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Econometric Analysis of Forced Geoheat Recovery for Low-Temperature Uses in the Pacific Northwest

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ABSTRACT

The Cenozoic volcanic areas of the Pacific Northwest, including the Columbia River basin and Snake River plain flood-basalt areas, provide a favorable environment for low-temperature geoheat resources. There appear considerable prospects that forced geoheat recovery techniques may be applicable and that very considerable amounts of heat for various low-temperature uses may be extracted from the Cenozoic and underlying Mesozoic volcanics.

An econometric analysis based on current economical and geophysical data indicates that econometric optimum production depths are of the order of 3.5 to 4.5 km. Since the optimum appears very flat, slightly suboptimal depths of 2.5 to 3.5 km appear preferable in actual operations. Depending on the subsurface temperature conditions, corresponding production temperatures are in the range 90 to 150°C.

INTRODUCTION

Rapidly increasing demand for energy and concern over environmental effects resulting from the burning of lower grades of fuel have caused an acute shortage of petroleum-based fuels in the USA. Because the rate of discovery of new petroleum reserves is decreasing and the development of nuclear fission energy is considerably behind schedule, an excessive strain on present petroleum reserves can be avoided only by the development of new types of energy resources. It is, therefore, an urgent task to investigate and develop all possible alternative energy sources which can replace fossil fuel—in particular, those resources which cause a minimal strain on the environment.

Geoheat, or in other words, geothermal energy, is an alternative source which in the short run, at least, appears to have prospects of bringing some relief to the energy market. Solar energy is still in its early stage of development, and the technological feasibility of nuclear fusion has yet to be demonstrated. The production of geothermal energy from various types of resources, mainly low- to medium-temperature and low-salinity type reservoirs, is, on the other hand, an already well-established technology. Due to the moderate-temperature character of geothermal resources in general, they are of special interest as a replacement for fossil fuels in the case of low-temperature uses.

The present rate of energy consumption in the USA is equivalent to approximately 2×10^9 petroleum-equivalent-tons/year (PET/yr). Some 25%, or about 5×10^8 PET/yr, are used for low-temperature applications, primarily space and other types of heating. Possibly 5% to 10% of this figure, namely, 2.5 to 5×10^7 PET/yr are used within regions of above average terrestrial heat flow in the western parts of the USA. This component of the national energy consumption is of particular interest in the present case. It is best adapted for conversion to geothermal energy, which, for brevity, may be nicknamed "geoheat."

Conditions for large-scale recovery of low- to medium-temperature geoheat appear quite favorable in the extensive areas of Cenozoic volcanism in the Pacific Northwest, mainly in the Columbia River basin, Snake River plains, and adjacent regions. Terrestrial heat flow is above normal in large sections of this region (Roy, Blackwell, and Decker, 1971) and geological conditions appear favorable. Moreover, there is a substantial market for low-temperature energy in the area. The present paper has been written for the purpose of discussing the use of forced or secondary recovery techniques for producing low- to medium-temperature energy for space and other heating purposes in this region.

FORCED GEOHEAT RECOVERY TECHNIQUES

Geoheat is extracted from hot subsurface formations by water circulating through openings in the rock. The circulation can be (1) free convective flow through natural openings such as fissures, fractures, and intergranular spaces; (2) partially forced by pumping through natural openings; and (3) totally forced by pumping through artificial openings which have been created by hydraulic or thermal fracturing. Using the oilman's terminology, the methods under (2) and (3) belong to the category of secondary recovery methods. The methods under (3) are generally referred to as the dry hot rock techniques of geoheat recovery. Most of the geothermal systems now in commercial operation apply the free flow process listed under (1).

Easily accessible geothermal areas with a sufficient free convective circulation are, however, relatively few and some of the known areas of great potential are not conveniently located for commercial utilization. The geothermal industry is therefore paying an increased attention to the possibility of using the forced recovery methods under (3) for the extraction of terrestrial heat from hot rock where conditions for natural geothermal circulation systems are less favorable or even totally absent. In fact, rocks with sufficiently high temperatures are present at varying depths everywhere in the earth's crust. The depth to the 100°C level varies from less than 1 km in thermally active areas to more than 5 km in old shield areas.

Forced geoheat recovery techniques encounter three basic difficulties: (1) all common rocks are relatively poor heat conductors, and large natural or artificial rock-water contact surfaces are required to extract economically significant amounts of heat; (2) the costs of drilling boreholes to sufficient depths are quite high; and (3) the locating or creating of permeable fractures at depth and the siting of boreholes to intersect such fractures are no doubt difficult. These are the principal obstacles of all dry hot rock projects. However, technological advances and the rising price of fossil fuel are now gradually changing the outlook in this field.

