Technological and Economic Assessment of Electric Power Generation from Geothermal Hot Water

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ABSTRACT

The U.S. is exploiting its geothermal resources by developing the technology to commercially extract energy from low- and intermediate-enthalpy subsurface waters and convert that energy to electric power and other useful end products. The construction of several 1- to 10-MWe geothermal power plants is planned to demonstrate the feasibility of generating electricity from such resources.

The geothermal engineer must evaluate various technical alternatives to design a geothermal energy utilization system that yields the lowest-cost power for any given set of circumstances. To facilitate this optimization process, a deterministic model for assessing the cost of power under various design alternatives has been developed. The model determines the exploration, construction, and operating costs necessary to continuously generate electricity from hot geothermal waters under the specified conditions.

With the use of this model, many cost analyses have been performed over a range of commonly occurring conditions. It has been found that electricity can be generated and profitably sold at 12 mill/kWh in geothermal areas where the temperature gradient is 5°F per 100 ft, a not too uncommon occurrence in certain regions of the U.S. Under this and other "typical" simulated conditions, the cost of power is proportional to the inverse of the permeability-thickness product of the geothermal reservoir. It was also observed that if an area could be found where the natural hydrostatic gradient was 0.1 psi/ft more than normal, then the cost of power could be reduced by as much as one-half. Further reductions are possible through optimum design of the power plant, production wells, drill holes, and the surface gathering system.

INTRODUCTION

Many unconventional energy resources, especially for use in power generation, are being considered to supplement the supply of our conventional resources. Among the many available choices such as geothermal, solar, tidal, and wind energy, technological prospects for geothermal energy appear most promising. This conclusion is partially justified by the fact that geothermal resources primarily in the form of steam are already being harnessed in a number of places. New sites with geothermal energy potential may be easily identified and evaluated since the exploration and production technology of geothermal energy evaluation resembles, in many ways, the practices in the petroleum industry.

Heretofore, development of geothermal resources has been restricted to areas having shallow, high-temperature, vapor-dominated reservoirs. Although these reservoirs are more desirable than are the deeper, lower-temperature, liquid-dominated systems, they are scarcer. Accordingly, the potential contribution of geothermal energy will be extremely limited if only vapor-dominated reservoirs are to be exploited. As an alternative, areas where crystalline rocks lie near the surface are numerous, but technology for exploiting them is still in its infancy.

On the other hand, if geothermal reservoirs filled with hot water are considered likely sources of energy, the potential of these resources appears nearly limitless (Sapre and Schoeppel, 1972, 1974). Such reservoirs can be identified easily as they exist in practically all geologic basins (Schoeppel and Gilarranz, 1966; Kehle, Schoeppel, and DeFord, 1970). Also, with present technology, these reservoirs are available for almost immediate exploitation. If this is the case, then the pertinent question to be resolved is not the availability of this resource, but the cost to extract and convert it into electricity using present technology.

When geothermal energy is utilized in power generation, the cost of power will depend upon the particular technology used in its production and conversion into electricity. The natural surrounding at the given location plays a dominant role in determining the cost of power so produced. Since many interactions can take place among the natural surroundings, technology, and cost, a "systems approach" is essential to properly assess all costs in producing geothermal power. The objectives of this paper are first to discuss some of the design criteria which should be addressed in assessing the cost of generating electric power from geothermal waters in such a system; and, second, to present the results obtained through applications of a techno-economic model of a geothermal power system developed to serve this purpose.

GEOTHERMAL POWER SYSTEM MODEL

The geothermal power system model was developed in several stages. First, the scope of the problem to be addressed in defining the total system was outlined. Based

