GEOTHERMAL RESOURCES: AN INTRODUCTION WITH EMPHASIS ON LOW TEMPERATURE RESERVOIRS

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ABSTRACT

Utilization of the enormous potential of terrestrial heat with today's technology is economically feasible if a subsurface reservoir exists from which a fluid with elevated temperature can be produced. For district heating the minimum temperature is 55-60°C (130-140°F) and the production rate around 70 m^3/h (300 gpm); thus the reservoir must have high natural porosity and permeability. In impermeable rocks artificial heat extraction loops can be created.

Geothermal background to describe low-temperature reservoirs is presented. The performance of thermal springs is described and production from deep aquifers and hot dry rocks is discussed in terms of heat content, permeability and reservoir lifetime. Environmental aspects are addressed which show that geothermal energy extraction will cause no climatic effects. Chemical effects are the most significant ones; more basic research is needed to predict the long-term chemical performance of geothermal systems.

1. Definition, Classification

Random drilling deep enough into the earth's crust would produce adequate heat for a geothermal resource. However, this heat must be in an accessible and usable form. This implies ample porosity and permeability to maintain the correct balance between a heat source and a working fluid, usually hot water. The volume of this fluid must be large enough to justify the effort of its exploration and exploitation. Although the criteria on heat content and volume may have been met, the working fluid must not be in a form that is corrosive or high in dissolved solids. Therefore, a geothermal resource will be defined as a region within the earth's crust that has sufficient porosity, permeability, heat content, water content, volume and accessibility with the water in such a state that it can be exploited profitably.

Geothermal resources can be divided into two broad classes (Muffler, 1976): 1) resources related to young igneous intrusions in the upper crust, and 2) resources not related to young igneous intrusions. The first class can be further subdivided into three types of resources: a) magma, b) hot dry rock, and c) convecting hydrothermal systems. The second class can be subdivided into four resources types: a) resources in a low permeability conductive environment (=warm or hot dry rock, depending on depth), resources in a low permeability environment modified by circulation of meteoric water (e.g. thermal springs), c) resources in a high porosity/permeability environment (confined or unconfined deep aquifers), and d) resources in a high-porosity environment at pressures greatly in excess of hydrostatic (="geopressurized").

In our considerations of low temperature reservoirs we focus on the types 2a-c. The lowest temperature level for electricity generation (by the binary cycle) for geothermal fluids is around 150°C (300°F), the lowest limit for economic utilization for space heating is about 55°C (130°F). Fluids at even lower temperatures can (under certain circumstances) be utilized for agricultural applications (Fig. 1).

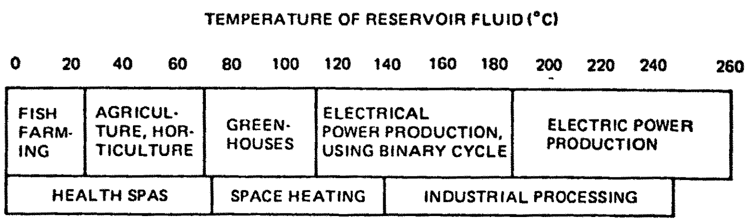


Fig. 1 Temperature ranges for possible uses of geothermal energy (from Jonsson 1976)

2. Geothermal Background

The interior of the earth is an enormous reservoir of heat; the total heat content is estimated to be $4 \cdot 10^{11}$ TWa ($3 \cdot 10^{24}$ kWh). This heat results mainly from the decay of the naturally radioactive elements uranium, thorium and potassium and is transmitted to the earth's surface at a rate of about 10^{21}J/a by three mechanisms: 1) conduction, 2) movement of water, 3) movement of magma. For low temperature resources the first two categories are of significance.

The conductive heat flow towards the surface is related to the geothermal gradient (increase of temperature with depth, dT/dz, usually given in °C/km). The conductive heatflow q is equal to K•dT/dz, where K is the rock thermal conductivity. Temperature estimates for a given depth z can be calculated in purely conductive regimes by

$$T(z) = T_0 + q \sum_{i}^{z} (\Delta z_i / K_i) \qquad (1)$$

where T_0 is surface temperature, Δz and K denote thickness and thermal conductivity of the individual strata in question.

