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A SECONDARY RECOVERY METHOD FOR THE EXTRACTION OF GEOTHERMAL ENERGY

Progress Report

by

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ABSTRACT

We are investigating the feasibility of forced geoheat extraction (FGE). The present report covering the period 8/76 to 2/77 is a continuation of the annual progress report issued in July 1976.

Computer programs have been written to carry out numerical modeling of the heat extraction by sheet-like conductors where the fluid flow is a function of time. New results on the effects of flow channeling have been obtained and we are devoting efforts to numerical modeling of convective flows. The fundamentals of the theory of fluid injection have been worked out and are being streamlined for application to simple cases. New results on minimum contact areas and borehole flows have been obtained.

Our previous conclusions that the contact areas required for economic operations of FGES are not excessive and within the possibilities of present-day technology remain unaltered. However, due to a number of intangible factors such as the possibilities for severe flow channeling, fluid losses, etc. a series of field experiments on natural conductors will have to be carried out before final conclusions can be drawn.

Due to the large thermal capacitance of rock surfaces, a combination of solar and FGE systems is an interesting possibility which is being investigated briefly.

(0) INTRODUCTION

The following is a six-month progress report (PR-II) for ERDA contract number EY-76-S-06-2227 entitled: "A Secondary Recovery Method for the Extraction of Geothermal Energy", covering the period 8/76 to 2/77. A progress report covering the period 7/75 to 7/77 was issued in July 1976 and will be referred to as PR-I.

Since the present report is an interim progress report, and we intend to prepare a detailed final report during June-July of this year, the following presentation will be limited to a brief description of present activities and results

(I) FUNDAMENTAL PROCESSES

(I.1) Heat extraction by a sheet-like fluid conductor

For problem definition and notation, we refer to sections (IV.1) and (IV.2) of PR-I and to the sketch in Fig. 1. Closed form analytical solutions for the fluid and rock temperature field can be obtained only in the case of a stationary, uniform and unidirectional fluid flow. Approximative and/or numerical methods have to be used in all cases where the flow varies with time.

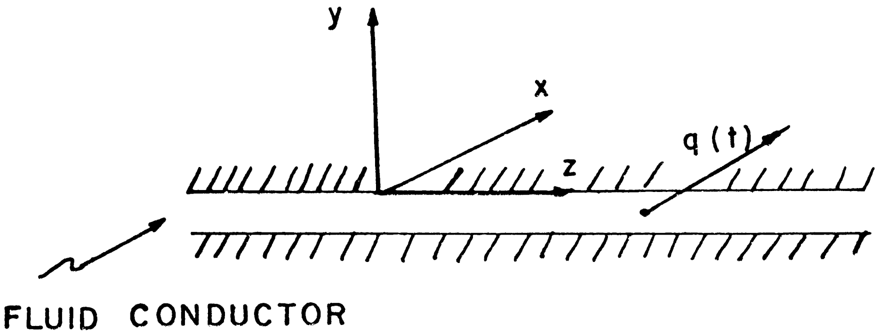

Figure 1

Mr. Chuen-Tien Shyu, graduate research assistant, has written a complete numerical finite-difference program which provides solutions for the fluid-rock temperature field in the case of an initial temperature $T_0(x) = f(x)$ and a flow (kg/m, sec) $q(t) = g(t)$ where $f(x)$ and $g(t)$ are given functions of the longitudinal coordinate x and time, respectively. The program provides solutions for a number of cases relevant to FGE.

(I.2) Numerical modeling of thermal convection

The numerical technique discussed in the previous section provides the basic tools for the application of the constrained-flow technique to a number of stability and flow-field problems in thermal convection. The method which was developed by Bodvarsson (1965) for porous media convection, and applied by Lowell and Bodvarsson (~~1972~~) to Rayleigh-type stability problems for viscous fluids, consists in an iterative approach starting with the assumption a zeroth order flow field based on physical reasoning. Having a given flow field, the associated conductive-convective heat transport and buoyancy forces can be computed enabling a first order flow field to be derived. The method provides quite satisfactory results for simple porous media convection cases. We are now testing the application of the method to thermal convection in fracture spaces which are relevant to the present FGE project.

(I.3) Flow channeling

The possible adverse effects of flow channeling were pointed out in section (IV.4) of PR-I. Mr. Jonathan M. Hanson, graduate research assistant on the project, has constructed the following model to investigate the implications of channeling for the heat extraction efficiency.