At present, the most ambitious investigation into the possibilities of extracting heat from solid hot rock at depth is being undertaken by the Los Alamos Scientific Laboratory (LASL) in Los Alamos, New Mexico. The ultimate goal of the research at LASL is to develop the technology of making geoheat from dry hot rock available for power generation. Water temperatures above 200°C are therefore required. Some aspects of the project have been described in recent papers by Harlow and Pracht (1972) and Smith et al. (1973).

In view of the difficulties of fracturing listed under (3) above it is of considerable interest in forced geoheat recovery to take maximum advantage of natural fractures and openings at depth. Of primary interest is the fluid conductance of geological structures which are easily recognized at the surface such as faults, dikes, and other types of intrusions. Bodvarsson (1974) has discussed the use of dikes for this purpose. Moreover, layered formations which contain extensive open formation contacts or permeable horizons are of great interest. In fact, permeable contacts and sedimentary layers are already being used in partially forced geoheat recovery in France (Maugis, 1969), Hungary (Boldiszár, 1970) and Iceland (Zoega, 1974).

The feasibility of economical forced geoheat recovery is highly dependent on the required temperature level. The technological and economical difficulties increase with increasing temperature. As already pointed out, power generation requires relatively high temperatures and therefore drilling to substantial depths. Domestic and other types of space heating as well as some industrial applications of thermal water require considerably lower temperatures and smaller drilling depths. In fact, space heating can be carried out successfully by thermal waters with temperatures as low as 50°C. At the present state of art, we may therefore conclude that forced geoheat recovery projects are considerably better adapted as energy sources for space heating systems than for electrical power generation.

GEOLOGICAL STRUCTURES

The great Cenozoic flood-basalt areas of the Columbia River basin, Snake River plains, and adjacent regions include three types of geological elements which appear suitable for forced geoheat recovery. These are (1) open horizontal contacts between individual lava beds, (2) numerous mafic dikes, and (3) fault zones. The pertinence of these elements is supported by field observations in the Cenozoic flood-basalt area of Iceland.

It is well known (Bodvarsson, 1961) that open contacts between individual flood-basalt type lava beds constitute the most important hydrological elements of the many geothermal systems of Iceland. As substantiated by numerous boreholes and hydrological studies, the open contacts provide for an extensive high horizontal fluid conductance at various depth levels.

Moreover, basaltic dikes provide perhaps the most important vertical fluid conductance within the geothermal systems of Iceland. The observational evidence is strongest in north-central Iceland where there are several dozen low-temperature thermal areas which issue from late Tertiary flood basalts (Bodvarsson, 1950, 1961). Observational data indicate that all of the areas are controlled by basaltic dikes, and there is evidence that the thermal water ascends along the walls of the dikes. Apparently, thermal contraction of the dikes upon solidification has left narrow open spaces between the country rock and the dikes. A simple quantitative analysis (Bodvarsson, 1973) shows that long very narrow open spaces can carry substantial flows of water even at small pressure gradients of convective origin.

The width of the basaltic dikes, which are very numerous in the Tertiary sections of the flood basalts of Iceland, usually amounts to a few meters. Due to block tilting, most dikes exhibit a slight inclination against the vertical. Little is known about their length, but the average dike is no doubt several kilometers long and cases up to 30 km are known. An inspection of outcrops shows that the walls of the dikes which have undergone rapid chilling are uneven and fractured on the scale of a few centimeters. Similar observations have been made on dikes in the Cenozoic volcanic areas of the Pacific Northwest (Waters, 1961; Taubeneck, 1970).

We can now envision basically two types of forced geoheat recovery systems which appear suitable for operation in the Cenozoic volcanics of the Pacific Northwest.

