet, and contains 2 million acre-feet of water. It is noted in the hydrological analyses in the Appendix that the northern aquifer could be a part of the much larger aquifer that underlies the Sand Dunes to the southeast.

This data definitely reflects a high probability of attaining feasible production rates of moderate temperature geothermal brines from the San Luis Valley. The only potentially major economic problem associated with exploitation of this resource is related to the rather great depths involved, of up to 8,000 or 9,000 feet. With respect to this point, however, it is to be remembered that the temperature logs that were run were made shortly after drilling was completed, and it is possible that full equilibrium was not attained. Thus, higher temperatures at shallow depths may yet be found.

III. Beet Sugar Processing

A. The Basic Sugar Factory-Process Design

Viewed in its totality, the production of sugar from beets is quite straightforward. The description of this section generally follows the block diagram of Figure 2, which indicates the processing steps and the points of energy consumption. The process can also be followed on the schematic flow diagram of Figure 3; although Figure 3 is developed for a geothermally heated system, the flow and processing steps are the same as for a conventional plant.

Sugar beets are cleaned and sliced, and then steeped in warm, low-salinity water in the diffuser battery. The sugar passes through the beet cell walls by osmosis into the water. Other compounds also enter the water by osmosis, and sugar and impurities also empty directly into the water from cells that have been broken or crushed during handling and slicing.

Two product streams leave the diffuser. The insoluble sugar beet pulp is washed and squeezed and then dried in a fossil-fuel fired kiln. This dryer consumes a significant fraction of the energy needs of the sugar refinery. The second stream leaving the diffuser is the raw juice, a dilute and impure sugar solution that is to be purified. Its concentration is in the range of 10 to 14 Brix (that is, 10 to 14% solids by weight), of which about 90% is sucrose. The raw juice passes through various purification stages. The water is then evaporated and sugar is crystallized. Some of the organic and inorganic impurities in the raw juice cannot be easily removed; they remain with the last quantities of sucrose leaving the sugar crystallizers to form the molasses byproduct.

BEET SUGAR PROCESS - MATERIALS , ENERGY FLOW DIAGRAM

FIGURE 2

Despite this overall simplicity, many aspects of sugar production remain an art, and much of the chemistry related to side reactions and impurity removal is still not completely understood. The quality of beets can change significantly from year to year and from one location to another. In addition, fairly rapid degradation occurs as the beets and various sugar solutions are stored and handled. These factors require that the sugar process be carefully monitored and adjusted by specialists who are often guided by their empirical learnings. Another aspect significant to our study is that a typical evaporating unit does not exist. Many old factories with low pressure and inefficient evaporating systems are still in service. Thus, it is not easy to develop a model plant that can be compared with a geothermally heated refinery.

Nevertheless, the basic evaporation principles in all sugar refineries are similar and are described below. This description follows a modern refinery with a high heat efficiency. It is expected that a geothermal heat source would be used simply to replace steam in the evaporating and crystallizing sections of the plant. The various purification operations would not be changed in temperature levels, processing equipment or heat loads. Accordingly, they will not be discussed further, but they are shown on the flow sheets because they are an essential part of the cascading heat transfer system. On the other hand, the relative sizes and operating levels of the various evaporators must be changed, as discussed in the next sections, so as to accommodate the low-temperature geothermal heat source.

After purification, the thin juice is at about the same concentration as the raw juice. It is preheated and enters a multiple effect evaporator. Modern evaporators will have five effects, with evaporation occurring at about 276°F in effect one and about 146°F in effect five. The product is thick juice at a concentration of about 65 Brix. Thus, at this point about 93% of the water has been evaporated.

The thick juice is stored and sent to a battery of white pans. Several white pan evaporators operate in parallel, each on a batch basis, and dump their charge to a mixing tank when a concentration of about 93 Brix is reached. About 6% of the initial water charge, or about 85% of the water in the thick juice, is removed in the white pans. However, the total heat load on the white pans is somewhat larger than is implied by these factors because of recycle streams of wash water.

The white pans carry the sugar solution into the supersaturated zone, and crystallization is initiated by seeding. Continued crystal growth is carefully controlled in the mixer where temperature, residence time and agitation levels are adjusted to provide a uniform distribution of crystal sizes. The slurry leaves the mixer and is centrifuged. These crystals are dried and are the pure sugar product.

The liquid overflow from the white pan centrifuge is sent first to the high raw pan and, from there, to the low raw pan. In each instance, the feed to the pans is diluted by either thin or thick juice. The same series of operations as those that take place in the white pan system (evaporation to super saturation levels, seeding, crystal growth, and centrifugation) is repeated in each of the raw pan systems. The evaporation load, and thus the energy consumption, in the raw pans is relatively small. The sugar crystals formed in these

units are of lower purity than the white pan crystals because of the higher impurity level in the solutions fed to the raw pans. Therefore, the crystals are melted and recirculated to the white pan for recrystallization.

The liquid leaving the high raw pan centrifuge provides the feed for the low raw pan. The solids in the liquid leaving the low raw pan centrifuge may have a purity as low as 70% sucrose. This solution is the source of molasses, where most of the remaining sucrose is recovered in a lower purity state.