The stationary unidirectional flow varies periodically in the coordinate z perpendicular to the flow direction. The heat conduction equation for the solid retains the conduction term in the z-coordinate and the initial rock temperature is assumed $T_0(x) = (a + bx)$. A Laplace-transform Fourier-expansion technique is applied resulting in a set of coupled first order differential equations which are easily integrated using the unconditionally stable BDA = Backward Difference Approximation technique (see Isaacson and Keller, 1966). To invert the transforms a numerical technique by Gaver (1966) is used.

Examples for two flow channel configuration are given in Fig. 2. The FGE system involved is assumed to be an upflow system with an injection depth of 3 km and production depth of 2 km. The geothermal gradient is assumed to be 50°C/km, the disposal temperature 40°C and the injection temperature 30°C. The average flow density is the same for both channel configurations. Figure 3 compares the extraction thermal power (relative to the disposal temperature) for both cases with the uniform flow density case. Although the channeling assumed is quite severe, cross-flow heat conduction prevents a significant degradation of the thermal power relative to the uniform flow case.

(I.4) Fluid injection theory

To study the pressure flow phenomena associated with the injection of fluids into narrow fracture spaces, a theory of the propagation of the rock deformation and fluid pressure fields is being developed. In briefest terms, the fundamentals of the theory are the following. For notation, we refer to the sketch in Figure 4 showing a fracture in a homogeneous and isotropic type of linearly elastic rock.

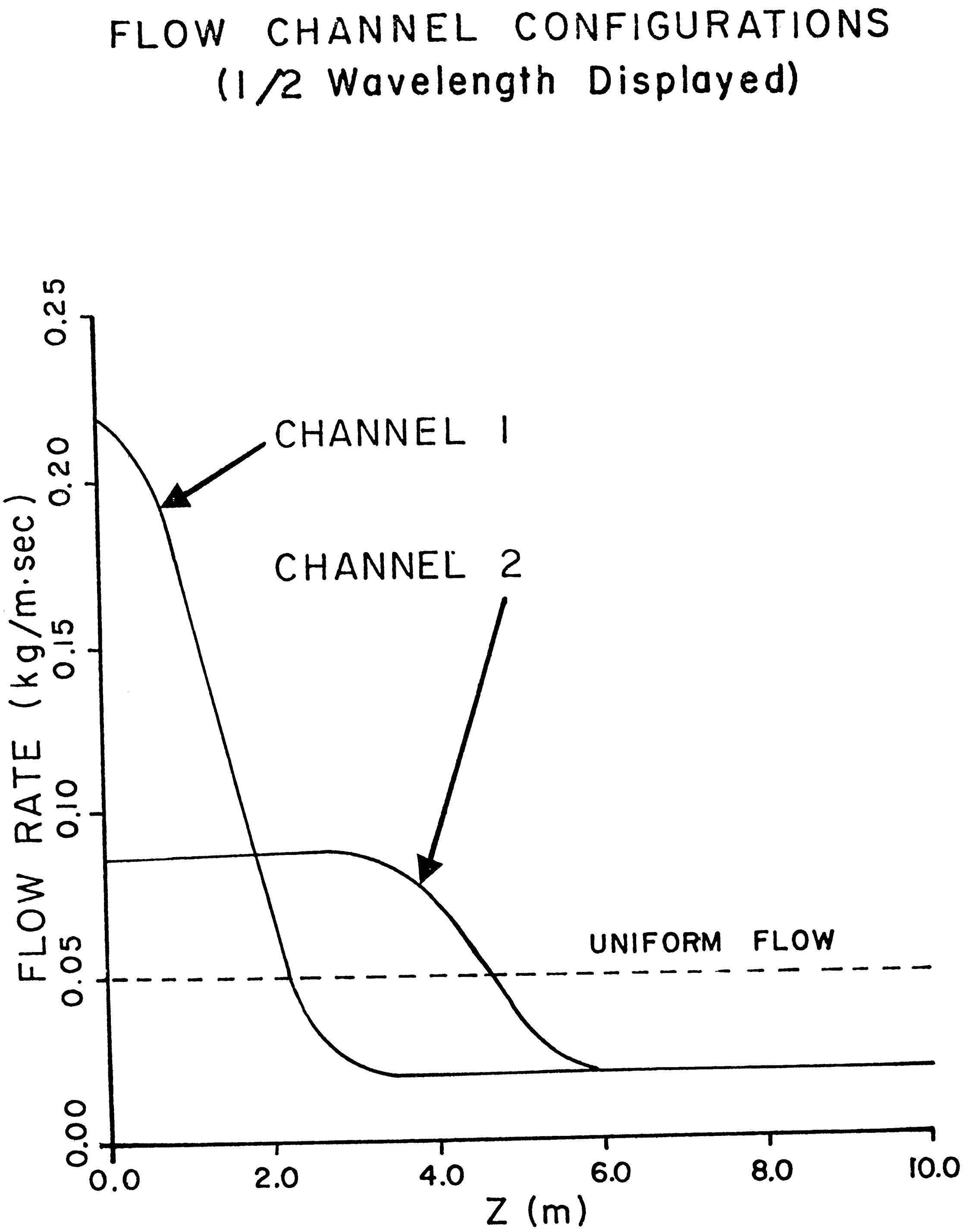
FLOW CHANNEL CONFIGURATIONS
(1/2 Wavelength Displayed)
FLOW RATE (kg/m·sec)
0.00
0.05
0.10
0.15
0.20
0.25
CHANNEL 1
CHANNEL 2
UNIFORM FLOW
0.0
2.0
4.0
6.0
8.0
10.0
Z (m)