The first type is based on the use of open formation contacts of sufficient fluid conductance as shown in Figure 1. A borehole is drilled to intersect a contact and to produce thermal water by pumping. It is being assumed that the

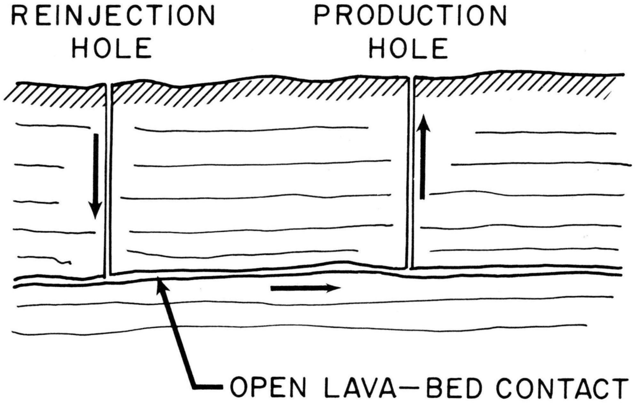

Figure 1. Forced geoheat recovery from an open lava-bed contact.

temperature of the thermal water produced is in equilibrium with conditions at the depth of the contact. Local hydraulic fracturing can be used to enhance the conductance between the borehole and the contact zone. Depending on local conditions a second borehole may have to be drilled for reinjection of the water following utilization. This will provide for pressure maintenance, waste water disposal, or both. The distance between the two boreholes is an important parameter which has to be taken up for special consideration (Bodvarsson, 1972). One can easily envision a large-scale operation of this kind where a number of borehole pairs are laid out along a regular pattern. One of the principal advantages of using open contacts of this type is that the siting of boreholes is not a major problem when the presence of the contact has been established.

As already quoted above, partially forced geoheat recovery of this type is in operation for the Reykjavik District Heating System in Iceland at the Reykir low-temperature thermal area about 10 miles northeast of the city (Zoega, 1974). The Reykir system is based on the pumping of thermal water at a temperature of about 80°C from highly conductive openings at the depth up to 2000 m. Since pressure maintenance is no problem, no reinjection holes have been drilled so far.

Similar systems can be designed for operation based on a dike or a fault zone. A discussion of the use of dikes for this purpose has been given by Bodvarsson (1974). A sketch of the system proposed is shown in Figure 2. Its operation is quite similar to that of the system shown in Figure 1. The principal difference is that here heat is being recovered along a more or less vertical surface and the correct siting of the boreholes is therefore a matter of major concern. Moreover, since the dike or the fault zone may have open contact with the ground surface, proper pressure and flow maintenance with the help of reinjection is probably much more important than in the case of the system shown in Figure 1.

Thermoelastic effects caused by formation temperature changes resulting from the flow of water through the structures are very important for most forced geoheat recovery operations. These phenomena are quite complex and will not be discussed here. We will only point out that the reinjection of cold water into hot formations will generally help to open fractures and thus increase the available permeability. In particular, this effect may be of major importance for the type of systems based on dikes and fault zones as sketched in Figure 2. The thermoelastic effects are also of critical importance for the LASL project mentioned above (Harlow and Pracht, 1972).

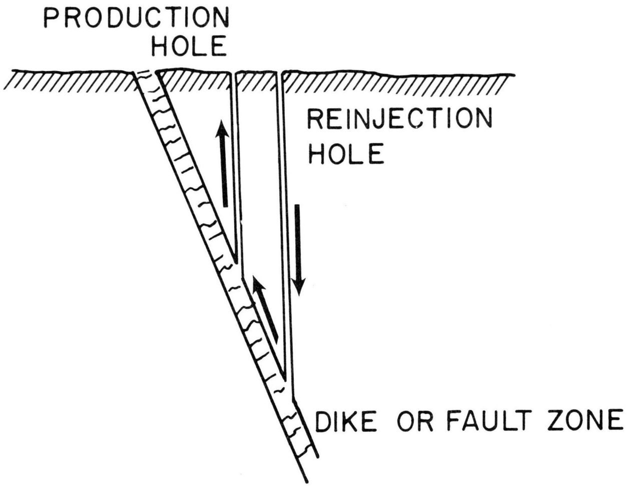

Figure 2. Forced geoheat recovery from a dike or a fault zone.

ECONOMETRIC ANALYSIS

A simple econometric analysis of forced geoheat recovery systems of the type discussed in the previous section will now be carried out. For convenience, we will base our analysis on the type of system sketched in Figure 1 and assume that thermal water can be obtained from open formation contacts which exist in a productive zone at depth. The formation temperature in this zone is assumed to be a function of the depth z only and given by the linear relation $T = (gz + a)$ where g is the temperature gradient and a is a constant. This implies the assumption of a purely conductive temperature field within the production zone. Water contained in openings is assumed to be in thermal equilibrium with the adjacent formation. At this juncture, we will assume that the required fluid conductance exists but make no assumption as to details of the distribution of the open contacts.