Although a linear gradient is a first approximation only (considerable curvature of the temperature-depth curve is often encountered in the uppermost 300-500 meters (1000-1600 ft)) it is customary to classify regions in geothermal terms into the following three broad categories: a) "hyperthermal regions (gradient >80°C/km), b) "semithermal" regions (gradient 40-80°C/km; 2.2-4.4°F/100 ft) and c)"normal" regions (gradient <40°C/km). In the following we will address resources associated with the latter two categories.

Even in normal regions and in many rocks which are often regarded as impermeable, significant transfer of heat can occur by convection of ground water: meteoric water can penetrate, along faults and fractures, to depths of several kilometers, acquire heat by conduction from rocks, and rise to the surface along conduits of relatively restricted cross sections. Heat flow and temperature gradient are enhanced above the rising limb of the convection cell and depressed above the sinking limb. The convective heat flow component is

$$q_{conv} = c_w v T_e \qquad (2)$$

where c_w is the volumetric heat capacity of the rising hot water ($J/m^3,K^w$), v the water velocity (given in m/s or as the flow rate per unit cross sectional area, $m^3/s,m^2$) and T_e the excess temperature of the rising fluid. Thermal springs (see next section) are typical examples for this kind of heat transfer.

Local geothermal anomalies, caused by contrasts in thermal conductivity and/or in radioactive heat generation, can be found even in purely conductive, "normal" regions. Relatively high temperature gradients can be encountered if a low-conductivity sediment (K_s) blanket is present, covering high-conductivity basement (K_b). Depending on the local heat low q and the sediment thickness D the temperature anomaly ΔT (relative to uncovered basement) at the bottom of the blanket will be

$$\Delta T = Dq \frac{K_b - K_s}{K_s + K_b} \qquad (3)$$

Increased radioactive heat generation in basement rocks (e.g. granites) can also cause positive geothermal anomalies. An example is given in Fig. 2 (together with the sediment blanket effect). From the geothermal point of view optimum targets in "normal" areas are at locations of thick accumulations of sediments of relatively low thermal conductivity overlying basement rocks of relatively high heat generation. For the condition characteristic of the eastern United States, see papers by Glover and Costain in this volume.

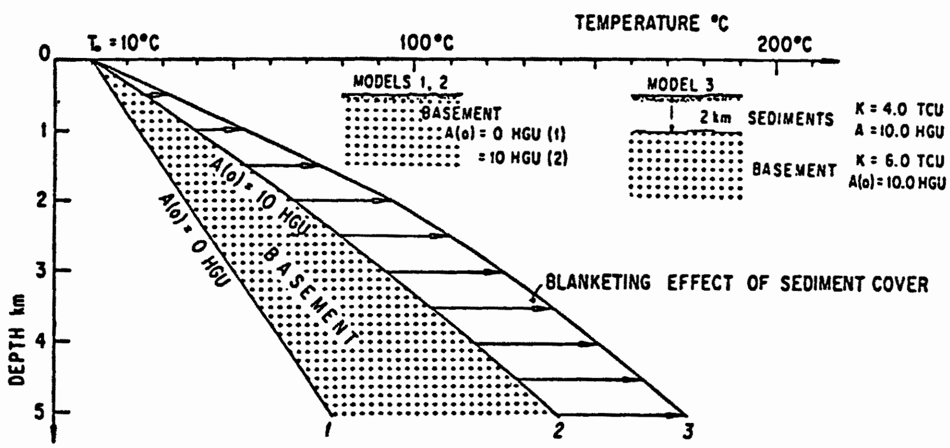


Fig. 2 Temperature-depth curves for different one-dimensional steady-state models showing the effect of increased heat production in basement rocks (e.g. granite batholiths) and the blanketing effect of sediments. Curves 1 and 2: basement with zero and 10 HGU (heat generation units) (= 4.18 $\mu W/m^3$) heat production and without sediment cover, curve 3: blanketing effect of a 2 km thick sediment cover. Calculated with a surface heat flow of 1.8 HFU (heat flow units) (= 75.2 $\mu W/m^2$). 1 TC = 0.418 W/m, K (from Rybach 1978)

