MASTER

PERFORMANCE AND FEASIBILITY OF FORCED GEOHEAT RECOVERY FOR LOW TEMPERATURE APPLICATIONS

Final Report

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ABSTRACT

Forced geoheat recovery systems (FGRS) are potential sources of heat for low-temperature utilization such as building heating. Possible resource structures or reservoirs are (1) permeable sedimentary horizons in fairly deep basins, (2) formation contacts such as deep lava-bed contacts in flood basalt areas, (3) fracture zones or mafic dikes of sufficient permeability and (4) some other types of intrusions with sufficient permeability at depth. The heat can be extracted either in uniflow where there is no artificial recharge or by loop systems where the water is reinjected and circulated through the reservoir formations.

Three temperature ranges are of interest, viz., LT ranging from 15 to 45°C where the water can be used in heat pump assisted systems, MT waters from 45 to 90°C for direct use in forced air systems and HT from 90°C to 150°C where the water may be used for heating and air conditioning. The present investigation covers mainly the LT and MT ranges but the results are also relevant to the HT range.

The principal parameters determining the economic feasibility of FGR for building heating are the temperature of the source formations, productivity of wells, size of heat market, load conditions and capital costs. To achieve feasibility in the case of near normal geotemperature conditions in the Pacific Northwest, the heating market should absorb a thermal power of no less than 6 MWt at a minimal load factor of 0.6 corresponding to the base load heating requirements of a community of 5,000 housed in low-rise apartments. The production wells should flow no less than 40 kg/s. The minimum economic source temperature in the case of

heat pump assisted systems is then 40°C for uniflow and 52°C for loop systems. In the case of forced air heating systems the corresponding minimum source temperatures are 52°C and 70°C respectively.

We conclude that FGR systems are potential sources of heat for low-temperature utilization and that more effort should be devoted to the development of FGR technology.

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Tables in Supplement (X) and Appendix (XV) not included in list.

The following is a report on the OSU Forced Geoheat Recovery (FGR) Project covering the period April 1978 to June 1979. During this period the work has been funded by the U.S. Department of Energy under a project entitled: "Performance and Feasibility of Forced Geoheat Recovery for Low Temperature Utilization" (#EY-76-S-06-2227, TA #36). The report is a continuation of an earlier report by Bodvarsson and Hanson (1977) on a project entitled: "A Secondary Recovery Method for the Extraction of Geothermal Energy" (#EY-7-S-06-2227, TA #21) which was also funded by the U.S. Department of Energy for the period July 1976 to December 1977.

The present report falls into two main parts, viz., part (A) including sections (1) to (33) that is devoted to FGR resources and production technology and part (B) including section (34) to (42) covering the utilization of geothermal fluids in the temperature range 15°C to 150°C for building heating and industrial purposes. The two parts are then followed by part (C) that summarizes the essential results of our work. Part (A) of the report has been the responsibility of Gunnar Bodvarsson and part (B) of Gordon M. Reistad. Part (C) is a joint effort.

To facilitate the presentation of topics of essential interest, some of the more theoretical development of part (A) has been relegated to a Supplement consisting of section (29) to (33). Moreover, copies of a few published papers that are essential reference material are included in the Appendix consisting of sections (45) to (48).

The SI system of units is being used throughout part (A) of the report. Conventional engineering units are used in part (B). Unfortunately,

because of the multitude of topics treated it was impossible to retain an unique system of notation in part (A). A few letters denote each more than one physical quantity.

(1) Concepts in geoheat recovery

Geothermal wells may produce in artesian free-flow or the flow may be partially or totally enforced by pumping. Moreover, the production can be enhanced by hydraulic fracturing and/or artificial recharge by fluid injection into suitably located boreholes. In our terminology, the concept of forced geoheat recovery (FGR) refers to largely forced flow with or without further enhancement by fracturing and/or artificial recharge.

Clearly, on the above terminology, the Hot Dry Rock (HDR) Project now in vigorous development by the Los Alamos Scientific Laboratory of the University of California would also be defined as an FGR project. As will emerge below, however, there is really little overlap between the LASL and the OSU projects. The HDR project concentrates on the artificial fracturing of solid rock at very considerable depths to produce geothermal fluids of sufficient temperature for the generation of electrical power. The FGR project has more modest goals.

It is convenient to refer to FGR projects with no artificial recharge as uniflow systems and to systems with fluid injection as loop systems.