Figure 2

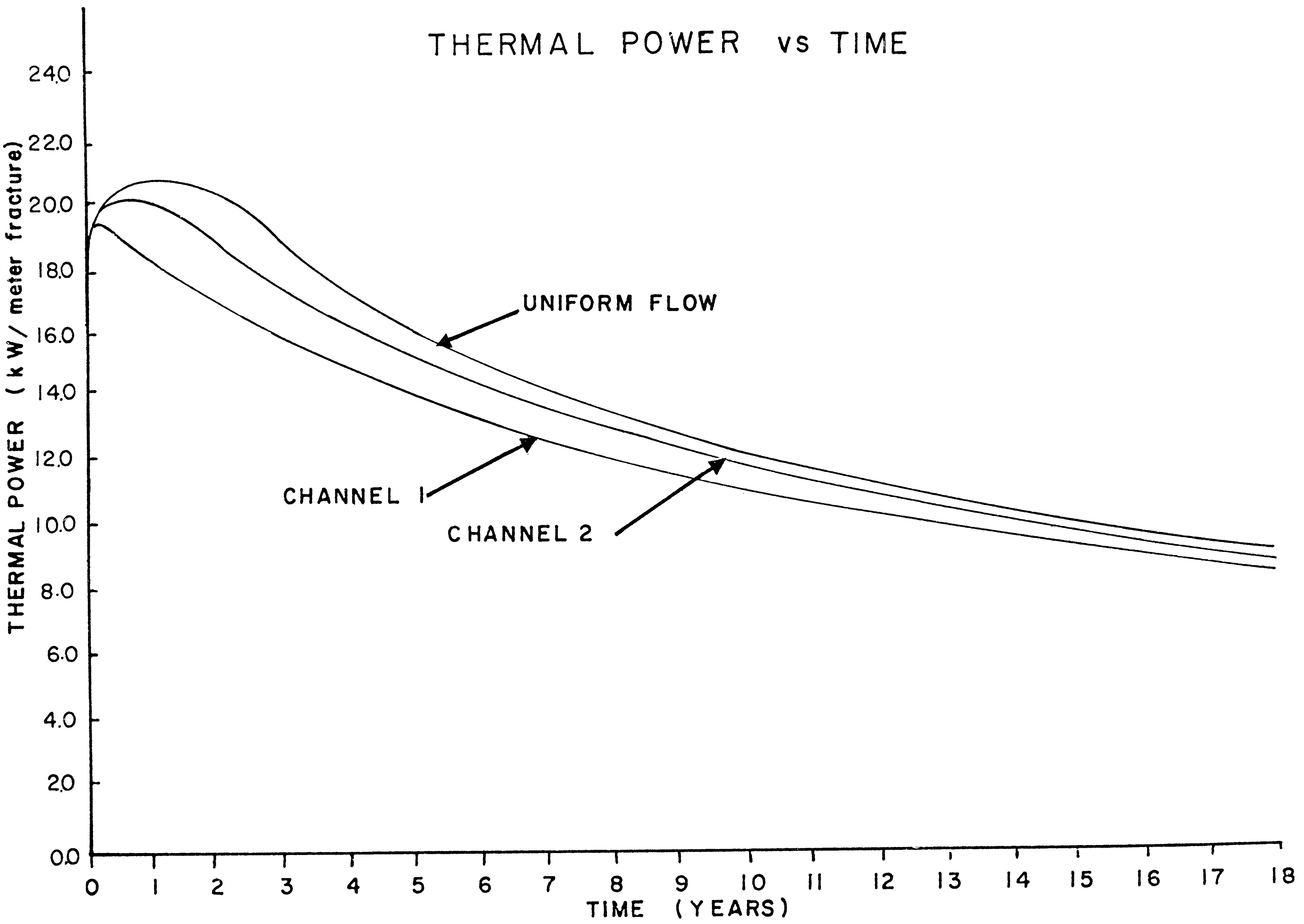
THERMAL POWER vs TIME
THERMAL POWER (k W/ meter fracture)
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
TIME (YEARS)
UNIFORM FLOW
CHANNEL 1
CHANNEL 2