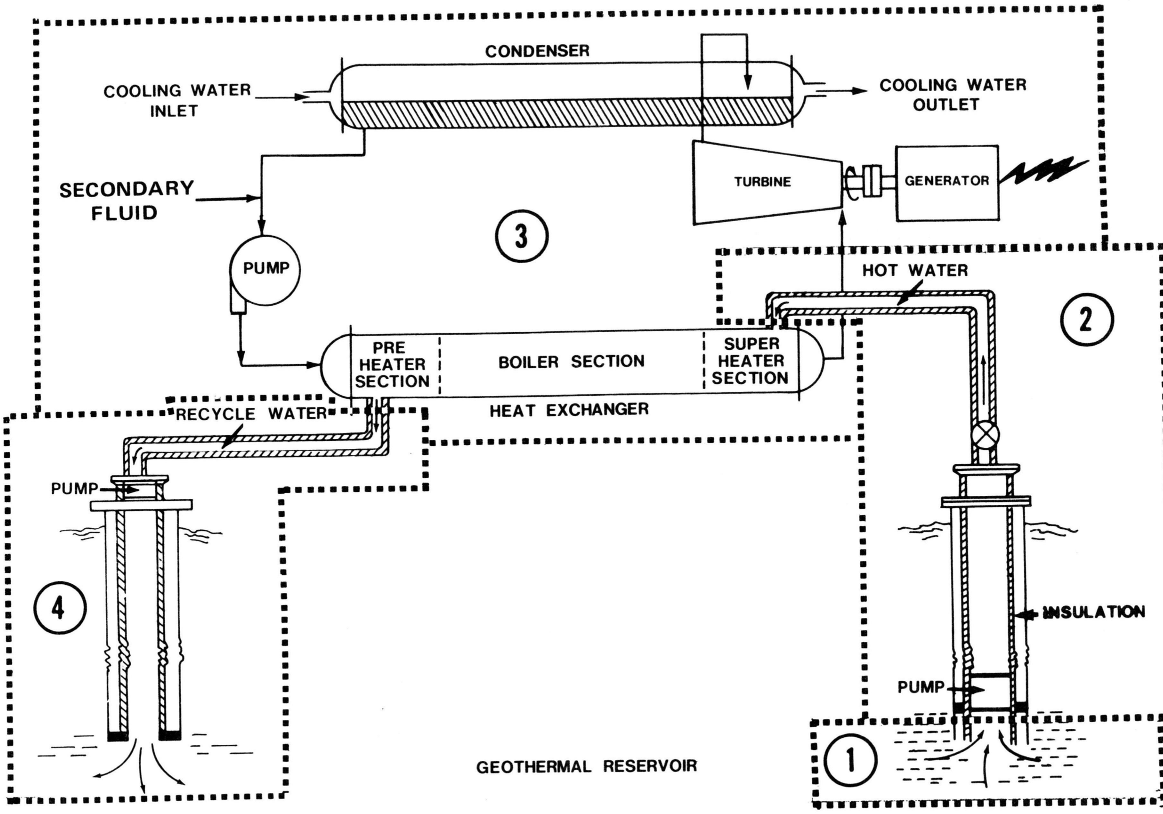

Figure 1. A schematic diagram of a geothermal power system.

on this scope, the elements and subcomponents of the system were then identified and defined mathematically and in terms of economics. A procedure was next developed to correlate the calculations and interrelate the essential data to compute the cost of generating power using geothermal waters as a source of energy.

SCOPE

In this study, areas considered as potential sources of geothermal energy for widespread utilization are mainly sedimentary basins where large quantities of water are contained in the pores of the rock. This water can be produced and transported to a power plant where the thermal energy in the water can be used to generate electricity. Waste water from the power plant can be disposed of in an environmentally acceptable manner and possibly in a way that would assure a continuous supply of water to geothermal reservoirs. Thus, the geothermal power system is basically comprised of the four elements shown in Figure 1: (1) geothermal reservoir, (2) hot water production and transportation means, (3) power plant, and (4) water disposal means.

DEFINITION

In defining the geothermal power system, first the physical characteristics of each of the four elements just described were identified, and then mathematical expressions interrelating them were developed.

The first element, a geothermal reservoir, is defined as a bed of hot porous rocks saturated with pressurized water at some equilibrium temperature. Such a reservoir may be characterized by its goethermal gradient, pressure gradient, and flow capacity.

The water production and transportation element is required to conduct the water from the geothermal reservoir to the power plant with a minimum loss of energy. This loss of energy, due to a reduction in either temperature and/or pressure, may be reduced through control of the design variables such as well-bore completing technique, submergible pump capacity, tubing and casing design, and type and thickness of the insulation. The loss is also influenced by the size and insulation thickness of the surface pipe used to convey the produced fluids from the wells to the power plant.

For the power generation element, a binary fluid system was chosen based on its technological merits as described by Anderson (1970, 1972). As will be shown below, this type of power plant is especially suited for extracting energy from fluids produced from low-temperature-gradient geothermal areas. A binary fluid power plant is characterized by the choice of the power fluid and by the flow rate of hot water needed to generate the required amount of power.

The waste-water injection system is an essential element to reduce thermal as well as air and water pollution. Also, it has the potential to extend the life of a geothermal reservoir. The waste-water disposal system may be characterized by the number and distribution of injection wells and their depth.

Mathematical expressions interrelating the characteristics of the various elements of the geothermal power system were developed by letting the power plant assume the central role. The size and type of power plant establishes the flow rate of hot water necessary to generate power at full capacity. The type of power plant is described by the secondary