B. Energy Consuming Patterns in a Sugar Refinery

As has been indicated above, the three main consumers of energy in a sugar refinery are the beet pulp dryer, the multiple effect evaporators within which thin juice is concentrated to thick juice, and the white pan in which the sugar solution is saturated and crystallization begins. The pulp dryers have not yet been considered in detail as a consumer of geothermal heat because of the high temperatures normally involved, but this operation will be looked at more closely to determine if a means may be found to substitute geothermal heat for fossil fuel. The multiple effect unit evaporates about 93% of the water in the thin juice while the white pan evaporates about 6%. However, the energy consumption within the multiple effect is only about twice as great as that consumed within the white pan. This is because the steam vapor produced in one effect condenses in the steam chest of the next effect, and thereby evaporates additional water from the sugar solution. Thus, each pound of prime steam from the boiler results in the evaporation of 4 to 5 pounds of water in the multiple effect system. The white pan, on the other hand, is a single effect

system wherein each pound of prime steam evaporates only one pound of water.

This description is simplified in that the multiple effect system is not a true five-effect evaporator. Only part of the vapor from an effect is sent to the next effect, while the remaining vapor is used to provide heat to other unit operations within the refinery. This approach is taken because of the very specialized requirements for heat at specific temperature levels because of such factors as boiling point elevation of the sugar solutions, equipment size considerations, and heats of reaction and change of state. Complexities also enter into the white pan design in that recycled water increases its heat duty, and in that it is actually, to a certain degree, part of a two-effect evaporator unit. This latter condition results because of the fact that first vapor (that is, vapor leaving the first effect) is used to drive the white pans.

These factors complicate the adaptability of low-temperature geothermal heat to a sugar refinery in two ways. First, great care must be taken while modifying the evaporator units so as to be certain that the essential principals of plant operation, many of them developed empirically over many years, are not violated. Secondly, once the geothermal design is developed, the analysis required to determine exactly where and how much fossil fuel has been saved is still quite complex.

As the sugar refining process has been modernized over many years, one of the primary motivating forces has been to reduce the energy consumption. This is accomplished by going to a large number of effects in the evaporator unit. As the number of effects increases, the temperature range from the first effect to the last effect

increases, so that the temperature of prime steam from the boiler must be increased. In principal, the number of effects could be greatly increased so as to further reduce the energy consumption. In practice, several factors limit the maximum temperature allowed and the number of effects of evaporation that can be used. As the temperature increases, sugar degradation rates increase as well. At a given temperature, the rate of degradation increases as the sugar concentration increases. This limits the first effect to a maximum temperature of about 176°F, and requires that higher concentration solutions be attained at lower and lower temperatures. The minimum allowable temperature is that of the available cooling water which condenses vapor leaving the last effect; in practice, the last effect is considerably warmer than this temperature level since solution viscosity increases rapidly, and heat transfer coefficients decrease rapidly as the temperature drops. Thus, the last effect is usually at a temperature of about 146°F.

Given a maximum temperature range of about 130°F (276°F minus 146°F), the number of effects that can be used is dictated by an optimized economic balance where energy costs are balanced against equipment costs. More effects complicate the system and introduce more pieces of equipment, and thus tend to increase the overall cost of the evaporator system per square foot of heat transfer surface. Also, increasing the number of effects decreases the temperature driving force for evaporation available to each effect, thus increasing the total required surface area. In making the above economic balance, other factors are involved as well: the heat transfer coefficients decrease as

temperatures decrease and as solution concentration increases; and boiling-point elevations increase dramatically as the concentration and the temperature increase. These factors generally lead to a five-effect evaporator in modern plants.

Since evaporation is achieved more economically in terms of energy in the multiple effect unit than in the white pan, it is advantageous to increase the thick juice concentration as much as possible. Balancing this factor is the high boiling-point elevation and viscosity and low heat transfer coefficient as the concentration increases; this same change in the last two properties also occurs as the temperature decreases (the temperature being smallest in the last effect). A balance of these factors leads to a thick juice concentration of about 65 Brix.

The operating temperature of the white pans is also chosen as a compromise among several factors. Higher temperatures promote a lower viscosity and higher heat transfer coefficients. Opposing this are the higher solubility levels which increase concentrations, viscosities and boiling point elevations, as well as the increased product degradation rates at higher temperatures. The compromise reached for white-pan operation is a temperature of about 195°F and a solution concentration of about 93 Brix.

The source of steam to a modern refinery is a fossil-fuel fired boiler. Since steam generation costs in low pressure boilers are approximately independent of the pressure of generation over a broad range of pressures, the generation pressure is usually high enough for the steam to drive a turbine-generator set. Steam leaves the back-pressure turbine at a pressure level high enough to drive the

multiple-effect evaporator. Thus, sufficient electricity can be produced to meet plant needs at a relatively low-energy cost. A geothermal source that provided only process heat, and included no electricity-producing units, would thus be somewhat disadvantaged with respect to a modern fossil-fuel fired sugar refinery that produced its own electricity.

C. Geothermal Heat Applications--General Considerations

The present design is for a moderate temperature, liquid-dominated geothermal heat source, which has been defined as possessing a maximum temperature of 302°F (150°C). It can be readily seen that water at 300°F, with an enthalpy of about 270 Btu per pound, is a much poorer heat source than the normal steam feed to a sugar refinery which is at about the same temperature and has an enthalpy of about 1180 Btu per pound. The most effective way to use the geothermal brine from the wellhead is to flash it to a lower temperature, separate the vapor so formed from the unflashed brine, and then direct the vapor to the first effect evaporators. The geothermal vapor condenses in the evaporating steam chest, and provides higher heat transfer coefficients and a less aggressive chemical environment than if the geothermal brine itself were used directly in the evaporator shell.