3. Thermal Springs

Thermal springs indicate the presence of greater quantities of water at depth. Sufficient vertical permeability (often at the intersection of steeply dipping faults and/or fractures) can lead to the formation of thermal springs. These occur at places where buoyantly rising hot water reaches the earth's surface again, after it has infiltrated in the recharge area down to greater depths. Obviously at such places the heat flow regime is strongly influenced by the convecting thermal water: the heat carried by the water which depends on flow rate and temperature (cf. equ. 2) may be large in comparison with the conductive heat flow field.

A study of the distribution of thermal springs in Switzerland revealed that the absence of springs in the sedimentary Molasse basin can be attributed to the lack of vertical permeability in this area (due to impervious shaly formations in the sedimentary sequence); on the other hand the springs with the highest temperatures (up to 62°C; 145°F) and flow rates (up to 400 L/min; 100 gpm) are situated in the area of elevated seismicity (Jaffe et al., 1976a) where the channels of ascent in dense rocks are kept open by the natural seismic activity.

In many cases a deeper-lying reservoir with high temperatures exist from which the thermal waters emerge to the surface; significant cooling can occur during ascent due to the mixture of cold ground water. Thus higher temperatures and in many cases higher flow rates as well can be achieved by tapping the source more close to its reservoir after detailed exploration. Besides detailed investigation of the fault/fracture pattern in the area of interest geochemical methods are now frequently used to answer basic questions of such exploratory studies: a) determination of reservoir size and temperature, b) identification of recharge and source areas of thermal water, c) residence time of thermal water in the subsurface, d) determination of the extent of mixing of thermal water with near-surface ground water. An excellent account along these lines can be found in Edmunds et al. (1977).

Thermal springs have been utilized for medical purposes since ancient times. In addition, they can contribute significantly to local energy needs for space heating. A recent example is the development of the Lavey spring (Valais/Switzerland). Detailed hydrogeological and geophysical exploration, followed by drilling and pump tests, led to an increase in its temperature from 42°C (108°F) to 62°C (144°F) and its discharge rate from 60 L/min (15 gpm) to 400 L/min (100 gpm) (Jaffe et al., 1976b). The thermal energy of the spring (1.5 MW above ambient temperature) is utilized in cascades to heat a building complex, two indoor and outdoor swimming pools and to preheat the domestic warm water consumed in the complex (Fig. 3).