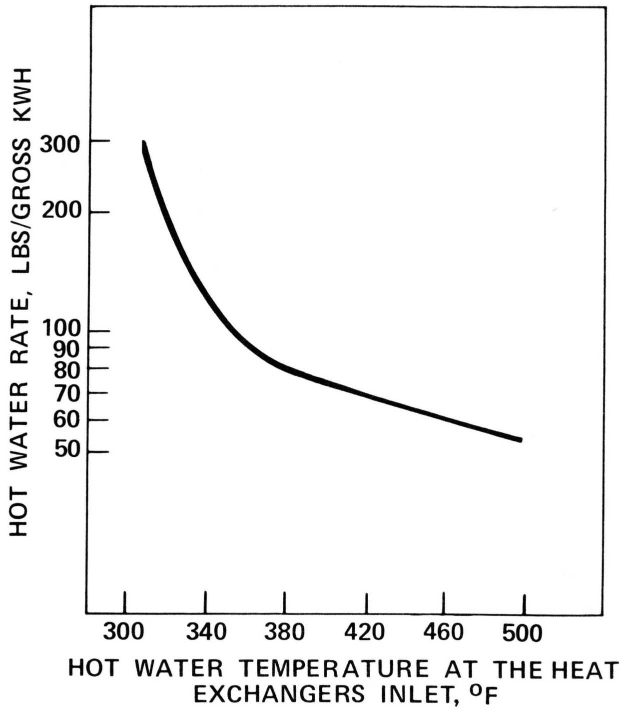

Figure 2. Water rate requirements for an isobutane power plant with a condensing temperature of 80°F (Anderson, 1972).

fluid. In this study, isobutane was chosen to be the secondary fluid because of its preferred physical and transport properties (Anderson, 1970, 1972; Kuwada, 1972).

The required flow rate of hot water for an isobutane plant is shown in Figure 2. The flow rate of water is a function of the plant inlet water temperature. The success of the geothermal power operation depends upon developing a hot water production and transportation system that satisfies the temperature and flow-rate requirements of the power plant.

When hot water is transported from the wellhead to the power plant, it loses some of its heat content to the surroundings. Thus, to maintain power output, the water temperature required at the wellhead must be higher than the temperature of the water at the power plant inlet. Likewise, the water flow rate and temperature requirements at the wellhead must be satisfied from the subsurface system. The subsurface system consists of a production well bore and the well-bore equipment as illustrated in Figure 3.

It is essential to meet water temperature requirements. It is equally important to keep the water in the liquid phase throughout the water production, energy conversion, and water injection stages. This is accomplished by maintaining the water above the saturation pressure. Required pump horsepower to meet these demands can be calculated by taking into account pressure losses in the various parts of the geothermal power system. The use of a submergible pump, however, also reduces the amount of power available for sale, since the pump itself consumes electricity. The electric power for sale is the gross amount of power generated at the plant minus the power used by any pumps and other internal utilities.

The geothermal system model described so far deals with the movement of water from the reservoir to the well bore and up to the power plant. Water coming out of the power plant is routed to the injection wells. The number and distribution of the injection wells will depend on local geological and hydrological conditions. In the waste-water disposal system, temperature and pressure maintenance is not critical.

ECONOMIC MODEL

Analysis up to this point identified the major characteristics of the geothermal power system. This design will meet the technological requirements. However, many such feasible designs are possible and the final selection of one design must be made. The design that yields the minimum cost of power for a given location is the most desirable one. Assessing the cost of geothermal power involves, first, allocation of costs to the equipment in the geothermal system and, second, application of a procedure to account for these and other costs of "doing business."

A set of data was developed for the cost allocation (Sapre, 1974). It represents the cost of equipment prevailing in the 1972–1973 period. In allocating costs, a basis for cost estimation must first be established. Furthermore, this basis must be compatible with the technological requirements of the system and with the procedure adopted for the cost assessment. The general scheme of developing a basis for cost data in this study is shown in Table 1. The major items of expenditure are broken down into the five categories necessary for the complete development of a geothermal power system. The data base, as it relates to the technological aspects of the system, is selected with consideration given to equipment availability and limiting operating conditions recommended. All equipment required can be produced with current technology. Costs of land and of exploration will depend on the location. For this study, they were estimated from geothermal and petroleum industry experiences.

The cost allocation gives data on expenditures associated

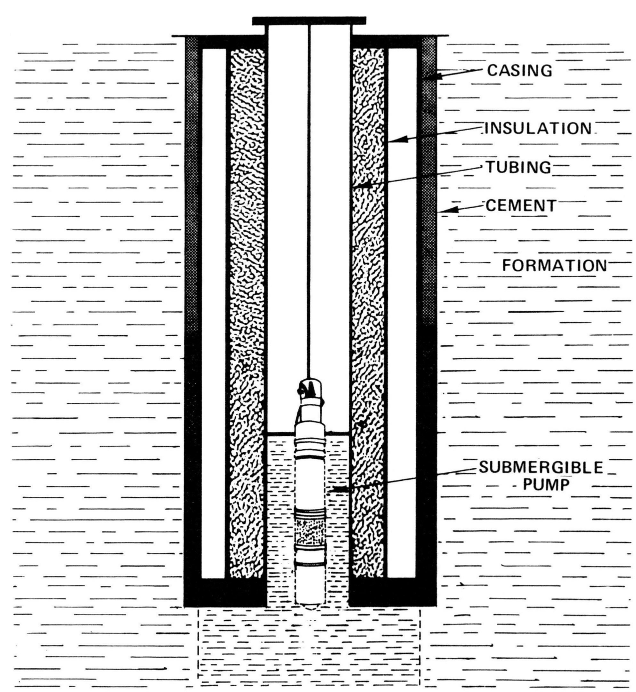

Figure 3. A schematic diagram of an annular well-bore completion with insulation.