The cost of a geothermal heat source is directly related to the number of production and reinjection wells that must be drilled; that is, the cost is almost a direct function of the quantity of geothermal brine required. This quantity of brine is approximately determined by the following equation:

$$B = S \frac{h_{BW} - h_{BF}}{h_{SF} - h_{BF}}$$

Where: B = required flow rate of wellhead brine, pounds per hour

S = required geothermal steam flow rate to the first effect, pounds per hour,

h = brine or steam enthalpy, Btu per pound

and subscripts refer to:

BW = wellhead brine

BF = brine leaving the flash vessel

SF = steam leaving the flash vessel.

The denominator in the above fraction is the latent heat of vaporization of water, which is approximately constant over the temperature range of interest. Thus, as shown by the equation, the brine flow rate is minimized as the steam flow rate (S) is reduced, or as the enthalpy difference term ($h_{BW} - h_{BF}$) is increased. Unfortunately, as shown below, these are contradictory requirements so that optimization of a geothermally heated sugar factory requires a compromise.

Since h_{BW} is fixed by conditions in the geothermal reservoir, the enthalpy difference term is maximized as h_{BF} decreases, which requires low temperatures in the flash tank and low temperatures of the prime steam that drives the first effect. As we have seen in the previous section, low prime steam temperatures either decrease the number of effects that can be used, or decreases the differential temperature for heat transfer in each effect. The first factor leads to an increased amount of steam needed, S, and an increased number of geothermal wells. The second factor leads to a greater surface area and increased capital costs in the evaporators. In general, a moderate temperature geothermal source will lead to a sugar process with fewer effects operating at lower temperatures. That is, old-fashioned technology will

tend to replace modern technology.

In arriving at an optimized plant, several other complicating factors must be considered. In particular, multiple stages of flash of the geothermal brine will be employed. It would probably be desirable as well to adapt modernized high performance heat exchanger equipment from other industrial applications to the sugar refinery, so as to mitigate the effects of the low-temperature heat source. These factors have not been considered for the simplified two-effect sugar refinery described in the next section for the reasons discussed there. They are being considered in the ongoing design studies of more efficient systems.

It should be pointed out that this problem of adaptability of a geothermal heat source to a sugar refinery is largely the result of the arbitrary definition of 150°C as the maximum geothermal brine temperature to be considered. If higher temperatures are encountered, the efficiency of the geothermal system increases very rapidly. Conversely, lower temperatures rapidly decrease the efficiency. On balance, basing initial studies on a 150°C (302°F) heat source appears to be a good choice. This follows from the fact that such sources are likely to be relatively abundant, and from the likelihood that if the process can be made feasible with this source, its potential application to various process industries is enhanced.

A final factor strongly affects the economic feasibility of geothermal heat for a sugar refinery. The number of operating days per year, or the length of the campaign, is usually as low as 120 days. In good weather locations such as southern California where the growing season is long, the campaign can be increased to 200 to 220 days per year.

Such rapid processing of beets once they are harvested is essential since degradation of the contained sugar proceeds rapidly while the beets are stored. Accordingly, a single-purpose geothermal plant providing only process heat to a sugar refinery would be idle from 1/3 to 2/3 of the year. The amortized cost of produced steam would thus be high by the same factor. Clearly, a multipurpose installation would reduce costs, even if the associated process were an electric power plant operating, to be sure, at a low efficiency because of the low-temperature heat source, but operating all year long.

D. Geothermally Fueled Sugar Refinery--Preliminary Design

The two-effect process shown on Figure 3 is a preliminary design for a geothermally fueled sugar refinery. Its efficiency is low, but it contains several simplified features. In particular, both effects operate above atmospheric pressure which simplifies the venting of inert gases, originally present in geothermal brine, from the steam chests. It also provides a relatively high temperature vapor leaving the last effect, that can be more easily used for preheating and for providing heat to the raw pan systems. The primary reason for developing this simplified process, however, is that it permits an easier evaluation of the many complicating factors that enter into a refinery design, and points clearly to those steps that must be taken to improve efficiency. Two improved designs are underway. The first is a four-effect system operating at lower temperatures; this system involves multiple flash stages for the geothermal brine and multiple vapor takeoffs from the evaporators, and may include a simplified preheat system. The second is centered upon a vapor-recompression evaporator system in which prime steam from the geothermal flash vessel drives

FIGURE 3

a vapor compressor. Thus, mechanical work is used to increase the efficiency of energy utilization for evaporation. These improved processes will be included in the final project report.

The process presented in Figure 3 should be self-explanatory based on the previous discussions. The key to the various notations shown on the flow streams is shown below.

Symbol	Meaning	Units
W	Flow rate	1000 pounds per hour
T	Temperature	Degress F
P	Pressure	Psi
Brix	Concentration	Percent weight solids

IV. The Barley Malting Process

About 250 million pounds of barley are produced each year in the San Luis Valley. The grain is partially dried as soon as practical after harvesting, and is stored in a relatively dry state so as to prevent germination before being sent to the malting process. Malting consists of steeping the barley in water at various temperatures for several days, and then drying the germinated product. The resultant malt is used for either beer production or for animal feed. The malting system is not so closely tied to seasonal factors and the malt plant can be operated essentially all year.

It is estimated that the San Luis Valley barley crop requires a total of about 200,000 million Btu per year for the combined drying and malting operations, with each step consuming about half of the total heat load. Thus, energy consumption will peak during the harvest season when both drying and malting take place. The barley processing and sugar refining systems appear to be supplementary users of geothermal heat rather than complementary users.

The campaign for barley drying occurs at about the same time during the year as the sugar campaign and they both require heat in the same general temperature range. However, it may be feasible in an optimized study to use waste heat from the sugar factory to at least partially fuel the barley dryers. In this preliminary review it is assumed that the two plants are operated on completely independent energy-feed streams.