We will base our considerations on a simple total rate-of-return analysis as follows. Let V represent the total yearly net income from the sales of thermal water from a production unit consisting of a borehole or a borehole pair. For systems consisting of several units, V is defined as the average income per unit. Net income is defined as total yearly sales minus yearly cost of energy for pumping. Moreover, let C be the total capital investment per production unit. The annual total rate of return is then defined as $r = V/C$.

The income or, in other words, the value V of the thermal water depends on the production temperature T and therefore on the production depth z. The total capital C is clearly also a function of the depth which implies that r is a function of z. Our principal task is to investigate whether there is an optimal value of z with respect to r, that is, any value of the depth of production which would maximize the annual total rate of return. In other words, we shall derive the depth at which we prefer to find sufficient fluid conductivity. To carry out our analysis, we have to make specific assumptions as to the two functions $V(z)$ and $C(z)$ defined above.

According to data which will be supplied below, the value per unit mass of thermal water for space and other heating purposes is predominantly a function of its enthalpy and a number of scale and design factors. At fixed conditions, and above a certain lower temperature limit, the value can be assumed to be a linear function of the temperature. In the case of the data supplied in Figure 3, this limit is of the order of 90°C and an extrapolation of the value line to the temperature axis gives an intersection at $T_o = 70°\text{C}$. Since we are mainly interested in production temperatures above 90°C we can use this information to construct the value function $V(z)$ in the following way. Let z_o be the depth at which the formation temperature $T = T_o$, that is,

$$z_o = (T_o - a)/g \tag{1}$$

For water temperatures above 90°C, the value function can then be expressed

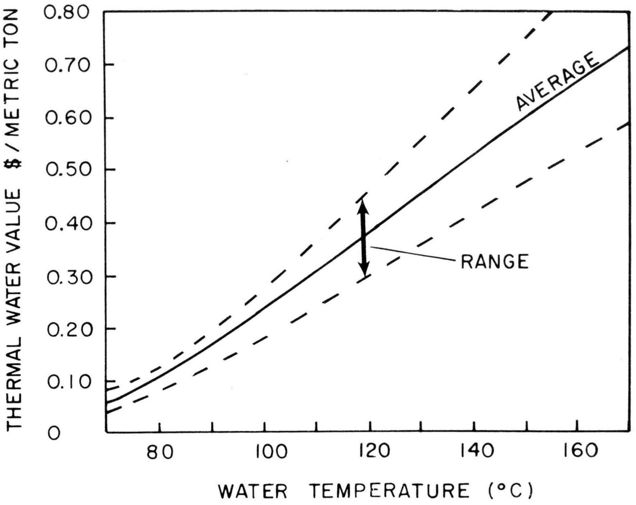

Figure 3. Economic value per unit mass of thermal water as a function of temperature.

$$V(z) = \nu Fg(z - z_o), \quad z > z_1 \tag{2}$$

where

$$z_1 = (90 - a)/g \tag{3}$$

is the depth to the temperature $T = 90°\mathrm{C}$, ν is the value per unit mass and degree temperature of the thermal water, and F is the yearly mass production of thermal water per production unit.

The total construction cost per production unit consists of two components; that is, (1) the cost of drilling, and (2) the cost of equipment such as pumps, pipelines, and so on. At a given location we can assume, for the present purpose, that the cost of drilling per unit depth is a linearly increasing function of the depth. The equipment constitutes a fixed cost per production unit. Hence we will assume that

$$C(z) = c_o + c_1 z + c_2 z^2 \tag{4}$$

From (3) and (4) we obtain the annual rate of return

$$r(z) = \frac{K(z - z_o)}{c_o + c_1 z + c_2 z^2} \tag{5}$$

where $K = \nu Fg$ is a constant. For values of z_o below a certain bound, this function has a maximum for $z = z_m > z_o$ which is easily derived by simple algebra. Omitting details we find that

$$z_m = z_o + \sqrt{(c_o + c_1 z_o + c_2 z_o^2)/c_2} \tag{6}$$

which can be expressed as

$$z_m = z_o + \sqrt{C_o/c_2} \tag{7}$$

where C_o is the capital cost of a production unit for the depth z_o. The corresponding maximum of the total rate of return is

$$r_m = \frac{K(z_m - z_o)}{2C_o + h_o(z_m - z_o)} \tag{8}$$

where h_o is the marginal capital cost per unit depth for $z = z_o$, that is,

$$h_o = \left(\frac{dC}{dz}\right)_{z=z_o} = c_1 + 2c_2 z_o \tag{9}$$

For the maximum total rate of return to exceed a certain value r_o we obtain the inequality

$$K > r_o[h_o + 2C_o/(z_m - z_o)] \tag{10}$$

which gives the required minimum value of the product νFg.