Table 1. Basis for estimating cost of various items in a geothermal power project.

Category	Item of expenditure	Basis and units
Land	Lease bonus	Area leased ($/acre)
	Lease rental	Area leased ($/acre·yr)
	Lease royalty	Water produced ($/lb)
Exploration	"Capitalized" cost	Area explored ($/acre·yr)
	"Expensed" cost	Area explored ($/acre·yr)
Drilling and development	Intangible drilling	Drilling depth, hole diameter; $/ft for a given hole diameter
	Casing and tubing	Setting depth, diameter; $/ft for a given diameter
	Insulation (subsurface and surface)	Thickness, diameter and type; $/ft length for a given thickness and diameter
	Submergible pump	Horsepower ($/pump stand available)
	Wellhead equipment	$/well
	Surface pipeline	Length and diameter; $/ft for a given diameter
Power plant	Power plant installed	Size of the power plant; $/kW installed capacity
	Operations and maintenance	Power plant size and cost ($/kW)
Injection system	Surface pipeline, Intangible, Casing	Same as in drilling and development category

with geothermal resource development. A method for calculating the cost of power is still required.

Geothermal power development is a long-term commitment involving financial expenditures in the initial years of the project and continuous revenue generation after the power plant is operational. The time value of money is important. For a project of this nature, the discounted cash flow (DCF) method is particularly suitable for cost estimates. This method determines the rate of return on the equity portion of the investment. Conversely, it can also be used to calculate the "required" cost of power for the desired rate of return.

In geothermal resource development, the subsurface environment is important. It determines the availability of power at the bottom of the well bore. Also important are the variables associated with the design of the total system. These variables determine the net power available for sale at the power plant. Both types of variables, as shown in Figure 4, are factors in determining the cost of geothermal power.

Cost Analyses

The procedure used in assessing the cost of geothermal power is (1) to develop data related to the subsurface environment, (2) to choose a technically feasible design, (3) to allocate cost to each category of expenditure, and (4) to determine the cost of generating power, based on the DCF model for the surface environment and system design.

The cost analyses performed may be classified into three primary areas: (1) influence of the subsurface environment on the cost of geothermal power, (2) effect of system design on the cost of geothermal power, and (3) variation in cost of geothermal power due to change in economic criteria.

Influence of Subsurface Environment

Three subsurface characteristics unique to each geothermal reservoir containing hot water primarily influence the cost of geothermal power: (1) temperature gradient, (2) hydrostatic pressure gradient, and (3) reservoir rock properties related to water flow rates.

In evaluating the geothermal potential of any location, a primary concern has to be the prevailing geothermal gradient. Therefore, variation in cost due to change in temperature gradient has been studied in all cost analyses presented in this paper. Also, to fully exploit the geothermal energy potential, areas with relatively low temperature gradients must be evaluated. Accordingly, the results shown here cover the range of 2 to 5°F per 100 ft. However, the methodology and techniques used in this study are applicable to all areas where geothermal gradients are lower or higher.

The pressure gradient of an area is usually between 0.435 psi/ft, resulting from the hydrostatic head of fresh water,

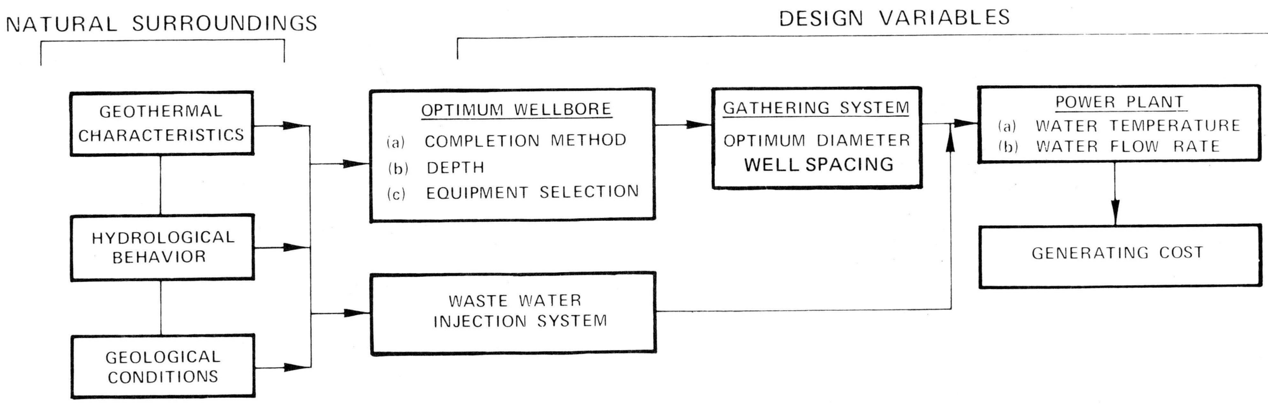

Figure 4. Natural conditions and design variables that affect the power generation cost.