Fig. 3

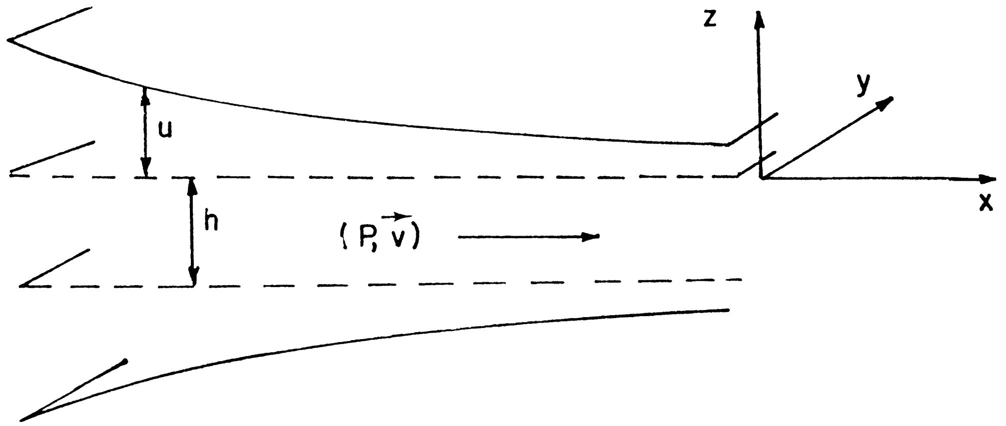

Figure 4

In equilibrium, i.e., when the internal pressure p is zero, the fracture is assumed to be plane and have a uniform width h. Let the coordinate axes be placed in one of the equilibrium surfaces with the z-coordinate into the solid. Increasing the fracture pressure to a positive value p, which is assumed constant over the fracture width, displaces each rock surface by an amount u (in the z-direction). Moreover, let $\vec{v}$ be the fluid velocity vector averaged over the fracture width.

In the case where the scale of variation in u is much larger than the effective fracture width (h + 2u), we can express the equation of motion for the fluid

$$\rho \frac{D\vec{v}}{Dt} + R(\vec{v}) = -\nabla_2 p \tag{1}$$

where D/Dt is the material derivative, $R(\vec{v})$ is an appropriate flow resistance function and $\nabla_2 = (\partial_x, \partial_y)$. Conservation of fluid mass requires that

$$\rho(h + 2u)\nabla_2 \cdot \vec{v} + 2\rho\partial_t u = F \qquad (2)$$

where F is the fluid source density. Using the approximation technique developed in Appendix E of PR-I, the relation between the fracture pressure p and the surface displacement u can be obtained on the basis of elementary potential theory. Using Poisson's relation for elastic solids ($\lambda = \mu$) and assuming that the fracture has a great extension in the $\Sigma = (x,y)$ plane, we find that

$$p(S) = -3\mu\int_{\Sigma} \partial_z G(P,S')\Big|_{z\to 0} u(S')da_{S'} \qquad (3)$$

where $S = (x,y)$, $S' = (x',y')$, $da_{S'} = dx'dy'$, $P = (x,y,z)$ and μ is the shear modulus. Moreover,

$$G(P,S) = z/(2\pi\sqrt{3}r^3_{PS}) \qquad (4)$$

when

$$r^2_{PS} = (x-x')^2 + (y-y')^2 + (1/3)z^2 \qquad (5)$$

Equations (1), (2) and (3) are our basic equations which form a non-linear system in the unknowns u, $\vec{v}$ and p.