It is of some interest to point out that the bulk of the present world geoheat production is carried out in free flow based on natural

artesian or buoyancy head. In particular, this is the case in all high temperature areas ($> 150^{\circ}\text{C}$) now in production.

Flow enhancement by well pumping is, nevertheless, gaining in importance, and is now being carried out in a number of low-temperature geothermal areas, in particular, in Iceland where geoheat is widely used for building heating. Wells flows are 40 to 60 kg/s and since some of the wells would not produce in free flow, they represent cases of FGR. Because of a substantial fluid conductivity of the source formations, the drawdowns are, however, rather modest, viz., a few tens of meters.

The FGR systems now in operation in the Paris Basin in France (DGRST, 1976) are of particular interest to our work. This will be evident from the development below.

In the following, we will refer to the formations and structures where the water takes up heat as fluid conductors.

(2) Purpose of the OSU FGR project

The principal purpose of the present project is to investigate the technoeconomical feasibility of constructing uniflow and/or loop FGR systems that produce thermal water in the temperature range 15°C to 150°C . The emphasis is on field and market conditions in the Pacific Northwest. It is convenient to divide the above temperature range into three subranges:

(i) Low temperature (LT): 15°C to 45°C where the water is to be used as a heat source in heat-pump assisted heating systems,

(ii) medium temperature (MT): 45°C to 90°C where the water will be used directly for heating, and

(iii) high-temperature (HT): 90°C to 150°C where there are possibilities for using the water for both heating and air conditioning.

It should be noted that the present concepts of LT, MT and HT do not comply with some current terminology. For example, White and Williams (1976) (USGS Circular 726) refer to LT as $\leq 90^{\circ}\text{C}$, MT: 90°C to 150°C and 150°C and HT as $> 150^{\circ}\text{C}$. Our terminology has been chosen solely to serve the purposes of the present report.

Because of the limits on the manpower and effort that was set by the total funding of the project, we have chosen to devote our investigations into FGR feasibility largely to the LT and MT ranges where economical constraints are generally more critical than in the HT range. As a consequence, we have not looked into the possibility of combined use of HT waters for heating and air conditioning.

PART (A) RESOURCES AND PRODUCTION TECHNOLOGY

(II) RESOURCE TYPES AND HEAT RECOVERY

(3) Prospective resource structure

In selecting resource structures and fluid conductors for FGR, we are primarily interested in that (i) the natural fluid conductivity be adequate, or that an adequate conductivity could be induced by pressuring or fracturing, (ii) the formation temperature be sufficiently high and (iii) a sufficiently large rock/fluid contact area be available to extract the required amount of heat during a prescribed period of time.

The conductor structures that come into consideration fall into mainly three classes, that is (a) porous slabs, (b) thin-sheet fault zone or formation contacts and (c) fractured lava beds and some types of intrusions such as fractured dikes and sills. Some characteristics of the conductors and further information are given in Table A.I.

The sketches in Fig. A.1 and A.5 serve to illustrate the types of FGR systems that we envision for recovering heat from the above types of conductors. As indicated in Fig. A.3 and A.4 it is convenient to introduce the concepts of upflow and downflow in connection with the quasi-vertical fluid conductors.

(4) Heat recovery in porous media

The fundamentals of the theory of heat extraction in intergranular Darcy type flow are given by Bodvarsson (1974) (Section (45) of the Appendix). For many practical purposes, we can assume homogeneous/isotropic formations and non-dispersive flow with a pointwise rock/fluid

TABLE A.I

Potential fluid conductors for forced geoheat recovery

<u>Type</u>	<u>Field observations on large scale fluid conductivity</u>	<u>Role in geoheat recovery</u>
(a) <u>Porous-slab conductors</u>		
(1) Sedimentary horizons	Many major sedimentary basins contain large volumes of hot permeable rock.	Large scale FGR from sedimentary basins in France (DGRST, 1976), and stimulated production in Hungary (Boldizsar, 1975)
(b) <u>Thin-sheet conductors</u>		
(2) Fault zones	Many major geothermal systems are controlled by faults.	Borehole production obtained by intersecting fault zones.
(3) Formation contacts	Lava-bed contact are major aquifers in the flood-basalt plateau of Iceland (Bodvarsson, 1964).	Major production in South-Western Iceland obtained from lava-bed contacts.
(c) <u>Intrusions & lava beds</u>		
(4) Basaltic dikes in flood-basalt areas.	Many geothermal systems in Iceland are controlled by dikes (Bodvarsson, 1964).	Boreholes in Central North Iceland produce by intersecting dikes.
(5) Other intrusions and lava-beds	Few data available, but columnar structure possibly indicative of conductivity.	Some production in Iceland appears to be obtained from basaltic sills or lava-beds.