A preliminary schematic diagram of the grain-drying process is presented in Figure 4. Geothermal brine at 300°F is flashed in a multi-stage system to provide vapor at continually decreasing temperatures. Recycled air passes counter-currently through the heat exchangers in which steam condenses, until the air finally exits at a temperature of

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FIGURE 4.1: BARLEY DRYING SCHEMATIC FLOW DIAGRAM

about 250°F. The brine and condensate leaving the last flash stage pass through a direct contact heater where recycle air from the dryers plus makeup air are preheated. The hot air leaving the steam heaters passes through two consecutive barley dryers, where it is cooled, successively, to 235°F and 130°F. Part of the cooled air is vented to discharge the water vapor collected, and the rest is recycled to the direct contact heater.

Barley containing about 45% moisture by weight is dried to a moisture content of 12% before being stored for malting. Thus, about 83% of the initial water content is removed in a two-step operation. About 77% of the initial moisture is removed in the first-stage dryer at a maximum temperature of about 122°F, to discharge a product containing about 16% moisture. In the second stage of drying, another 6% of initial moisture is removed at a maximum temperature of 194°F.

The basis for the heat loads and flow rates of Figure 4 is the entire annual barley production in the San Luis Valley. It is assumed that the entire crop is dried during a 120-day campaign in a continuously operated plant. As has been stated, Figure 4 presents preliminary concepts only, and provides an impression of the magnitude of the important flow rates and heat loads. Preliminary analyses indicate that a single geothermal well could supply the energy needed for grain drying during the fall campaign, as well as the reduced rate of energy required for malting during the rest of the year.

The malting process consists of steeping the barley in cold water. This is followed by several days of germination, during which the barley is periodically exposed to a low-temperature air stream saturated with water vapor. When the proper state of germination is achieved, the barley

is kilned for moisture removal. Kilning starts at a temperature of about 130°F, during which step the malt is dried to a moisture content of about 25% by weight. This is followed by a final drying step at higher temperatures to a final moisture content of about 4%.

This final drying step is itself broken down into two stages. Moisture content is reduced to roughly 10% by weight at 150°F, then to below 5% at a temperature that ranges from 175°F to 220°F. The exact final temperature that is used to dry the malt depends on the type of beer that is to be made and on the brewer. This information is considered to be highly proprietary and is not released. In general, however, temperatures at the low end of the above range are used for pale malts, while temperatures in the range of 205°F to 220°F are used to produce a dark malt.

More detailed analyses of the barley processes are under development. They will be presented with the final project report.

APPENDIX A

A Preliminary Evaluation of Geothermal Prospects in
San Luis Valley, Colorado

Prepared for Coury and Associates, Inc.

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APPENDIX A

INTRODUCTION

General

This report discusses the geothermal potential of the San Luis Valley, located in south-central Colorado. The valley is in the counties of Saguache, Rio Grande, Alamosa, and Conejos. Figure A1 shows the topographic features of the area.

This report is based upon a study of data either published or extracted from the files of various public agencies. The primary objective has been to synthesize existing geological and geophysical information on the study area and to evaluate the prospective geothermal resources.

Summary and Conclusions

Present information on geothermal resources of the San Luis Valley indicate the most promising target is a reservoir underlying the cross hatched area of Figure A2. It is estimated that in a zone between approximate depths of 8,600 and 9,500 feet there is about 1.3×10^{12} cubic feet of water at a minimum temperature of 121°C. The water is estimated to contain about 2,000 mg/l dissolved material. Permeabilities in the zone are probably high and capable of supporting high levels of production and reinjection through well systems.

There is no direct information on deeper strata. Geophysical data suggest that the igneous basement floor is at a depth of 30,000 feet. This estimate is probably somewhat too great. In any event, the potential for finding reservoir temperatures in excess of 121°C at depths below 9,500 feet exists.

The aquifer system which includes the primary reservoir resource probably outcrops and is recharged in the San Juan Mountains. In the central San Luis Valley the reservoir is tightly contained under several thousand feet of shale and clay. Some minor upward discharge occurs, probably along fault zones.

GEOLOGIC SETTING

General

The San Luis Valley is in the northern part of a geologic feature called the Rio Grande Rift (Chapin, 1971). In simple terms, the rift is a north-south zone along which the earth's crust has been downdropped relative to the crustal material east and west of the zone. It is postulated as a tensional feature bounded by normal faults along the valley walls. The east wall of the valley is formed by the granitic and metamorphic rock mass of the Sangre de Cristo Mountains (Figure A1). The west wall of the valley consists of the volcanic terrain of the San Juan Mountains. This somewhat simplistic pattern is complicated by a plethora of secondary and tertiary faults, folds, and volcanic features which are not yet entirely deciphered.

According to Chapin (1971), rifting along the Rio Grande Valley began at least 18 million years ago during the Miocene epoch. Prior to that time, a series of sedimentary Paleozoic rocks had been deposited unconformably over a Precambrian crystalline complex of igneous and metamorphic rocks. Beginning in the Oligocene, just prior to the development of the rift, volcanic eruptions spread lava and ash across the valley. The eruptions continued during the development of the rift, ending during the late Miocene.