A tremendous simplification is obtained when a small amplitude linearized theory can be applied. Assuming in this case that $|u|<<h$, the fluid flow is laminar and all second order terms can be neglected we find following an elimination a single equation in u

$$[\partial_t + (12\nu/h^2)][(1/h)F-(2\rho/h)\partial_t u] = -\nabla^2_2 Lu \qquad (6)$$

where ν is the kinematic viscosity and L is the integral operator on the right of equation (3).

Although equation (6) in linear in u, it is characterized by an unusual singular differential-integral operator on the right. Moreover, boundary conditions are rather complex and solutions are, therefore, not altogether easy to obtain.

In the case of fluid injection by boreholes, where F is a point source function, the pressure-flow regime can be divided into (i) a near-field and (ii) a far-field. The former is governed by the non-linear equations (1) to (3), whereas the latter is approximately governed by the linear equation (6). We are now investigating various possible methods of obtaining approximative solutions to the equations in the cases of models of practical interest.

(I.5) Thermoelastic effects

The long term aspects of the flow channeling and injection processes discussed in the previous sections are dominated by thermoelastic effects on the fracture widths. We are, therefore, looking further into the rather complex phenomena involved.

(II) ECONOMICS

(II.1) Minimum contact area and flow

Referring to our discussion in section (VII) of PR-I, we continue to regard the size of the fluid-rock contact area required to amortize the invested capital as a primary measure of the feasibility of FGES. Some contact area estimates were already presented in Tables 1 to 4 of PR-I.

In continuation of this work, new graphs giving further information on the contact area required as a function of the invested capital have been prepared. Figure 5 shows our results for building heating purposes

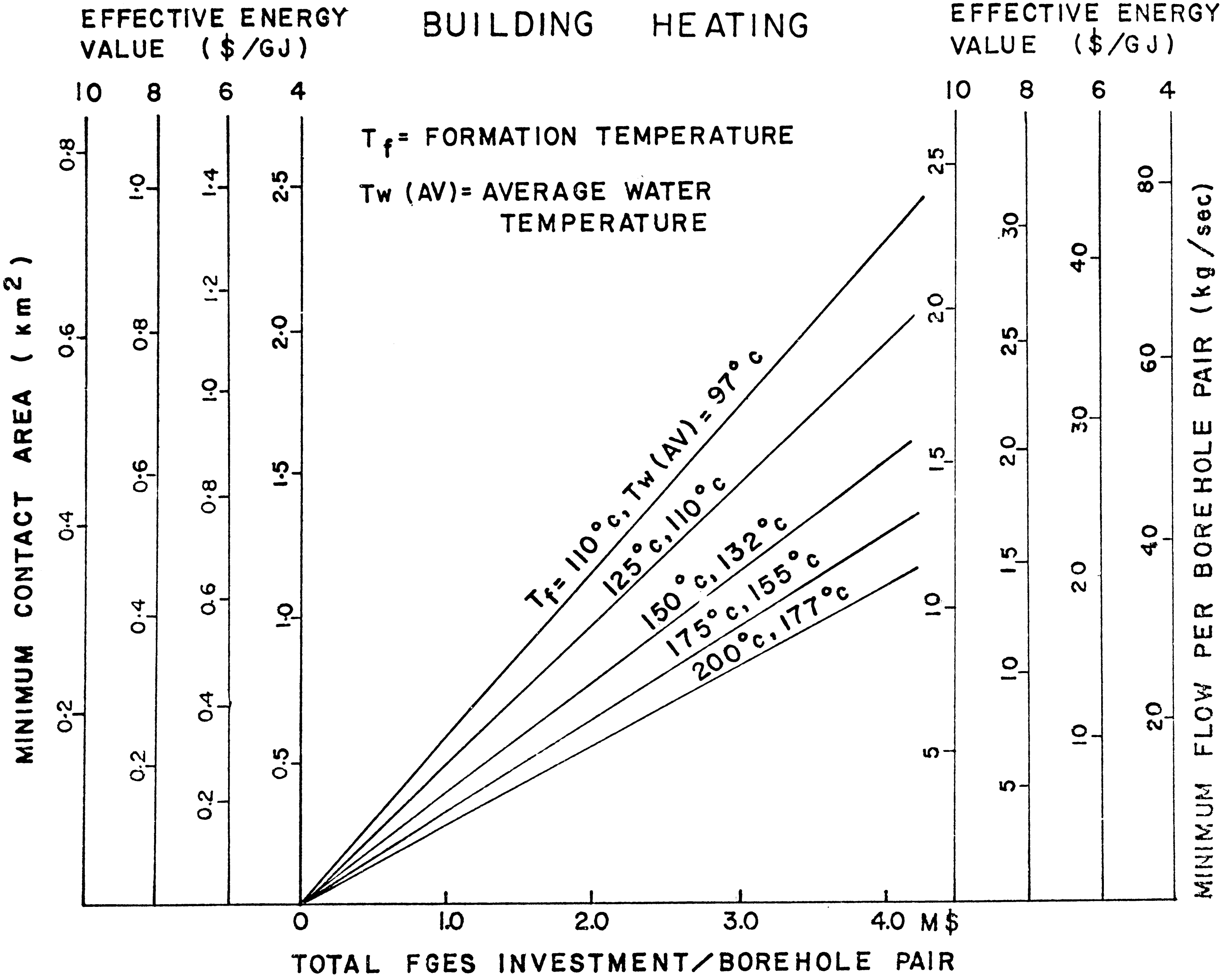
BUILDING HEATING
EFFECTIVE ENERGY VALUE ($/GJ)
10
8
6
4
EFFECTIVE ENERGY VALUE ($/GJ)
10
8
6
4
T_f = FORMATION TEMPERATURE
Tw (AV) = AVERAGE WATER TEMPERATURE
MINIMUM CONTACT AREA (km²)
0.8
0.6
0.4
0.2
1.0
0.8
0.6
0.4
0.2
1.4
1.2
1.0
0.8
0.6
0.4
0.2
2.5
2.0
1.5
1.0
0.5
T_f = 110°c, Tw (AV) = 97°c
125°c, 110°c
150°c, 132°c
175°c, 155°c
200°c, 177°c
25
20
15
10
5
30
25
20
15
10
5
40
30
20
10
80
60
40
20
MINIMUM FLOW PER BOREHOLE PAIR (kg/sec)
0
1.0
2.0
3.0
4.0 M$
TOTAL FGES INVESTMENT/BOREHOLE PAIR

