FORCED GEOHEAT EXTRACTION FROM SHEET-LIKE FLUID CONDUCTORS

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Geoheat is now being extracted for electrical power generation from a number of resources in thermally active regions. The most notable examples are The Geysers, California; Larderello, Italy, and Wairakei, New Zealand. Common to all these cases is that the energy is being extracted from natural hydrothermal resources on the basis of free flowing boreholes. This type of operation may be termed as free geoheat production.

Large scale space heating by geoheat has been carried out in Iceland for more than three decades. The Reykjavik District Heating System, which now supplies energy for domestic heating for more than 100,000 people, is a low-temperature operation where large scale resource stimulation by borehole pumping is being applied.

The free and stimulated production methods as described above are based on the presence of natural fluid conducting openings in the resource formations and on a natural recharge of the withdrawn fluid. One can also envision forced geoheat extraction systems (FGES) with an artificial recharge of the heat extracting fluid which flows to some extent through artificial openings created by hydraulic fracturing or other pressurizing operations. For the operation of such systems to be successful, the openings have to provide adequate contact areas or contact volumes between the fluid and the rock such that a sufficient amount of heat can be extracted from the hot formations.

In the following, we will discuss a number of economical and physical aspects of FGES with emphasis on heat extraction from sheet-like natural fluid conductors in volcanic formations such as sufficiently open (conducting) fault zones, dikes and formation contacts. We envision applications of our results in some regions in the western U. S., the Pacific Northwest, in particular.

Limitations on Geoheat Transport

Thermal waters and natural steam are bulky heat carriers which cannot be transported economically over long distances. In the case of power generation the limits are of the order of a few kilometers only. For direct uses such as space heating, the maximum distances may in extreme cases amount to a few tens of kilometers. At the present state-of-art where only natural convective type sources are being harnessed, geoheat utilization, non-electrical uses, in particular, are therefore severely limited by the low transportability. The major convective sources are not favorably located with regard to the heat market. There is consequently a great interest in the possibility of extracting geoheat at suitable temperatures over much wider areas than has been possible so far.

FGES in Regions of Moderately High to Normal Heat Flow

The FGES which we envision involve the circulation of a heat extracting fluid through hot formations at depth between sets of injection and production boreholes. The principal factors that have to be considered in the design of such systems are the following:

(1) thermal properties of the formations
(2) fluid conductivity at the depth of interest
(3) drilling and equipment costs
(4) pumping power required to provide the necessary penetration and contact area
(5) fluid losses, scaling.