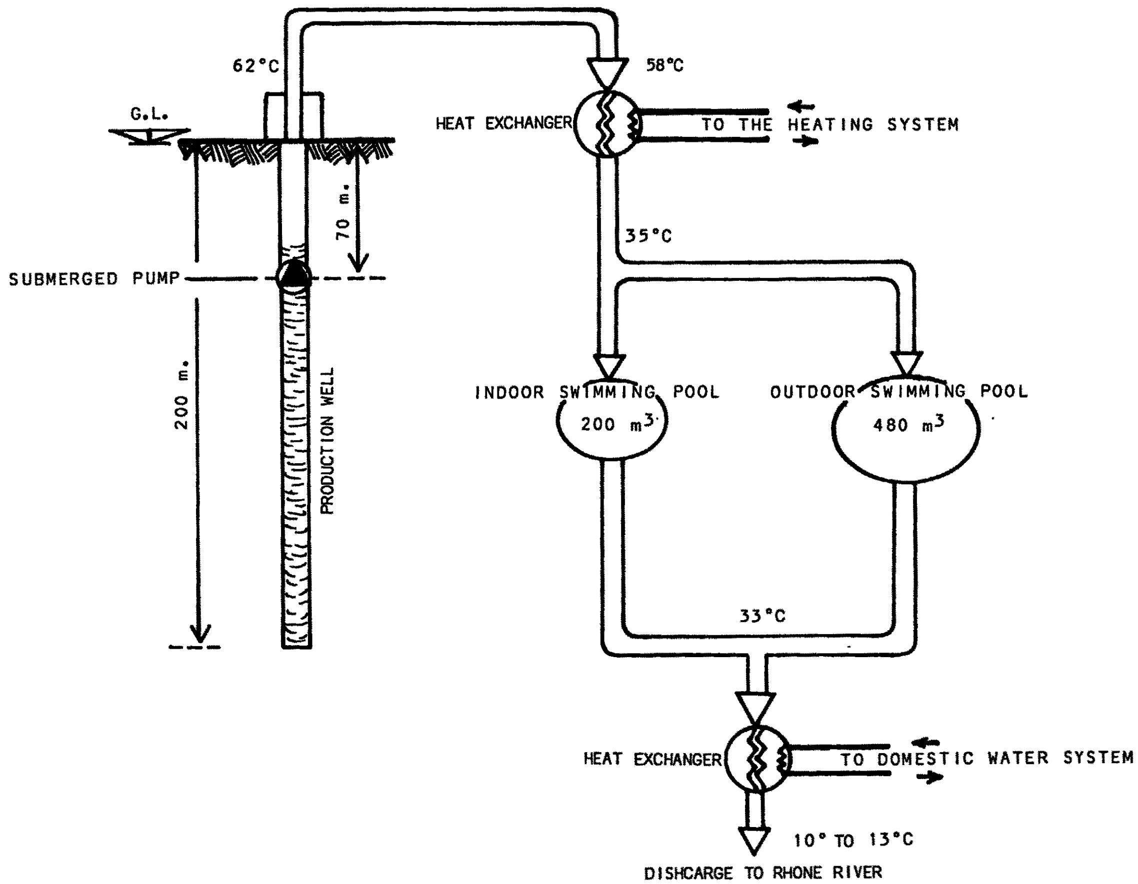
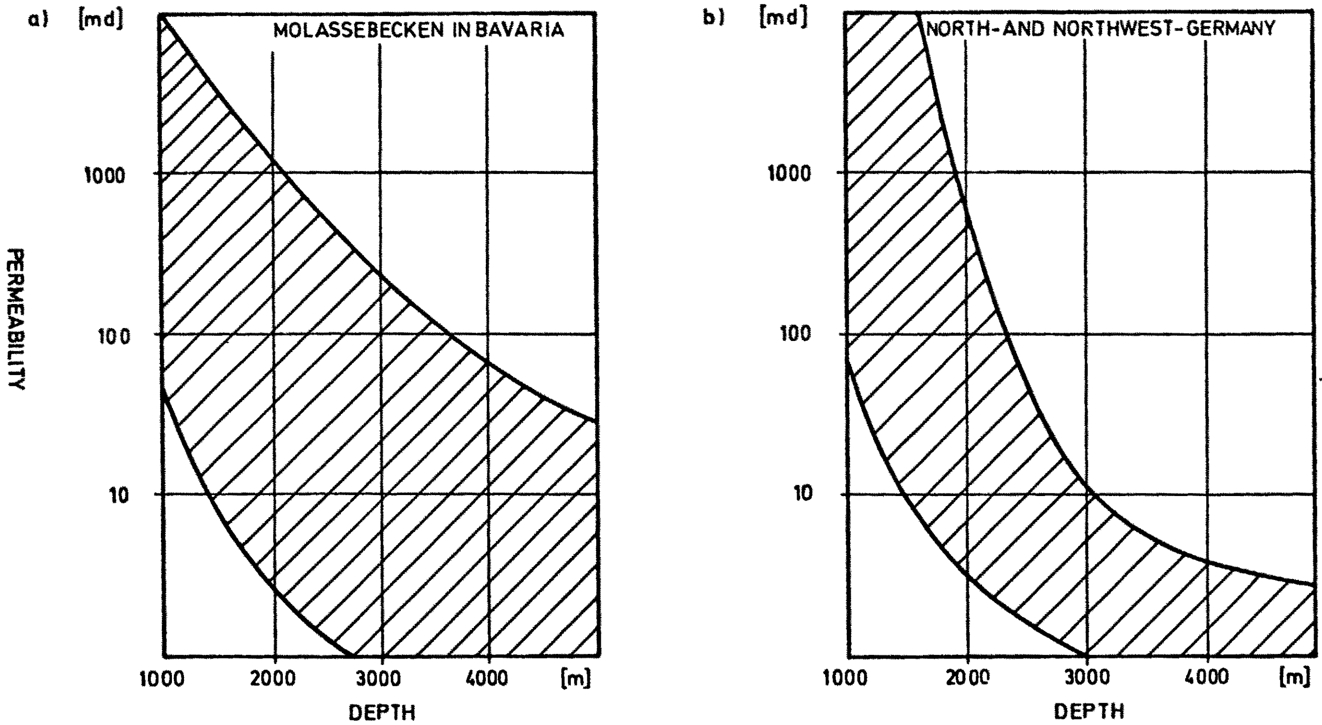