As the rift valley developed, sediments began to be eroded from the bounding higher, mountainous areas. These sediments were spread across the valley floor as coalescing alluvial fans interbedded with Miocene age lava flows. Deposition of the sediments, called the Santa Fe formation (Powell, 1958), continued into the Pliocene epoch. The sedimentary portion

FIGURE A1
GEOTHERMAL STUDY

San Luis Valley, Colorado

LOCATIONS OF WELLS
AND CROSS SECTIONS

by
Richard W. Davis
Consulting Hydrogeologist
July, 1977

0 5 Miles 0 5 10 Kilometers

LEGEND

- A-A' CROSS SECTION
LOCATION
○ NONTHERMAL WELL
● THERMAL WELL
Q THERMAL SPRING

38°00'

37°00'

106°00'

of the Santa Fe formation consists of conglomerate, sand, gravel and clay, probably nearly all of fluvial origin. The volcanic material is most abundant in basal portions of the formations, becoming scarce or absent in higher strata. Maximum thickness of the Santa Fe formation in the San Luis Valley is thought by Powell (1958, p. 20) to be in excess of 5000 feet.

During the Pleistocene the Alamosa formation was deposited over the Santa Fe formation. The Alamosa ranges from zero to more than 2000 feet in thickness. It consists of alluvial fan sediments along the valley walls, grading into fine-grained playa deposits near valley center. It is thinnest and coarsest near the valley walls becoming finer grained and thickest near valley center.

A thin veneer of Recent sediments of variable thickness overlies the Alamosa formation.

Subsurface and Geophysical Investigations

Measurements of heat flow have been made in the San Luis Valley region and are discussed in Reiter, et. al. (1975). He points out that the highest heat flow values were measured along the west margin of the valley. The values there range up to about $2.5 \mu \text{ cal/cm}^2 \text{ sec}$ which is about 1.5 times the global average of $1.5 \mu \text{ cal/cm}^2 \text{ sec}$. Ostensibly, the area of high heat flow would seem to be the best prospect for exploration for geothermal resources. However, the paucity of data points measured by Reiter, et. al. may have caused them to overlook high geothermal gradients in the vicinity of a well, #1-32 Mapco-State (Figure A1) in the eastern portion of the valley near Alamosa, Colorado.

Barrett and Pearl (1976), have accumulated information on the

thermal springs and wells of the valley. The concentration of these features (Figure A1) in the central and eastern portions of the valley indicates that the best geothermal prospects are in that area. Using the geochemical methods described by Fournier, White, and Truesdell (1974) and by Fournier and Truesdell (1974), Pearl (personal communication, 1977) obtained the reservoir temperatures listed in Table A1. Depths of the reservoir was not specified. Renner, et. al. (1976, page 136) also used the geochemical data to calculate reservoir temperatures based on data from Mineral Hot Springs. They derived a reservoir temperature of 105° C. at 5000 feet depth. Estimated heat content of the reservoir was 0.12×10^{18} calories. Appendix AA contains the full report.

Table A1. Geothermal reservoir temperature derived by the Colorado Geological Survey using the geochemical methods described by Fournier, White, and Truesdell (1974) and by Fournier and Truesdell (1974). See Figure A1 for well and spring locations.

<u>Location</u>	<u>Temperature (°C) and Analytic Method</u>		
	<u>Na, K, Ca</u>	<u>Minimum</u>	<u>Maximum</u>
Shaws Warm Springs	100	120	197
Splashland Well	197	140	
Mineral Hot Springs	90	95	129
San Dunes Hot Springs	140	145	
Valley View Springs		Too Complex	

Keller (1974) described the results of surface geophysical studies of the northern portion of the San Luis Valley near Mineral Hot Springs (Figure A1). The method used was electrical resistivity. Since that time additional detailed studies have been conducted by Arestad (1977) and Stoughton (1977) using, respectively, resistivity and seismic prospecting methods. Results of this work have been largely confined to the extreme

northern end of the San Luis Valley near Mineral Hot Springs, Valley View Springs, and Fullinwider Springs. The geophysical studies were interpreted to indicate a downfaulted basin containing between 6,000 and 8,000 feet of sediments overlying crystalline basement material. Resistivities in the basal sediments are low, possibly indicating a liquid thermal resource. As will be discussed later, there appears to be a discrepancy between this interpretation and the gravity data.

Stoughton (1977) also made a cursory interpretation of seismic reflection profiles from traverse data supplied by Amoco Production Company. Two of the profiles include the sites of oil exploration wells Colorado State F-1 and #1-32 Mapco State (Figure A1). Stoughton's interpretations agree with the well log data from Colorado State F-1 but may not agree with the data from #1-32 Mapco State. Stoughton appears to show the depth to Precambrian basement in the latter well as much deeper than logged. This ambiguity will be discussed more later. Gaca and Karig (1976) conducted a gravity survey of the valley (Figure A2). They analyzed the data along a number of traverses and drew up profiles of the Precambrian rock surface underlying the volcanic and sedimentary sequence filling the valley (Figures A3 and A4). In general, the lower the Bouguer gravity values shown in Figure A2 the greater the depth to the Precambrian interface. The significance of the depth to the bedrock is that it represents the maximum depth to which reservoirs capable of yielding significant volumes of thermal fluid might be found. Since temperatures normally increase with depth, the areas of deeper Precambrian rock are presumed to be the best areas in which to prospect for geothermal resources. The gravity data, as interpreted by Gaca and Karig (Figures A3 and A4) indicate a deeper basin than Stoughton.

FIGURE A2

Bouguer Gravity Map

This is the same as Figure 1 of Chapter II of the main report.

Please refer to page 4.

Figure A3. Geologic cross-section along line A-A' (Figure A1) constructed using what is believed to be the most reliable data available.

Figure A4. Geologic cross section along line B-B' (Figure A1) constructed using what is believed to be the most reliable data available.

(1977) and Arestad (1977) predicted in the extreme northern end of the valley. Stoughton's interpretation of Amoco seismic data agrees with the gravity interpretation of Karig and Gaca.