and 0.5 psi/ft in the case of saline water. Assuming all other conditions are the same, an increase of the pressure gradient increases the bottom-hole flowing pressure; this reduces the amount of energy required to lift and transport water from the bottom of the well bore to the power plant. This reduction then causes a corresponding reduction in the submergible pump capacity and in its electricity consumption, and increases the amount of power available for sale from a given system. Therefore, higher pressure gradients will tend to reduce the unit cost of power by making more power available for sale. This benefit will not be indefinite because as the pressure gradient increases and reaches a point where water will lift itself, any additional increase in the pressure gradient will not reduce the cost of power.

The influence of change in the pressure gradient on the cost of geothermal power is shown in Figure 5. A substantial decrease in the cost occurs as the pressure gradient increases from 0.4 to 0.6 psi/ft. The cost of power reaches a minimum around 0.7 psi/ft and stays at that level even with the increased pressure gradient. The lowest cost of geothermal power, based on the data in Figure 5, appears to be 1.2¢ ($0.012) per kilowatt-hour for the temperature gradient of 5°F per 100 ft and the pressure gradient of 0.7 psi/ft or more. The highest cost, 4.0 ¢/kWh as it may be anticipated,

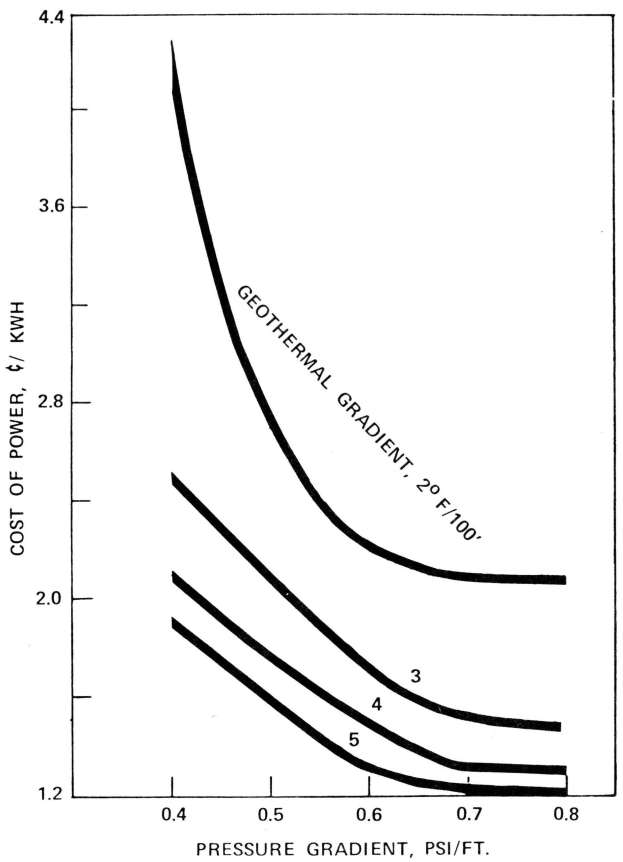

Figure 5. The effect of geothermal gradients (from 2 to 5°F per 100 ft) on the cost of power for various pressure gradients. The basis for evaluation is: a reservoir characteristic of 0.3 Darcy·ft; a pressure gradient of 0.5 psi/ft; a flow rate of 50 000 lb/hr per well; nonannular well-bore completion; 400°F water at plant inlet; 10% rate of return; 65% borrowed; 20-yr project life; straight-line depreciation; and a power plant cost of $230/kW.

is for the temperature gradient of 2°F per 100 ft and the pressure gradient of 0.43 psi/ft.

The effect of the pressure gradient on the cost is of particular significance since there are areas where the pressure gradients are greater than 0.5 psi/ft. As Figure 5 shows, in some cases the cost of power can be reduced to less than half, even if the pressure gradient exceeds normal by only 0.2 psi/ft. Thus, the relative advantage that can be gained in exploring geopressure zones for geothermal power generation is obvious.