Figure 5

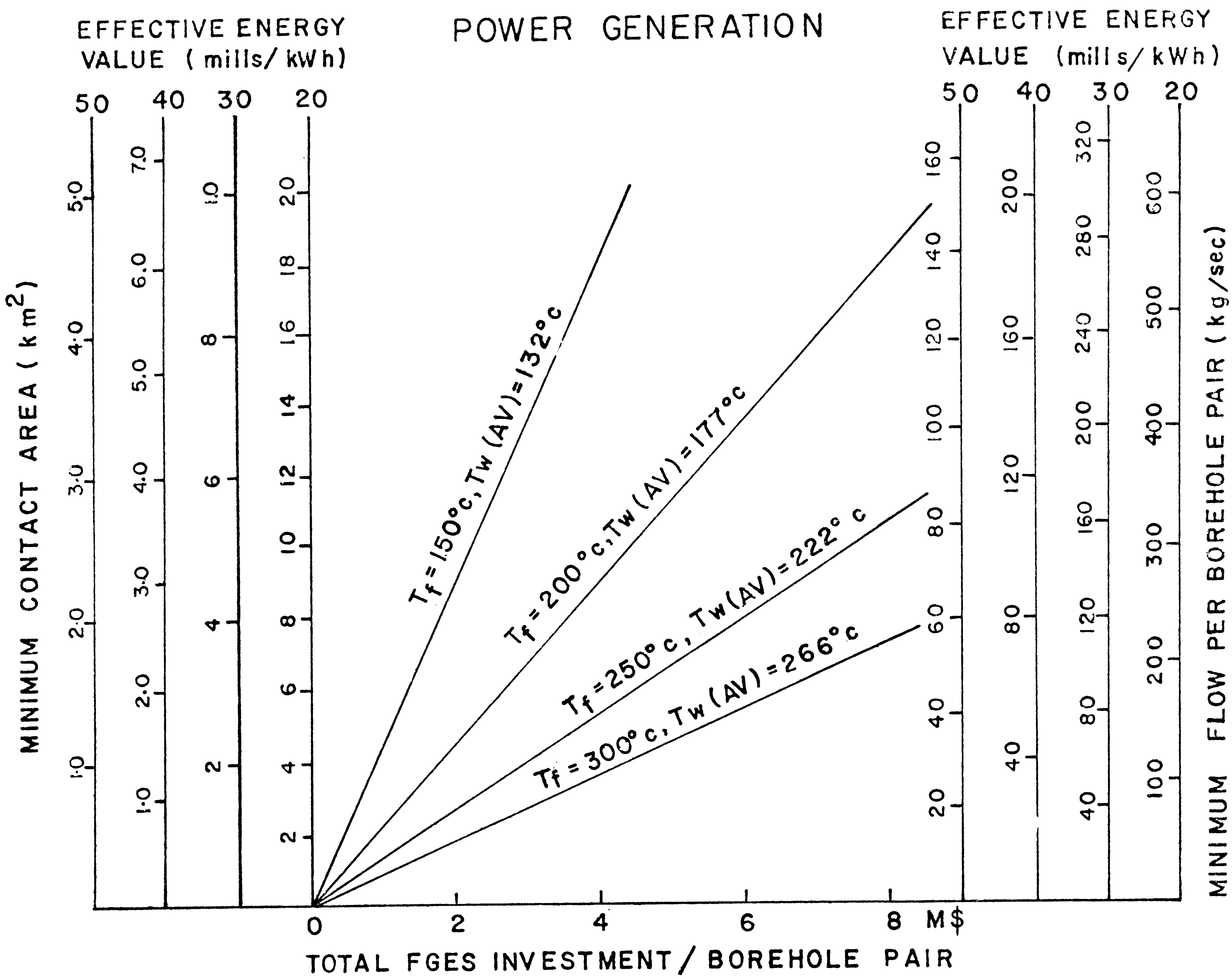
POWER GENERATION
EFFECTIVE ENERGY VALUE (mills/ kWh)
50
40
30
20
MINIMUM CONTACT AREA (k m²)
1.0
2.0
3.0
4.0
5.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
2
4
6
8
10
2
4
6
8
10
12
14
16
18
20
Tf = 150°c, Tw (AV) = 132°c
Tf = 200°c, Tw (AV) = 177°c
Tf = 250°c, Tw (AV) = 222°c
Tf = 300°c, Tw (AV) = 266°c
0
2
4
6
8 M$
TOTAL FGES INVESTMENT / BOREHOLE PAIR
EFFECTIVE ENERGY VALUE (mills/ kWh)
50
40
30
20
20
40
60
80
100
120
140
160
40
80
120
160
200
40
80
120
160
200
240
280
320
100
200
300
400
500
600
MINIMUM FLOW PER BOREHOLE PAIR (kg/sec)