When the temperature gradient g is constant throughout, we obtain the relation $T_o = gz_o + T_s$ where T_s is the temperature at the ground surface. It is important to note that although the above results have been obtained on the basis of rather strong assumptions as to the form of the functions $V(z)$ and $C(z)$, an iterative trial-and-error procedure will allow the results to be used in more general situations.

DISCUSSIONS

In practical situations, the parameters entering the functions $V(z)$ and $C(z)$ defined above will vary within wide limits. Although the picture is somewhat complex, we can, nevertheless, draw some fairly interesting conclusions on the basis of the development given. To this end, we will furnish a brief simplified discussion which will provide an overview of the economic feasibility of forced geoheat recovery systems in the Pacific Northwest and elsewhere.

First, a realistic estimate of the capital investment in a production unit has to be provided. In this respect we will mainly rely on the report by Dagum and Heiss (1968) which gives a very comprehensive survey of drilling costs in the USA. In numerous diagrams they summarize their findings as to the cost of drilling oil and gas wells in various petroliferous regions of the USA. The data are given as cost per unit depth as a function of depth, diameter, and rock drillability or hardness. Since the Cenozoic volcanics in the Pacific Northwest are quite hard compared with most oil or gas field formations, we will select the cost data obtained for drilling to depths of the order of 3 km in formations which are referred to as being very hard. Moreover, we estimate the fixed cost required for a single borehole production unit to amount to \$200 000. Assuming routine drilling operation and allowing for cost increases since 1968 including additional costs of greater depths and casing, we arrive at the following estimates for the cost parameters for single borehole units with main diameters of 250 to 300 mm.

c_o = \$200 000
c_1 = \$60 000/km
c_2 = \$50 000/km^2

Moreover, we have derived estimates of the possible value of thermal water as a function of its temperature. The results which apply to conditions in the Pacific Northwest are illustrated in Figure 3. The data show a range of values at the source assuming a sufficiently large district heating market nearby. The results represent the value of conventional fuels (natural gas and oil) minus the cost of distribution for the geothermal fluids. The fuel value is taken as the average residential rate divided by an assumed efficiency of use for that fuel (\$7.90/0.75 per MWh for natural gas and \$8.90/0.70 per MWh for oil). The assumed distribution system is a two-pipe design which returns the geothermal fluid to the source. The yearly average load density of the assumed market is 6 MW/km². The distribution cost for 100°C effective temperature drop is \$6.1/MWh. The full line of Figure 3 represents a reasonable average for the Pacific Northwest.

We shall consider two types of temperature conditions which are realistic for the region under consideration. First, let the surface temperature be 10°C and the vertical temperature gradient be $g = 40$°C/km throughout the production zone. In mafic volcanics this corresponds to a heat flow of about 0.08 W/m², or 2.0 hfu, which is 30% above the global average. A value of $z_o = 1.5$ km is obtained. Second, assuming the same surface temperature, let the temperature be 70°C at the depth of $z_o = 1.0$ km and the temperature gradient below this depth be 30°C/km. The conductive heat flow at the ground surface is then 0.12 W/m² and decreases to 0.06 W/m² below the depth z_o.

The data given can now be used to evaluate the function

$$u(z) = \frac{z - z_o}{c_o + c_1 z + c_2 z^2} \qquad (11)$$

and other results of interest for the two cases defined above. Of primary importance is the yearly mass flow per production unit F_o required to provide a minimum total rate of return r_o. Recognizing the risks involved in operations of this type, we shall for the present purpose apply a figure of $r_o = 0.25$ which would be sufficiently high to cover operational costs and give a relatively high net rate of return on invested capital.

The values of $T(z)$ and $u(z)$ for the two cases are shown in Figures 4 and 5, and our main results for the optimum simple single borehole production unit with $z = z_m$ are given in Table 1. In accordance with the assumptions made, and allowing for a temperature loss of 10°C, the temperature of the water produced is derived as $T_w = (gz + a - 10)$ and its value per unit mass is $W = v(T_w - 70)$. The maximum flow or water f_o is obtained by assuming an operation time of 6000 hr/yr.