Reservoir rock properties such as the formation permeability, its productive thickness, and the radius may be combined in one parameter, W, defined as

$$W = \frac{Kh}{\ln\left(\frac{r_e}{r_w}\right)} \qquad (1)$$

where K is the reservoir rock permeability in Darcy, h is the thickness of the productive formation in feet, r_e is the radius of the productive formation in feet, and r_w is the well bore radius in feet. The parameter W then controls the flow rate of water from a geothermal reservoir. Higher values of W mean less resistance to the flow of water and consequently greater flowing pressure. As mentioned before, greater flowing pressure at the bottom of the well bore is desirable since less electricity is consumed in pumping. Similar to the effect of the pressure gradients, beyond a certain value of W this advantage disappears, since the increase in the bottom-hole pressure beyond that point offers no additional benefit.

Results of a series of cost calculations made for various values of the reservoir rock characteristic W are shown in Figure 6. The range of W was varied from 0.3 to 0.9 Darcy·ft. The cost of power decreases rapidly between the value of 0.3 to approximately 0.7 Darcy·ft. Beyond the value of 0.7 Darcy·ft, however, the cost remains the same for all the values of W. This situation occurs for all the geothermal gradients, as shown in Figure 6. Unlike the effect of the pressure gradients, the effect of the reservoir flow characteristics is not nearly as dramatic, especially at lower temperature gradients. Also, the lowest cost reached in this case, about 1.30 ¢/kWh, is still higher than the lowest achieved in the case of pressure gradient increase. This occurs since even at $W = 0.7$ Darcy·ft some energy is expended to lift water from the bottom of the well bore to the power plant. The effect of the reservoir rock flow characteristic on the cost of power is significant, and the range of advantage that high permeability or "fractured" reservoirs offer could be a deciding factor in the geothermal power operation.

System Design

In addition to the subsurface environment, many design variables affect the cost of geothermal power. Of primary importance are two factors: (1) wellbore completion method, and (2) power plant design.

Two well-bore completion methods were considered. The annular well-bore completion method, with air-filled or insulated annulus, offers an advantage in that the temperature loss from water to the surroundings is less: hence, shallower well bores would seem satisfactory to meet the

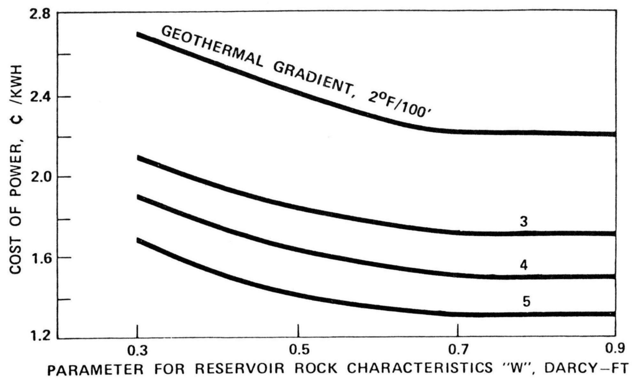

Figure 6. The effect of geothermal gradients on the cost of power for various reservoir rock characteristics (basis for evaluation same as Figure 5).

temperature requirements at the plant inlet. Thus, on one hand, the annular well bore completion tends to reduce the cost of power by reducing the drilling and equipment expenses, while on the other hand, it tends to add to the cost by requiring two well-bore strings, and tubing as well as casing.

In the case of nonannular well-bore completion, the advantage is that only one well-bore string is required; however, the savings are somewhat offset by the additional cost of deeper boreholes which are necessary to meet the same temperature requirements. The net effect of the advantages and the disadvantages will result in either a higher or lower cost of power for a particular well-bore completion method, and therefore it is of interest.

The results of the cost analyses are shown in Figure 7 which shows the effect of the borehole completion technique on the cost of power for various geothermal gradients. The cost varies from a minimum of 1.7 ¢/kWh to over 4 ¢/kWh. The minimum cost occurs for a nonannular well-bore completion when the temperature gradient is 5°F per 100 ft. The highest cost occurs in the case of air-filled annular completion for a geothermal gradient of 2°F per 100 ft. As it is shown in Figure 7, the cost of power is always lower for the nonannular well-bore completion. In this case, the range of cost is between 2.7 and 1.7 ¢/kWh. The highest cost occurs at the lowest temperature gradient while the lowest cost is attained at the highest temperature gradient.

It was mentioned earlier that in the case of nonannular completion, the temperature loss in the well-bore is greater, and hence deeper boreholes are required to satisfy the temperature demand at the plant inlet. Calculations from the mathematical model show that when the temperature gradient is 2°F per 100 ft, the temperature of hot water lowered approximately 92°F in the well-bore for nonannular completion as compared with only 19°F for annular completion with insulated annulus. Accordingly, the necessary well-bore depth varied from 21 150 ft in the former case to 17 466 ft in the latter case.

Not only the well-bore completion technique influences the cost of power, but also the design of the power plant. One of the most important variables in the plant design is the choice of temperature at the plant inlet.