Figure 6

and Fig. 6 for power generation. The new graphs, which also give the required flow per borehole pair, have been obtained on the basis of an interest rate of 8% and a total lifetime of 20 years. Since a higher interest rate and shorter lifetime were used in PR-I, the new graphs give a somewhat more favorable picture.

A noteworthy feature of the graphs in Fig. 5 is that in the case of building heating the flow per borehole pair is rather small. For example, assuming a formation temperature of 110°C at the depth of 2 km, a total FGES investment per borehole pair ranging from 0.5 to 1.0 M$ and an effective energy value of 5 $/GJ (gigajoule), which is close to the present value in the domestic market, we find that the required flow per borehole pair varies from about 7 to 15 kg/sec. These flow rates can be produced by relatively slim boreholes which open up to possibility of reducing the drilling costs by the use of slim-hole drilling equipment.

(II.2) Heat storage, combination of solar and FGES

The considerable thermal capacitance of the rock surfaces is implied by the results of sections (IV.3) and (VII.4) of PR-I. Large rock surfaces are capable of storing very substantial amounts of heat and can thus be applied as a long-term storage for off-peak or waste heat.

The combination of solar and FGES heating systems is a notable possibility. In many areas, the solar collectors can absorb a great amount of heat during the summer which the FGES can store for use during the colder periods of the year when little or no solar heat can be absorbed. Although it is beyond the scope of the present project, we plan to carry out a brief investigation of the economical aspects of the combined solar-FGES systems.

(II.3) Energy for pumping

It is of some interest to make a brief comment on the significance of the pumping power required for FGE operation. The FGES which are designed to produce energy for building heating have to draw on external electrical power for the operation of their pumps. Since a large proportion of available electrical power is generated by thermal processes, a complete picture of the overall FGE efficiency can only be obtained by including the heat expended for power generation in the overall system energy balance. To illustrate this matter, we will consider a numerical example.