Fig. 3 Utilization of thermal spring water in cascades (Lavey/Switzerland, installation in operation since 1978)

4. Deep Aquifers

In sedimentary basins deep water-bearing formations can be present without displaying any surface activity. The heat content of these aquifers can be of economic interest: developments in the Paris basin (see Rybach, this volume) and in Hungary clearly indicate that for district heating and agricultural applications a formation temperature range of 55°(130°F) - 80°C (176°F) at flow rates of about 100 m^3/h (440 gpm) per producing well (=5-8 MW thermal output[1] above ambient temperature) can be of economic interest.

Whereas the formation temperature depends on the geothermal situation in a given area the flow rate and performance of a deep aquifer depend on many parameters: the volume of water (which in turn depends on porosity), the pressure conditions, the permeability of the formation, the physical restrictions of the production well and casing (e.g. diameter) and the type of completion equipment utilized (e.g. pump). Production rates of the above-mentioned order can only be maintained for water-bearing horizons of high permeability. The permeability of sedimentary rocks depends on the interconnected pore space fraction as well as on the degree of fracturing (=secondary permeability). The permeability (given in millidarcies (md), 1 md = $10^{-15} m^2$) usually decreases with depth (Fig 4). To obtain the above-mentioned extraction rate the transmissivity (aquifer thickness x permeability) must be in the order of several hundreds of md m.



PERMEABILITY OF ROCKS IN DIFFERENT LOCATIONS

a) MOLASSEBECKEN IN BAVARIA

b) NORTH-AND NORTHWEST-GERMANY

Fig. 4 Decrease of permeability with depth in the Molasse basin (Northern Foreland of the Alps)

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[1]Thermal output, $\dot{Q}$ (MW) = 1.17 $10^{-3} \dot{m}$ ΔT; where m is the rate of production (m^3/h) and ΔT the useful temperature drop (deg).

The static heat content of aquifers is easily calculated from formation temperature and porosity data. However, only a fraction of this volume is extractable since distinction must be made between static, elastic and dynamic reserves as well as of the exploitable reserves (for a detailed discussion see Franko & Mucha, 1976). The maximum exploitable quantity of water (m) at constant temperature (i.e. without thermal drawdown) depends on the heat flow (q) at the aquifer base and is given by

$$\dot{m} = \pi \frac{q R^2}{c_w \Delta T} \qquad (4)$$

where R is the radius of the piezometric depression cone (to be determined by pumping tests), c_w the volumetric heat capacity of water and ΔT the useful temperature drop (aquifer temperature minus surface temperature). Prior to the economic exploitation the reservoir must be characterized by the abovementioned parameters. A good example is the documentation of the aquifers in the Paris basin (Housse & Maget, 1976).

A standard technique of exploitation of deep aquifers is the "doublet" method: a pair (or pairs) of production and reinjection wells. The reinjection (after heat extraction by heat exchangers) maintains constant reservoir pressure and also disposes of dissolved solids which could create severe pollution problems (see section on Environmental Considerations). Reinjecting the used fluid also enables better thermal utilization of the reservoir: on its way from the reinjection to the production well the cold inlet water extracts part of the heat contained in the rock matrix. After a certain time with constant production temperature (=lifetime of the doublet system) the thermal influence of the reinjection well reaches the production well, causing a slow drawdown of temperature. The lifetime depends on the reservoir thickness, porosity, temperature, extraction rate and production/reinjection well spacing. Fig. 5 shows this dependence (result of model calculations) for a single doublet. Considerable enhancement of the lifetime can be obtained by multiple doublets (Gringarten 1978). The lifetime can be up to 30% higher than shown on Fig. 5 due to the changing viscosity of reinjected water on its way to the production well (L. Bjelm, personal communication).