From the point of view of conversion efficiency at the power plant, it is certainly desirable to have the highest possible temperature of water at the heat exchanger inlet to the power plant. From the point of view of the cost, higher conversion efficiency results in a smaller number of production wells and hence a smaller amount of associated expenditures. However, at the same time, the higher temperature is achieved by drilling deeper, and it results in more expensive boreholes. Deeper wells also need more power to lift water to the surface and thus tend to reduce the amount of power available for sale. The two latter situations would tend to increase the cost of power, and hence it is desirable to evaluate the net effect of these offsetting tendencies.

Four levels of temperatures at the plant inlet were selected to determine the cost of power for well-bores producing 50 000 lb/hr. The range of required water temperatures

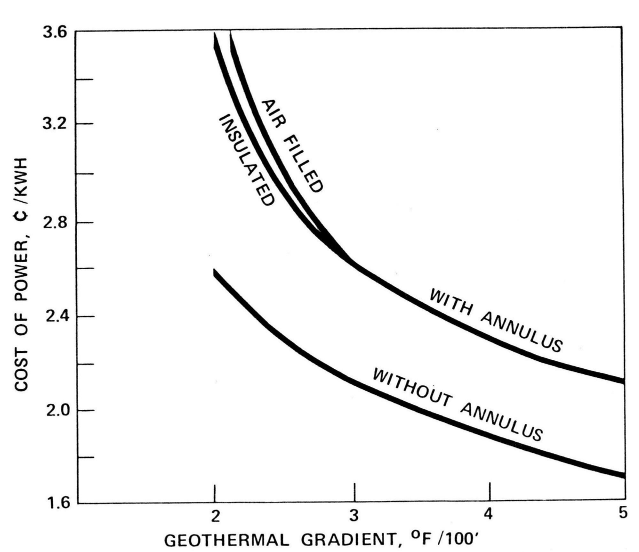

Figure 7. The effect of borehole completion technique on the cost of power for various geothermal gradients (basis for evaluation same as Figure 5).

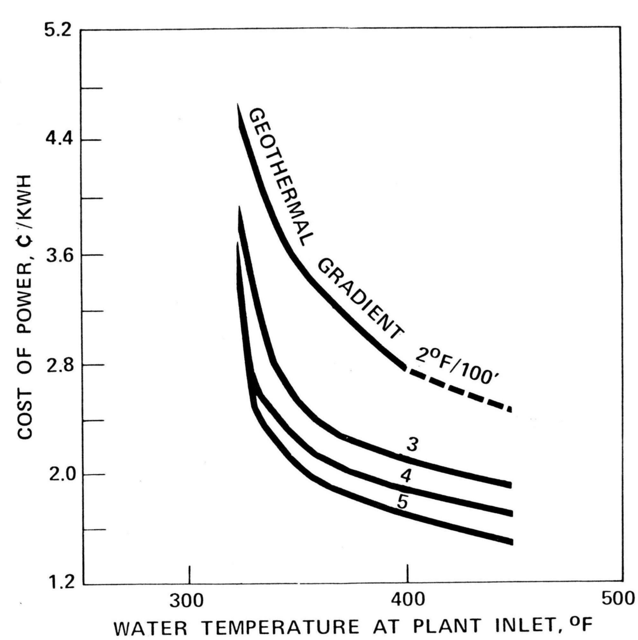

Figure 8. The effect of geothermal gradients on the cost of power for various power plant inlet water temperatures (basis for evaluation same as Figure 5).

at the plant inlet was varied from 325 to 450°F. Anytime the bottom-hole temperature exceeded 450°F, that particular situation was considered beyond the temperature limits of available equipment. The results of cost analyses are shown in Figure 8.

Initially as the temperature increases from 325°F to about 350°F, the cost of power decreases drastically. This sudden change is due to many reasons. First, as the temperature of water at the plant inlet increases, the flow rate required to produce the same amount of power decreases. As shown in Figure 2, for a particular plant design this decrease is very rapid until a temperature of around 360°F is reached. Beyond this temperature (the decrease is still logarithmic), the rate of decrease is much smaller and hence it does not affect the flow rate in the same proportion. Also, with reduced water flow rate requirements, the number of production and injection wells is reduced proportionately.

The rate of change of cost with water temperature at the plant inlet is extremely high around 325°F. If the temperature required at the power plant inlet is reduced to slightly less than 325°F for the chosen system, the cost of power increases exponentially. However, cost reduction beyond 350°F appears to be almost linear. It is estimated that temperatures greater than 450°F at the plant inlet will not be feasible due to thermal limits of the well-bore equipment.

Changes in Economic Criteria

Two types of cost analyses were made to indicate the range of variation in cost due to changes in the cost data and economic criteria. In all previous calculations, the cost of the power was assumed to be $230 per kilowatt installed. Though this was the best information available, it is likely that the cost could vary significantly, since as yet there is no plant in operation. In order to compensate for this possibility, the cost of power is evaluated for various unit costs of the power plant beginning with $180 to $310 per kilowatt installed.