The maximum flow rates obtained in the last column of Table 1 are moderate when compared with available data on the flow rates of fairly productive geothermal boreholes. For example, the flow pumped from deep boreholes in the Reykir area in southern Iceland is of the order of 40 to 50 kg/sec (Thorsteinsson, 1975). It is to be underlined that in the above analysis we have not taken into account additional costs due to unsuccessful boreholes. Proper use of local hydraulic fracturing can probably keep losses of this type at a low level.

The situation appears somewhat more marginal in cases where reinjection is required. The addition of the reinjection borehole and the required pumping equipment, pipeline, and so on, may approximately double the required capital investment. The corresponding flow rates in the last column of Table 1 will also have to be doubled, that is, increased to 40 and 46 kg/sec respectively. Nevertheless, these flow rates appear feasible, at least in areas where open formation contacts of high fluid conductance are available.

A review of the relatively flat maximums in the graphs for $u(z)$ in Figures 4 and 5 indicates that slightly suboptimal production depths $z < z_m$ can be chosen in the design of actual production units of this type. For the two cases

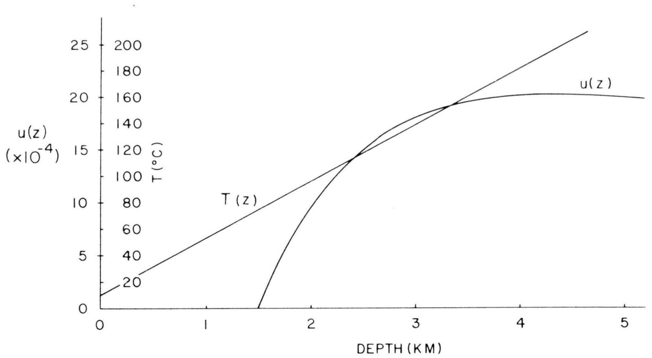

Figure 4. Case (1) with a constant thermal gradient of g = 40°C/km.

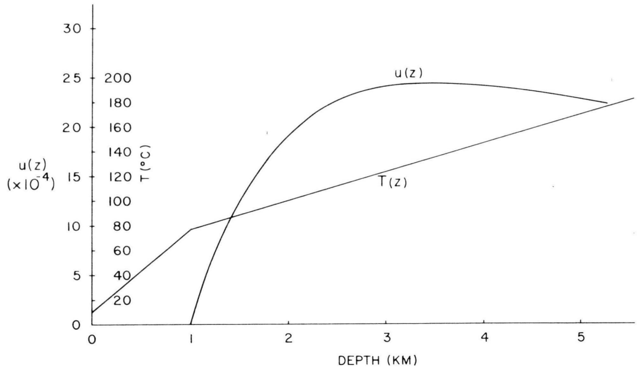

Figure 5. Case (2) where the temperature gradient decreases from g = 60°C/km in the uppermost one kilometer to g = 30°C/km below.

Table 1. Numerical results for an optimal single borehole unit.

Case	z_o km	g °C/km	z_m km	T_w °C	W \$/10³ kg	C_m M\$	$r_o C_m$ k\$/year	F_o 10⁶ kg/year	f_o kg/sec
(1)	1.5	40	4.2	168	0.75	1.3	330	440	20
(2)	1.0	30	3.5	135	0.50	1.0	250	500	23

z_o = Depth to T = 70°C
g = Temperature gradient for $z > z_o$
z_m = Optimum depth of production
T_w = Temperature of water produced
W = Value per unit mass of water produced

C_m = Total capital investment for system operating at $z = z_m$, (M\$ = 10⁶ \$)
r_o = Total rate of return for the optimal system
F_o = Yearly mass production of thermal water
f_o = Maximum instantaneous flow of thermal water

discussed this would imply the selection of depths in the range 2.5 to 3.5 km. On the other hand, the flat maximums also indicate that production depths of the order of 4 to 5 km might be feasible in cases where relatively high temperatures are required and adequate fluid conductance is available.

The econometric results given above will also be more or less applicable to the type of system sketched in Figure 2 where production is obtained from a dike or a fault zone. The two types of systems differ in some respects, but it is unlikely that the main conclusions as to the suitable production depths will be substantially different.

The results of the analysis above appear encouraging. They indicate that forced geoheat recovery of the type described may be economically feasible in those areas in the Pacific Northwest where conditions are reasonably favorable. A more detailed investigation of the prospects in this field is indicated.

ACKNOWLEDGMENT

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