Let a FGES produce water with an average temperature of 95°C and require circulation pumping against a total pressure of 50 bars. The electrical energy expended for pumping will amount to 2 kwh/metric ton of water which is equal to about 0.007 GJ/metric ton. Considering the generation and transmission efficiency this is equivalent to about 0.028 GJ/metric ton heat input at the power plant. Assuming, on the other hand, that an effective temperature differential of 50°C can be extracted from the water, the effective heat utilized is 0.2 GJ/metric ton. The heat expended for pumping power generation is thus about 14% of the total heat produced. This ratio is not insignificant and the heat equivalent of the pumping energy will thus have to be considered in the overall energy balance. We are faced with an energy production loop which degrades the system efficiency.

(III) OUTLOOK PRO TEMPORE

No results have been obtained so far which call for a modification of the main conclusions drawn in sections (VIII.1) and (VIII.2) of PR-I. At moderately high temperature gradients, and provided that nature complies reasonably well with our assumptions, the contact areas required for the

FGES under discussion do not appear excessively large. To throw further light on the situation, we can consider two rather extreme cases.

First, we will consider a very favorable situation involving a formation temperature of 110°C at the depth of one km. We will assume that a total drilling of 2 km (injection and production) has to be carried out in order to establish an average production temperature of 95°C for a period of 20 years. Moreover, we will assume that the drilling can be performed with slim-hole equipment and that the total capital investment per borehole pair may amount to 0.3 M$. Looking a few years into the future, we can expect in the building heating market an effective energy value of about 6 $/GJ. Using these figures, the graphs in Fig. 5 indicate a minimum contact area/borehole pair of 0.1 km^2 and a minimum average flow/borehole pair of 3.5 kg/sec. The total effective heat production during 20 years will be around 4×10^5 GJ which is sufficient to provide space heating and hot water for about 125 average Pacific NW residential houses (1800 sq. ft.).

Second, we consider a much less favorable situation with a temperature 110°C at the depth of 2 km and hence a total drilling of 5 km which has to be carried out with standard drilling equipment. Assuming relatively high unit drilling costs, the total investment per borehole pair is estimated at 1.5 M$. Based on the same average production temperature as above, and the present effective energy value of around 5 $/GJ, we find on the basis of Fig. 5 a minimum contact area/borehole pair of 0.6 km^2 and a minimum average flow/borehole pair of 20 kg/sec. The total 20 year effective heat production will be around 2.4×10^6 GJ which is sufficient to supply a total of 750 residential houses of the above type.

The two examples given above furnish a picture of the range of values which can be expected in FGES. In the case of building heating minimum contact areas have to be greater than 0.1 km^2 but values in excess of 0.5 km^2 are required only in unfavorable situations where FGES are unlikely to be feasible.

The principal difficulties of FGE technology are due to the possible adverse flow effects listed in Table 1 below.

Table 1

Adverse Flow Phenomena

	Potential effects		
Type of phenomena	Inefficient heat extraction	Pumping power	Water losses
1. Non-uniform fluid 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

Although analytical and numerical modeling is throwing considerable light on the phenomena listed in the table, it is quite evident that a clear reliable picture of the magnitude of the adverse flow effects can be obtained only by an actual testing of the natural fluid conductors in the field. At this juncture, the lack of such field data constitutes the principal deficiency of our investigations of the feasibility of an economical forced geoheat extraction for building heating purposes. Final conclusions can be drawn only on the basis of such data. A brief review of the necessary field work is given in section (IV) below.

(IV) FIELD DATA AND EXPERIMENTS

The field data of interest fall into two groups, viz., data on (i) the nature and physics of fluid conductivity in natural conductors and (ii) the response of the conductors to the injection of the heat extracting fluid.

The first category involves field observations on potential fluid conductors such as fault zones, dikes, formation contacts, intrusions, porous horizons, etc. Various hydrological, thermal and chemical data on natural geothermal systems are of interest in this respect and will supplement the direct observations. Moreover, mainly in the case of fault zones, present creep as indicated by seismicity is of considerable interest.

The second category involving the direct testing of the fluid conductors is of principal interest. The aim of the field tests is mainly twofold. On the one hand, we are interested in the elastic, hydrodynamical and thermal response of the conductors to the injection of the relatively colder fluid. Pressure response and long term changes in the local conductivity are of particular importance in the present context. The establishing of a circulation between two boreholes intersecting a conductor is, on the other hand, obviously the ultimate goal of the field tests. Heat extracting efficiency and fluid recovery can then be observed directly.

It is advisable to carry out the initial field testing at relatively favorable condictions. A clearly defined fault zone or dike with a low contact pressure and embedded in an environment of very low fluid conductivity and with a relatively high temperature gradient is to be preferred. Initial test depths of about 1 km at a formation temperature of no less than 60°C appear advisable.

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