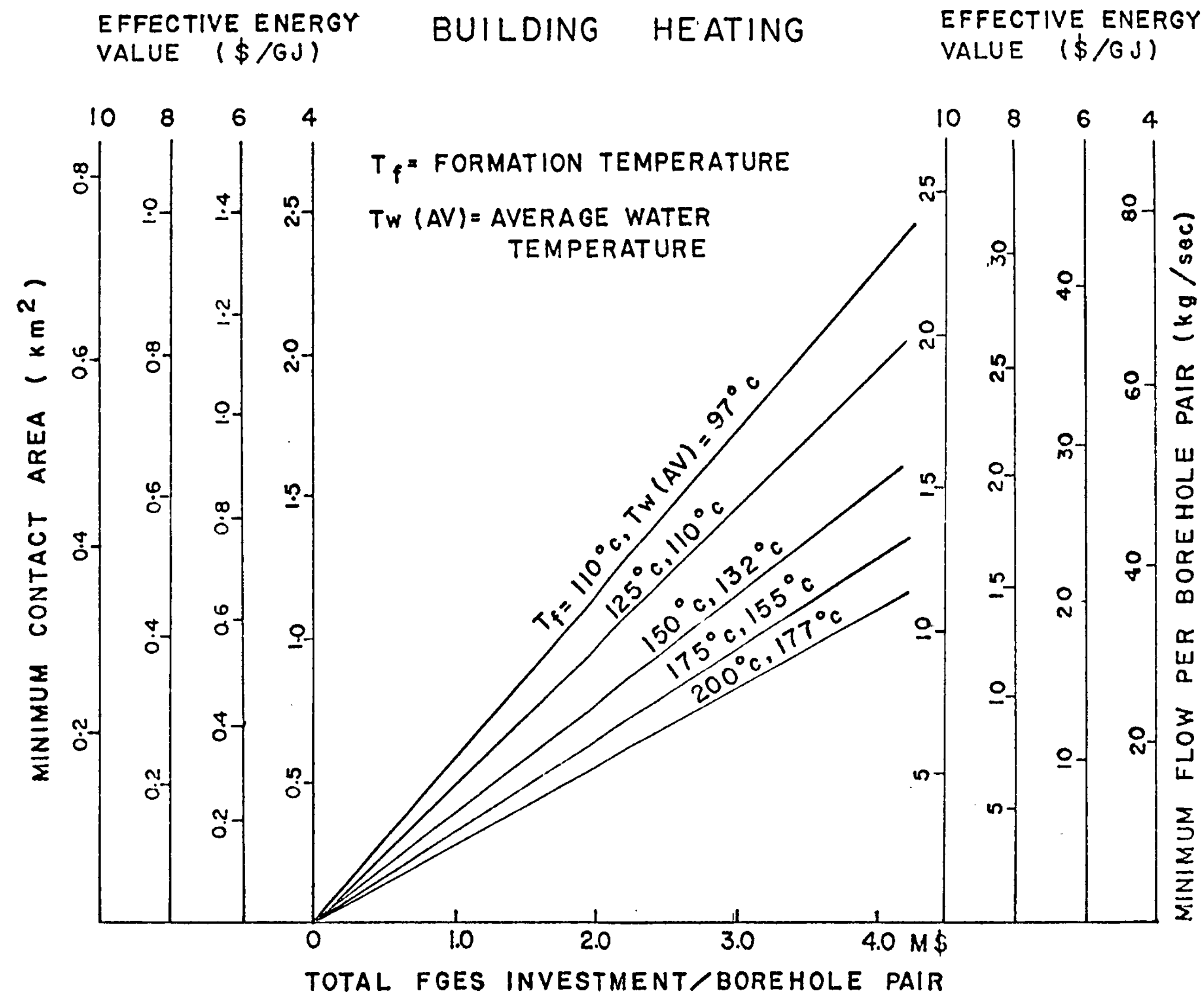
Minimum Contact Area

The size of the fluid-rock contact area required to produce a sufficient amount of hot fluid to amortize a given system investment depends critically on factors (1) to (5) above. The minimum economic area can be estimated on the basis of an idealized model. We assume that the circulating fluid is water absorbing heat from the rock in uniform and unidirectional flow through an infinitesimally thin fracture in a large volume of homogeneous rock which is isothermal at the initiation of the process. Using theoretical results by Bodvarsson (1974), the contact area as a function of plant investment and value of the energy produced can easily be calculated. The results for a single borehole-pair producing heat for building heating are shown in Fig. 1 and the corresponding results for electrical power generation are shown in Fig. 2. In both figures the useful life of the system is assumed to be 20 years, the interest on capital 8% and the operational and maintenance costs are 10% of capital per annum. Other factors are given in the figures. In the electrical case, the required power per borehole pair amounts to a few MW.

Suitable Fluid Conductors

There are two main possibilities of realizing FGES of the above type, viz., by using (a) natural subsurface fluid conductors or (b) artificial conductors obtained by hydraulic fracturing. The second

FIGURE 1.



BUILDING HEATING
EFFECTIVE ENERGY VALUE ($/GJ)
10 8 6 4
EFFECTIVE ENERGY VALUE ($/GJ)
10 8 6 4
Tf = FORMATION TEMPERATURE
Tw (AV) = AVERAGE WATER TEMPERATURE
Tf = 110°c, Tw (AV) = 97°c
125°c, 110°c
150°c, 132°c
175°c, 155°c
200°c, 177°c
MINIMUM CONTACT AREA (km²)
MINIMUM FLOW PER BOREHOLE PAIR (kg/sec)
0 1.0 2.0 3.0 4.0 M$
TOTAL FGES INVESTMENT/BOREHOLE PAIR