Results of the cost analyses are shown in Figure 9. The cost of power varies linearly for all geothermal gradients. For each increment of $50/kWh in the cost of the power plant, there is a corresponding increase of 0.2 ¢/ kWh for

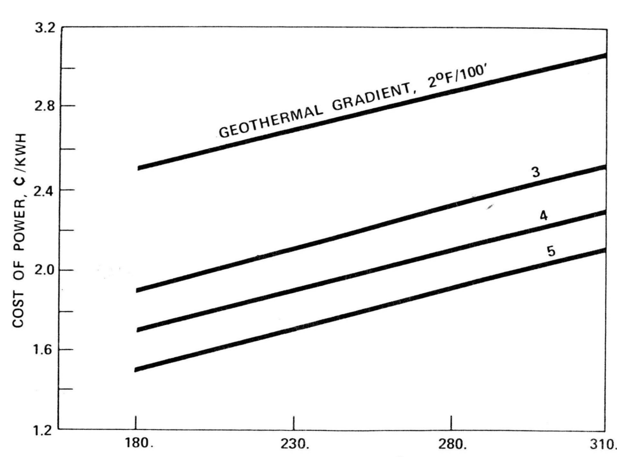

Figure 9. The effect of geothermal gradients on the cost of power for various power plant costs (basis for evaluation same as Figure 5).

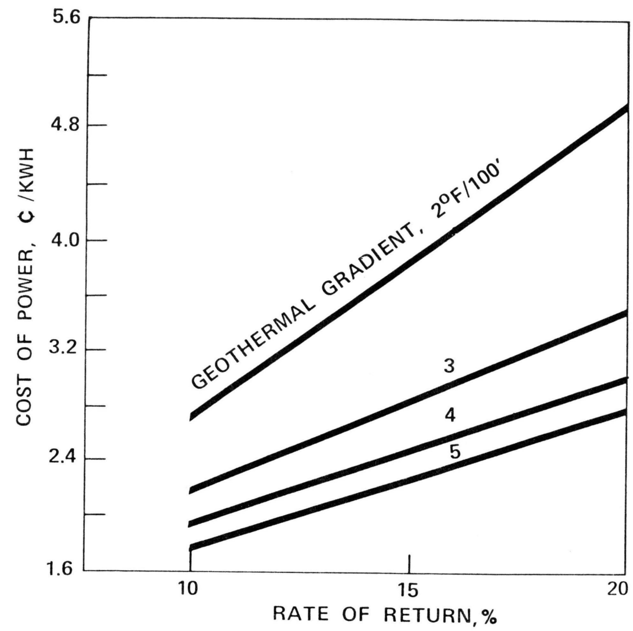

Figure 10. The effect of geothermal gradients on the cost of power for various required rates of return (basis for evaluation same as Figure 5).

the system chosen. These results, like all previous ones, were based on 10% DCF rate of return. If this criterion is changed, the cost of geothermal power would also change.

This effect was evaluated for various desired rates of return and the results are shown in Figure 10. The cost variation is also linear. For each 5% variation in the desired rate of return, the cost of power changes 1.2 ¢/kWh for a temperature gradient of 2°F per 100 ft. However, for the equivalent change, a change of only 0.6 ¢/kWh occurs for a temperature gradient of 5°F per 100 ft.

SUMMARY

It appears that the availability of geothermal energy should be viewed from a much broader perspective than is now commonly accepted, since this form of energy is generally available at all places on the earth's surface and is extractable with present technology. The real question, then, is not the availability of geothermal energy in general but the cost of harnessing it with current technology. This is particularly true when lower temperature gradient areas (less than 5°F per 100 ft) are under consideration.

No previous work could be found wherein a systems approach for assessing the cost of power from low-temperature-gradient geothermal energy was undertaken. This paper reports a techno-economic model of the geothermal power system which has been developed for this purpose. The model can be used to assess the cost of geothermal power at any location. The cost assessment is based primarily on three factors: (1) nature of the subsurface environment, (2) design of production and disposal wells and the gathering system, and (3) design of the power plant.

With the help of the model, it is possible to minimize the cost of geothermal power by optimizing various design parameters. The design parameters include: (1) well-bore completion technique involving the possible use of insulation, and so on, (2) sizing of casing, gathering and distribution lines, and (3) power plant design.

Each location possesses its own natural surroundings. Hence, an evaluation of the effect of the naturally occurring conditions on the power cost is important. The significant variables associated with each locale are: (1) geothermal gradient, (2) pressure gradient, (3) reservoir flow capacity, and (4) reservoir rock characteristics.

Finally, the cost of power is also affected by economic variables. These include primarily the desired rate of return, cost of equipment, financial resources of the company, and the development schedule.

Geothermal power extractable from hot water appears to be an attractive alternative to the use of natural gas, oil, coal, or nuclear fuel for the production of electricity.

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