A few deep wells have been drilled in the valley to develop water supplies or to explore for petroleum. A recently drilled well, #1-32 Mapco State (Figure A1) penetrated to 9500 feet through strata in what is probably the deepest portion of the San Luis Valley. Data collected during the drilling operations have revealed a great deal of useful information on the geology and geothermal potential.

Other oil and water exploration wells have been drilled in the valley. Most of the data from these are given in Powell (1958). Locations of the deeper wells (>500 feet) are shown on Figure A1). The numbered well locations are keyed to Powell (p. 238-280).

INTERPRETATION

Hydrogeology

Only the deeper thermal hydrogeologic systems are discussed here. These are the ones underlying Alamosa formation sediments at depths in excess of 2000 feet. Data from the Mapco State well indicate that the potential for highly permeable aquifers above a depth of 6400 feet is very poor and that prospects are best below 9000 feet. A drill stem test (DST #1 on Figure A5) was run in the shallower zone. A permeability of only 4 darcy feet (73 gpd/ft) was obtained.

Logs from the Mapco State well included drilling logs, sample descriptions, and electrical resistivity, spontaneous potential, bulk density, gamma, caliper, and temperature geophysical logs. The logs show that, except for the very shallow aquifers, shale is especially dominant down to 4000 feet. Below that depth coarser clastics and volcanic material become increasingly common with increasing depth. At a depth of 8,620 feet the sample logs indicate granodiorite was encountered. Granodiorite is a coarse grained, sialic rock close to granite in composition. Ordinarily its occurrence would be considered to mark the top of the basement sequence. However, the magnitude of the anomalous gravity deficiency (Figure A2) and the small breadth of the anomaly combined with the density differential of sediments and granodiorite indicate more sediments lie below the granodiorite (Figures A3 and A4). The geophysical logs also indicate high porosity material, probably either volcanic or sedimentary, lies below the granodiorite. The granodiorite may be a sill-like mass intruded into the deeper sedimentary/volcanic complex.

Figure A5. Graphs of temperature and density versus depth in the #1-32 Mapco State well. Data are from geophysical logs. Solid squares in the temperature graph are water temperatures from other deep wells in the San Luis Valley plotted versus total depth of well.

The sample logs indicate that vertical movement of fluids in the Mapco State well area is probably minimal. Constant temperature gradients from temperature logs confirm that above 9000 feet little vertical convective heat flow occurs.

The primary aquifers of interest to this study are located between depths of 8620 and 9460 feet in the Mapco State well. This zone appears to have a major disruptive effect upon the temperature profile (Figure A5). Bulk densities (Figure A5) indicate a porosity of about 25%. It is also the zone in which drilling logs note lost circulation problems. Further, the electrical resistivity and spontaneous potential logs indicate an aquifer of such high permeability that differences in density between drilling fluids and formation fluids may have caused the invading drilling fluid to flow along the top of the aquifer. Very high permeabilities are considered necessary to cause such a phenomenon. This latter conclusion requires that the formation water be highly saline and dense. Water quality data, discussed later, suggest that the formation water is only moderately more saline than the drilling fluid.

Patterns of circulation in deeper aquifers can only be speculated upon. Except for the Mapco State well there is little information on potentiometric heads. The data available from DST #1 (Figure A5) indicate pressures are less than hydrostatic at all depths below the aquifers in the upper 1000 feet of sediment. The seismic profiles presented in Stoughton (1977, Figures 23 to 27) suggest that aquifer systems may outcrop to the west and that recharge may begin over the San Juan Mountains west of the San Luis Valley. Some of the recharge circulates eastward through deeper aquifers to the Mapco State well. Discharge probably occurs only by slow

transfer upward, possibly along fault planes, into shallower aquifers. Gravity data indicate that the deeper aquifer systems are very restricted in area so that discharge southward toward New Mexico beneath the Rio Grande River is not possible.

Geothermal Data

Figure A5 shows the temperature profile from the Mapco State well. The data for the profile were taken from continuous temperature logs run at various times during drilling operations. Such logs are often run before drilling fluids in the well bore have had a chance to reach thermal equilibrium with formation fluids. In the case at hand, data in the form of drilling fluid temperatures taken at various times after circulation had ceased were available. These data from two different depths are plotted on Figure A6 and used to estimate equilibrium temperatures. Figure A6 indicates that water temperatures in the aquifer of interest are at least 121°C.

Water temperatures from various other wells in the San Luis Valley are also plotted on the Figure A5 temperature profile. The data came from Barrett and Pearl (1976) and Powell (1958, Table 7). The temperatures are plotted at the total depth of each well. If it is assumed that the water came from an aquifer near the total depth of the well and that it had not cooled significantly before reaching the surface, a second temperature profile is obtained. The profile parallels the one from the Mapco State well but is about 30°C cooler. Temperatures in the Mapco State well are apparently higher than those encountered to date in any other well in the San Luis Valley.

6

Figure A6. Change in temperature of drilling fluids versus time after circulation of the fluids ceased at 8012 and 5400 foot depths in the #1-32 Mapco State well.

Water Quality

Published data on quality of water from various thermal springs and wells are available in Barrett and Pearl (1976), Powell (1958, Table 7), and Renner, et. al. (1976, p. 136). Nomograms of some of this data are shown on Figures A7 and A8. Quality of this water, all from the low temperature sources, appears quite good.

Two types of information are available concerning quality of water in deeper, higher temperature zones penetrated by the Mapco State well. The first of these is from analysis of two water samples obtained during DST#1 in the zone between depths of 5304 and 5491 feet. Figure A9 is a nomogram showing the results of the two analyses. Copies of the original data on file with the Colorado Oil and Gas Commission are contained in Appendix AB. The two samples analyzed presumably came from the same test and were taken at the same time. The reason for the difference in dissolved material is not clear.