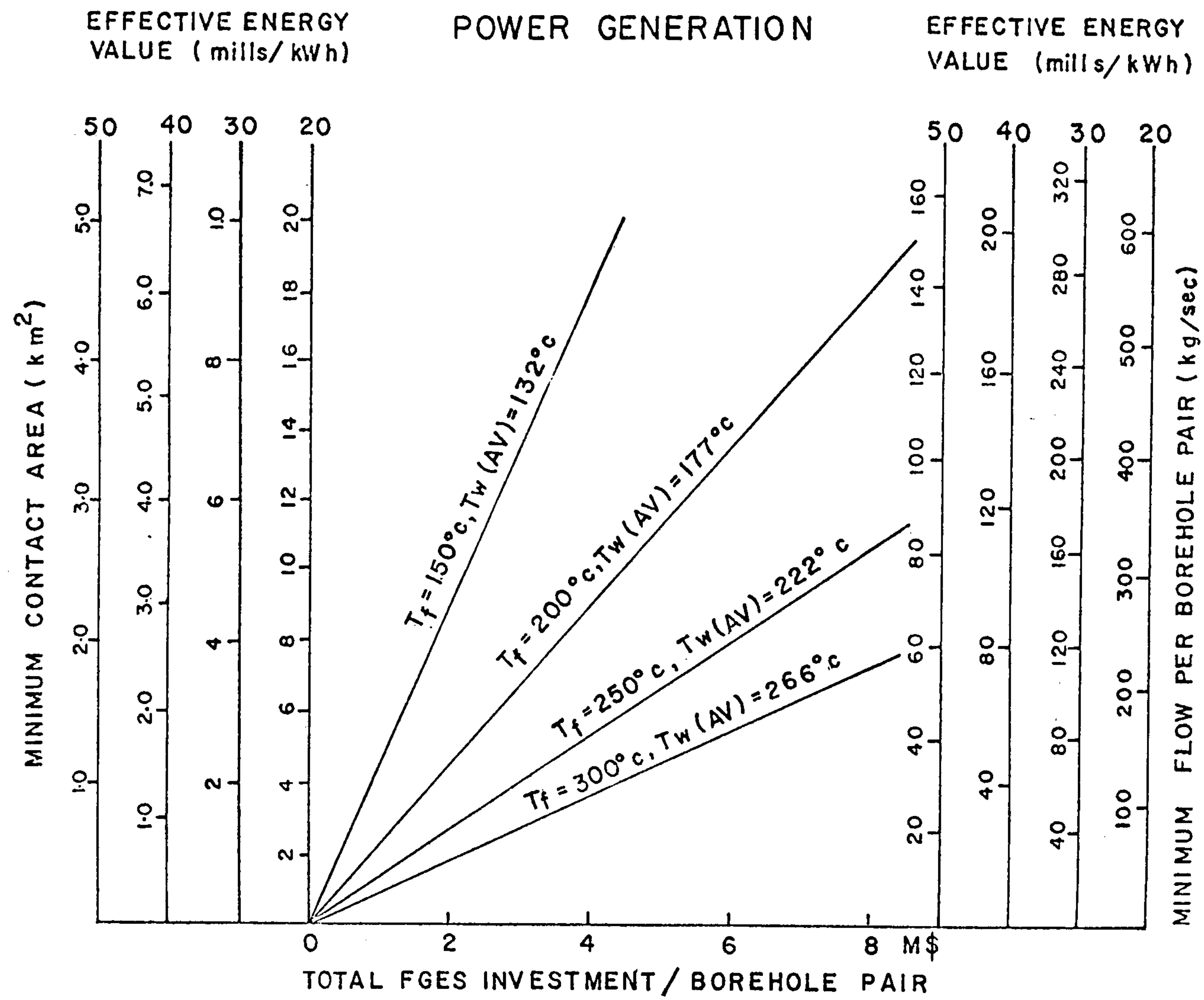

POWER GENERATION
EFFECTIVE ENERGY VALUE (mills/kWh)
50
40
30
20
EFFECTIVE ENERGY VALUE (mills/kWh)
50
40
30
20
MINIMUM CONTACT AREA (km2)
MINIMUM FLOW PER BOREHOLE PAIR (kg/sec)
Tf = 150°c, Tw (AV) = 132°c
Tf = 200°c, Tw (AV) = 177°c
Tf = 250°c, Tw (AV) = 222°c
Tf = 300°c, Tw (AV) = 266°c
0
2
4
6
8 M$
TOTAL FGES INVESTMENT / BOREHOLE PAIR