In general, cost of drilling to tap the reservoir increases with depth but this increase is balanced by the greater value of heat at the higher water temperature. If several aquifers with comparable reservoir performance are present at different depths in the sedimentary column, economic considerations will lead to the optimum one.

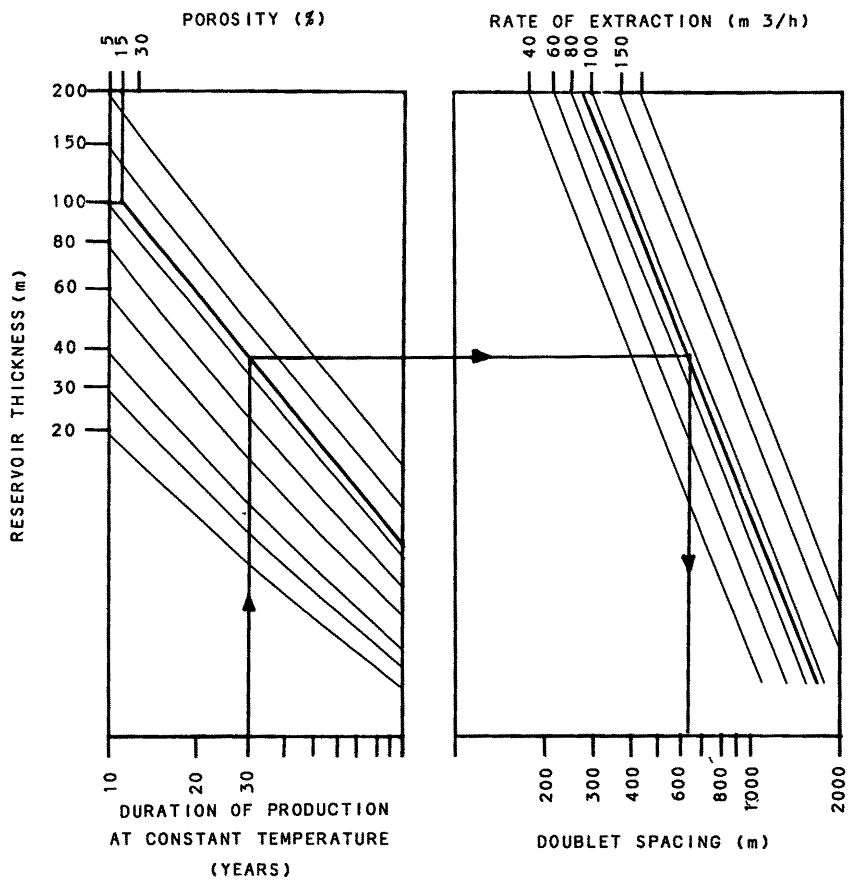

Fig. 5 System lifetime for a doublet as a function of reservoir thickness, porosity, temperature, well spacing and extraction rate (from "La geothermie en France", 1975)

5. Hot Dry Rock (HDR)

In most "normal" continental areas geothermal heat is present in great quantities at depths which are accessible with today's drilling technology, even when working fluids are absent due to the low natural permeability of the deep strata. From such HDR resources heat could be extracted by establishing artificial fluid circulation. One possible circulation system is now under development at the field test stage in New Mexico, USA and is known as the "Los Alamos HDR Concept" (see e.g. Smith 1978). It requires drilling of two holes deep enough to reach hot crystalline rock, connecting them at depth through a large hydraulic fracture (which serves as a heat exchange surface), and then circulating pressurized water through this closed system to recover heat from the rock. The theoretical value of HDR heat can be demonstrated by considering a 1 km^3 (0.25 mi^3) cube of granite: if its heat content could be "mined" over a useful temperature drop of 200°C (390°F) this small volume would yield about $4 \cdot 10^{17}$ Joules, equivalent to 10^{11} kWh or $3 \cdot 10^9$ $.