The second method of determining water quality is through analysis of the spontaneous potential logs. Using this method yields a formation water conductivity of about 6000 $\mu\text{mhos/cm}$ in the zone sampled by DST#1. This is very close to the value obtained by Yapuncich, Sanderson, and Brown Laboratories (Appendix AB). It indicates a total dissolved solids content of about 4,000 mg/l.

Analysis of the spontaneous potential log data in the aquifer at 8700 feet yields a conductivity of 3000 $\mu\text{mhos/cm}$, equivalent to a total dissolved solids content of about 2000 mg/l. The relatively good quality of this water suggests a rather efficient circulation system. In other words, the residence time of the water in the aquifer at a high temperature

Figure A7. Nomograms of water quality data from well and springs (Barrett and Pearl, 1976).

Figure A9. Nomograms of water analyses of samples obtained from DST#1, #1-32 Mapco State well. Solid line is analysis by Chemical and Geological Laboratories, Casper, Wyoming. Dashed line is analysis by Yapuncich, Sanderson, and Brown, Billings, Montana.

is too short for serious degradation of quality.

Aquifer Storage

The primary aquifer zone of interest appears to be about 840 feet thick. It might be thicker but drilling information is not available from deeper zones. Bulk densities yield a porosity of 25%. Using Bouguer gravity data to estimate the areal extent of the aquifer zone (Figure A2) yields a surface of 225 square miles. Total pore volume of the mass would be 1.3×10^{12} cubic feet. In other words, the aquifer zone is estimated to contain 1.3×10^{12} cubic feet of water.

Because present data indicate the northern portion of the San Luis Valley studied by Keller (1974), Stoughton (1977) and Arestad (1977) is a less valuable geothermal resource, little attention has been given to it in this report. Renner (1976, p. 136) estimates this part of the valley contains 8×10^{10} cubic feet of water at an average temperature of 105° C. This estimate assumes an aquifer thickness of 5000 feet at depths between 5000 and 10,000 feet. Total thickness of the potentially aquiferous sediments above the basement complex according to Stoughton (1977) and Arestad (1977) is approximately 6000 to 8000 feet. As noted earlier, Stoughton and Arestad's interpretations are hard to reconcile with data from gravity surveys. It seems likely that the reservoir in the northern areas may be the same unit as that penetrated in the Mapco State well. If so, the cross hatched area in Figure A2 could be extended northward some distance.

Production Potential

There is insufficient data available to estimate with any precision the productive capabilities of the deep geothermal aquifer in Mapco State. It seems safe to speculate that production rates in excess of 500 gallons per minute could easily be attained. ReInjection rates in the same range are also probably possible. Any system of withdrawal and reInjection wells would have to be located within the -270 mgal contour interval on Figure A2.

LAND AND MINERAL OWNERSHIP

Published maps (BLM 1975, 1976a, 1976b, 1976c) showing land and mineral ownership are available for about 50% of the San Luis Valley. The maps cover the extreme southern portion of the valley and the area east of Range 10E. The Mapco State well was drilled on lands owned by the State of Colorado. The Luis Maria Baca No. 4 Spanish land grant overlies much of the best geothermal prospect (Figure A2). With some minor exceptions the state and federal governments control the rest in the central San Luis Valley.

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APPENDIX AA

GEOCHEMICAL ANALYSIS OF MINERAL HOT SPRINGS

(from Renner, et. al., 1976, p. 136)

INR RECORD # 107 MIRRORED ON 3/76
NAME: MINERAL (CHAMBERLAIN) HOT WELL, COLO RESOURCE CATEGORY: HOT WATER 90 TO 150 C
WARNING FIG: 2 NUMBER: 023 DATE: 04/75

LOCATION:

STATE: COLO COUNTY: SAGUACHE
LATITUDE: 38 10.10 TOWNSHIP: 45N
LONGITUDE: 105 55.00 RANGE: 10E
ELEV: 7747 SECTION: 7, NE1/4 1/4 B&M: NMPM
SURFACE MANIFESTATIONS: SINTER, TRAVERTINE, HOT SPRING(S),

EARBY

ROCK AND STRUCTURE TYPE: GRABEN, FAULTS ACTIVE MIOCENE TO PRESENT; VALLEY FILL; UPPER TERTIARY VOLCANICS N

SURFACE DISCHARGE TOTAL: 189.0 L/MIN ESTIMATED: X

CALCULATED TOTAL DISCHARGE: L/MIN OF DEEP WATER

TOTAL SURFACE HEAT FLOW: 0.00E+00 CAL/SEC

AREA OF SURFACE EX: 0.0 KM**2

APPROX. # OF HOT SPRINGS: 30

TEMPERATURE: RANGE OF SPRING TEMP. 46 C TO 63 C OR

MAX. WELL TEMP 60 C AT 354 M DEPTH

BOTTOM HOLE TEMP. C AT 354 M DEPTH

CHEMICAL DATA ANALYSIS DATE 09/74 SOURCE: WRD 1974 UNPUBLISHED (FLOWING WELL)

SPRING FLOW

TEMP	L/MIN	PH	SI02	NA	K	CA	SO4	CL	HC03
63	132.5	7.00	51.00	140.00	14.00	56.00	160.0	39.0	348

OTHER CHEMICAL DATA SEE MALLORY & BARNETT FOR MINOR ELEMENTS, 1973; GEORGE, 1920

SI02	SI02	SI02	NA_K_CA	OTHER
ADIABATIC	CONDUCTIVE	CHALCEDONY	1/3	4/3
103.3	103.3	71.2	168.2	91.3

RESERVOIR PROPERTIES

RANGE IN RES TEMP 70 C TO 170 C ASSUMED

BEST EST. AVER. TEMP 105.0

AREA 0.0 TO 0.0 KM**2; BEST ESTIMATE 1.5 KM**2

BASED ON

DEPTH TO TOP OF RES. 0.00 KM TO 0.00 KM; BEST ESTIMATE 1.50 KM.