Figure 2

possibility is now under thorough investigation including field testing by the Los Alamos Scientific Laboratory Dry-Hot-Rock Group in Los Alamos, N.M. (ERDA, 1976). In this note we will concentrate on the natural conductors. The results for the minimum contact area given in Fig. 1 and 2 will obviously apply to both cases (a) and (b).

The natural fluid conductors which have the potential of providing sufficient fluid-rock contact and some relevant data are listed in Table 1 below.

Due to great horizontal extent, major open fault zones and basaltic dikes have very large wall surfaces which in a sufficiently hot environment could be used for heat extraction provided an adequate and sufficiently uniform longitudinal fluid conductivity is available. It is to be emphasized that the fluid conductivity can be enhanced by an increased injection pressure.

Table 1

Potential Fluid Conductors

Type	Field observations on large scale fluid conductivity	Role in geoheat extraction
(1) Fault zones	Many major geothermal systems are controlled by faults, e.g. in the Basin and Range Province.	Borehole production obtained by intersecting fault zones.
(2) Basaltic dikes in flood-basalt areas	Many geothermal systems in Iceland are controlled by dikes.	Boreholes in Central North Iceland produce by intersecting dikes.
(3) Other intrusions	Few data available, but columnar structure possibly indicative of conductivity.	Some production in Iceland appears to be obtained from thin basaltic sills.
(4) Formation contacts	Lava-bed contacts are major aquifers in the flood-basalt plateau of Iceland.	Major production in Southwestern Iceland obtained from lava-bed contacts.
(5) Sedimentary horizons	Many major sedimentary basins contain large volumes of thermal water.	Large scale forced geoheat production from sedimentary basins in France (DGRST, 1976).

Factors Affecting the Efficiency of FGES

The estimates given in Fig. 1 and 2 are based on an idealized model. Deviations from the assumed conditions will in one way or another affect the results and will have to be considered carefully.

First, rock temperatures are generally not uniform. The water may therefore flow along rock surfaces where the temperature varies in the direction of flow. Second, the load on FGES will vary considerably, in particular in cases where the heat is to be used for building heating. A varying production rate will usually be required in such cases. A somewhat more elaborate computer modeling indicates that these two effects will not be of major importance and can quite easily be taken into account.

Of greater concern is the rather complex interaction of three phenomena affecting the flow of thermal water in subsurface natural conductors, viz., (i) natural flow channeling, (ii) thermoelastic effects and (iii) buoyancy of convective effects. The quantitative theory of these effects in the natural environment is both uncertain and basically difficult. By nature, these flow phenomena are nonlinear effects.

Table 2 has been designed to furnish a very brief qualitative overview of the adverse influence of the above three flow effects on the design factors listed in section (3) above.

Experimental Preliminary Design of a Sheet-Controlled FGES

The fluid conductors under (1) to (4) in Table 1 appear suited for the type of FGES under consideration. The basically horizontal conductors such as the formation contacts and intrusive sills have, however, very frequently the disadvantages of not being directly observable. Lack of field data can in such cases greatly reduce the possibilities for arriving at a rational design of the heat extraction system. This type of difficulty is of much less concern in the case of the quasi-vertical conductors, such as (1) and (2) in Table 1, where surface outcrops can be inspected. Quite frequently the position of such conductors can be mapped with considerable precision.

We have therefore chosen to base our first attempt at the design of a FGES on the assumption of a sufficiently open quasi-vertical conductor such as a basaltic dike or a fault zone. We make the *ad hoc* assumption that such a conductor is available. Depending on the position of the injection-production boreholes, the main flow in systems of this type can be vertically up (Fig. 3), vertically down (Fig. 4) or quasi-horizontal. Considering the various phenomena indicated in Table 2 there appear grounds for assuming that the up-flow systems will exhibit the highest degree of flow stability and thereby achieve the most favorable conditions for heat extraction.