A HDR reservoir can mainly be characterized by its natural permeability and heat content. The natural permeability at depth (= degree of fracturing) is rather difficult to be determined from the surface. In formation on the variation of fracture permeability with depth can be obtained from the inversion of seismic refraction data (Rybach et al. 1978). The potentially useful heat contained in a HDR reservoir can be evaluated from the temperature-depth curve, T(z). For a given application there is a lower temperature limit T_ℓ (e.g. 150°C (300°F) for electricity generation by the binary cycle), hence a minimum drilling depth, z_ℓ, to reach this temperature in the subsurface. The maximum reservoir temperature is defined for a given T(z) distribution by an assumed maximum economic drilling depth z_m; the heat content Q per surface area above a minimum usable temperature T_{min} is

$$Q = c_v \int_{z_\ell}^{z_m} [T(z) - T_\ell] \, dz - c_v T_{min} (z_m - z_\ell)$$

where c_v is the volumetric heat capacity of the rock. This considerable heat content must be considered only as a resource base: only a small fraction of it (in the order of 0.1%) is expected to be technically recoverable (Cummings et al. 1978).

If the in situ permeability (=natural fracturing) of the HDR reservoir is low, artificial fracture(s) must be created to expose circulating fluid to hot rock. The thermal output depends mainly on the fluid flow rate $\dot{m}$, the fracture radius R, the temperature difference ΔT (initial rock temperature minus fluid reinjection temperature) and varies with time t according to

$$P(t) = c_w \dot{m} \, \Delta T \, \mathrm{erf} \left(K \frac{R^2}{\dot{m} \sqrt{t}}\right) \qquad (6)$$

where c_w is the volumetric heat capacity of water and K is a constant (includes material properties or rock and water). The thermal drawdown is governed by the parameter $R^2/\dot{m}$; with medium production rates quasi-stationary state can be established (e.g. 20 L/s (310 gpm) for 10 MW (th)).

In a deep reservoir with high natural permeability flooding techniques (known from oil production technology) using water drive could be feasible. In any case the development of relatively small HRD units in the order of 5-10 MW(e), which would supply 5,000-10,000 inhabitants, is envisaged. The Los Alamos project has so far shown that the HDR concept is technically feasible; its economic feasibility is still to be demonstrated. Obviously drilling costs will be a major issue in investment; regions with rapid increase of temperature with depth are favorable in this respect. As in the case of deep aquifer applications a certain concentration of users is necessary in view of the considerable drilling and installation costs for a heat extraction site.

6. Environmental Considerations

First of all it must be clearly stated that geothermal energy is not a renewable resource. In most cases the extraction of heat from the subsurface greatly exceeds the rate of replenishment by natural conductive heat flow; the lifetime of economic extraction will depend on the resource size. On the other hand, cooling of a geothermal area will not have direct climatic consequences since the temperature regime of the earth's surface is entirely governed by insulation.

Environmental effects to various degree are to be anticipated during the whole phase of geothermal development: from exploration through testing and construction to full production. Many of these impacts are very similar to oil/gas exploration and/or production. Subsidence effects can be avoided by reinjecting the waste fluid after heat extraction. Neither subsidence nor seismic effects are known from the Paris and Hungarian basin where field experience exists over more than a decade. No detectable environmental effects have been encountered so far at the HDR heat extraction test site at Fenton Hill, New Mexico.

The only severe problem that arises is a chemical one. Geothermal fluids, especially those from deep aquifers, often contain dissolved solids in great amounts (up to 30 g/L). This can cause, even with reinjection of the waste fluid, severe corrosional problems of surface equipment. Furthermore the lifetime of a doublet production system can be limited by the change of solution equilibria in time rather than by the thermal drawdown. Even in the "freshwater" system of HDR heat extraction solid outputs of 1 - 10 tons per day of silica or calcium carbonate type material must be anticipated (Cummings et al., 1978). Considerably more research is needed to fully understand the manifold environmental aspects of geothermal energy utilization.

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