DEPTH TO BOTTOM OF RES. 0.00 KM TO 3.00 KM; BEST ESTIMATE 3.00 KM.

THICKNESS 0.00 TO 0.00 KM; BEST ESTIMATE 1.50 KM.

VOLUME 0.00 TO 0.00 KM**3; BEST ESTIMATE 2.25 KM**3

HEAT CONTENT > 15 C 0.00 TO 0.00 E18 CAL; BEST ESTIMATE 0.12 E18 CAL

POROSITY TO BEST ESTIMATE

PERMEABILITY TO MDARCY;

AVERAGE WELL FLOW TO KG/HR; WELL DIAMETER CM

GEOPHYSICAL SURVEYS: GRAVITY, DC RESISTIVITY

DEVELOPMENTS: 1 WELL - IRRIG, SPA.

REFERENCES: LIPMAN, STEVEN, AND MEHNERT, 1970; JORDAN, 1974; KNEPPER, 1974; SIEBENTHAL, 1910; POWELL, 1958; GEORGE, 1920; MALLORY & BARNETT, 1973; GACA AND KARIG, 1965; KLEIN, 1971; SCOTT, 1970, WARING, 1965

TOPO MAPS: VILLA GROVE 1:24,000

SPRING IDENTIFIED: YES

COMMENTS:

JORDAN, COLO. SCH. MINES MS THESIS, 1974, HAS GEOPHYSICS FOR THE MINERAL HOT SPGS, VALLEY VIEW HOT SPGS AREA.

PREPARED BY: GALYARDT, RENNER

NAME: MINERAL (CHAMBERLAIN) HOT WELL, COLO

APPENDIX AB
CHEMICAL ANALYSES OF WATER FROM
#1-32 MAPCO STATE WELL
DST#1

P. O. Box 2794
Casper, Wyoming

SEP 20 1974

COLO. OIL & GAS COM. CO.

WATER ANALYSIS REPORT

OPERATOR Mapco, Inc. DATE July 18, 1974 LAB NO. 13169-3
WELL NO. 1-32 State LOCATION SE NW 32-40N-12E
FIELD Wildcat FORMATION _____
COUNTY Alamosa INTERVAL 5304-5491
STATE Colorado SAMPLE FROM DST No. 1 (MFE)

REMARKS & CONCLUSIONS: Mud, high water loss with quebracho colored filtrate.

Cations			Anions		
	mg/l	meq/l		mg/l	meq/l
Sodium	3614	157.21	Sulfate	1200	24.96
Potassium	23	0.59	Chloride	2800	78.96
Lithium	-	-	Carbonate	1068	35.56
Calcium	398	19.89	Bicarbonate	2330	38.21
Magnesium	0	-	Hydroxide	-	-
Iron	-	-	Hydrogen sulfide	-	-
Total Cations		219.29	Total Anions		177.69

Total dissolved solids, mg/l 10250
NaCl equivalent, mg/l 9367
Observed pH 9.9

Specific resistance @ 68°F.:
Observed 0.80 ohm-meters
Calculated 0.70 ohm-meters

WATER ANALYSIS PATTERN

Scale
Sample above described MEQ per Unit

(Na value in above graphs includes Na, K, and Li)

NOTE: Mg/l=Milligrams per liter Meq/l= Milligram equivalents per liter
Sodium chloride equivalent=by Dunlap & Hawthorne calculation from components

P. O. BOX 593
59103

BILLINGS, MONTANA

13 N. 32ND ST.

SEP 20 1974

WATER ANALYSIS REPORT

Lab. No. 11633

LO. OIL & GAS CONS. COMM.

Field Wildcat County Alamosa State Colorado
 Well No. 1-32 State Location 32-40N-10E
 Formation 5204-5401' Depths 5204-5401'
 Operator Manco, Inc. Date Sampled 7-12-74
 DST No. 1 Sample Bottom of Recovery Date Analyzed 7-12-74
 Other Data Fluid to Surface in 21 minutes, flowed for an additional 30
minutes. Open 60 minutes. Dark quebracho colored water.

Constituents	PPM	MEQ.	MEQ. %	Total Solids in Parts per Million
✓ Sodium	2133	92.79	44.81	By evaporation
✓ Calcium	198	9.88	4.76	After ignition
✓ Magnesium	11	0.90	0.43	Calculated
✓ Sulfate	564	11.73	5.66	pH <u>7.9</u>
✓ Chloride	3100	37.42	42.21	Specific Gravity @ 60°F <u>1.006</u>
✓ Carbonate	0	0.00	0.00	Resistivity @ 68°F
✓ Bicarbonate	270	4.42	2.13	ohms/ineter <u>1.12</u>

Chloride as NaCl 5112 PPM.Total Solids From Resistivity as NaCl 5319 PPM.

NOTE: Sodium and potassium reported as sodium. MEQ=milliequivalents per liter. PPM=parts per million (milligrams per liter). 1 PPM equivalent to 0.0001%.

WATER ANALYSIS PATTERN

Scale MEQ. Per Unit