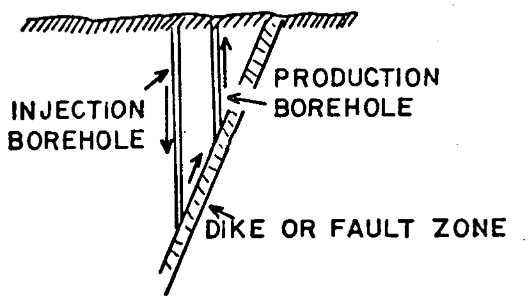


Figure 3. Upflow system.

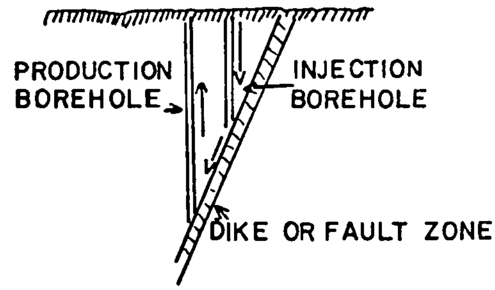


Figure 4. Downflow system

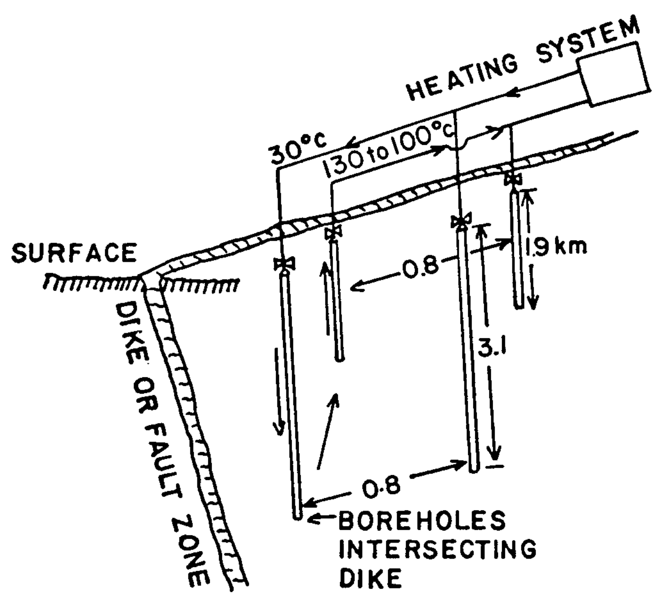


Figure 5. An experimental design of a multihole FGES system for building heating. The minimum flow per borehole pair is 25 kg/sec.

Table 2

Adverse flow phenomena

Type of phenomena	Potential effects: Inefficient heat extraction	Pumping power	Water losses
(1) Non-uniform conductivity, flow channeling	Potentially major factor	High pumping pressure may be required to overcome non-uniformity.	Can be a major factor in channeling injected cold water out of the heating zone.
(2) Thermoelastic effects	Enhances channeling of water colder than the rock.	Narrowing of fractures carrying water hotter than the rock requires increasing pumping pressure.	May increase water losses by enhanced channeling.
(3) Buoyancy and convection	Enhanced channeling in down-flow systems		Downward convective penetration of cold water may enhance losses.

A preliminary experimental design of a multihole upflow FGES is shown in Figure 5. The system is to produce water in the temperature range 130-100°C for building heating purposes. The system is envisioned to operate in an environment where the geothermal gradient is 50°C. The effective contact area per borehole pair is to amount to 0.5 km^2, the flow per hole is 25 kg/sec and the effective thermal power relative to an effluent temperature of 40°C is 3.1 MW.

Physical Parameters

The following rock and fluid parameters were used in the computations underlying Figures 1 and 2; rock thermal conductivity k_r = 2.1 W/(m.deg), density ρ = 2700 kg/m^3, specific heat of rock C_r = 1000 J/(kg.deg), and specific heat of water C_w = 4186 J/(kg.deg). The injection temperature was 30°C.

Epilogue

Having come to the conclusion that the estimated subsurface dimensions of the FGES under consideration are not unreasonable, our principal task will be to demonstrate that nature complies with our basic assumptions.

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