Figure A.1. Uniflow FGR system based on a horizontal porous slab fluid conductor.

Figure A.2. Loop FGR system based on a horizontal porous slab fluid conductor. Two types of borehole arrangements.

Figure A.3. Loop upflow FGR system based on a quasi-vertical fluid conductor.

Figure A.4. Loop downflow FGR system based on a quasi-vertical fluid conductor.

Figure A.5. Loop FGR system based on a horizontal thin sheet fluid conductor.

temperature equilibrium. Moreover, the mass flow is generally of a sufficient magnitude that macro-conduction effects (between grains) can be neglected. To obtain the major features of the temperature field, simple sweep theory is then applicable implying that we may assume that heat is being exchanged practically isothermally between the fluid and the rock. A unit volume of the fluid takes up heat from a rock contact volume of $V_c = C_f/C_r$ where C_f and C_r are the volumetric heat capacities of the fluid and the rock respectively. The sweep velocity of a mass flow m is $u = sm/C_r$ where s is the heat capacity of the fluid. In the case of water at temperature $T \leq 150^\circ\text{C}$ sweeping through common rock of moderate porosity, we can assume that on the average $V_c = 1.7 \text{ m}^3/\text{m}^3$ and $u = 0.0017m \text{ m/s}$. The calculation of the volume of rock required to heat a given mass of water is therefore extremely simple.

It is important that simple sweep theory is not applicable to obtain small scale details of the temperature field. Heat conduction results in thermal disperison and thereby a general smoothing of the field. Numerical details of the conduction smoothing of a temperature front are given in section (25) of the Supplement.

Even on a simple sweep theory, the modeling of the flow pattern in heat recovery in a loop type multi-borehole setting becomes numerically rather complex and closed analytical solution will often not be obtainable. Such problems will have to be solved by numerical methods.

In the design of multi-hole systems, we are primarily interested in the behavior of the production temperature as a function of time and/or total mass produced. In this respect it is useful to consider very

simple loop cases involving a single injection/production pair placed at a distance D . Referring to Section (26) of the Supplement we obtain for isotropic sweep type flows with a constant injection temperature and homogeneous rock temperature the following values for the breakthrough time, t_b , that is, the time when the first cold water arrives at the production hole.

Table A.II

Breakthrough Times in Sweep Flow

Flow Dimension	Breakthrough Time	
one	$t_b = DC_r/sm$	$m = \text{mass flow/unit area}$
two	$\pi D^2 C_r / 2sm$	$m = \text{mass flow/unit length hole}$
three	$0.75D^3 C_r / sM$	$M = \text{total mass flow}$

The one-dimensional case is added for comparison. Clearly, this case can be realized only with dense arrays of holes. The total temperature history of a loop well-pair in the two-dimensional (flow) case can be derived with the help of simple sweep theory. Omitting details of the computation, normalizing the injection temperature to zero and the rock temperature to unity, we obtain in dimensionless terms the results shown in Fig. A.6. Similar results, but in a slightly different context, have been given by Gringarten and Sauty (1975).

(5) Heat recovery in thin sheets

Fluids flowing through ultrathin sheets or fracture spaces take up heat by conduction from the walls. Macro-conduction is thus the dominant transport of heat in the formations and the mechanism of heat recovery is quite different from the sweep setting discussed above. The relevant theory is given by Bodvarsson (1974) (Sections (45) and (46) of the Appendix).

Figure A.6. Production temperature history of a loop well-pair in the two-dimensional sweep flow setting. Formation temperature normalized to unity and injection temperature to zero.

To summarize essential results, we consider the case of uniform and unidirectional flow of water through an ultrathin fracture. The flow is initiated at a fixed position at time $t = 0$. The bounding walls have a constant temperature T_0 and the temperature of the water entering the fracture is T_1 . Moreover, we assume that the water is recovered at another fixed position downstream with an end temperature $T_2(t)$. Let $r(t) = (T_2 - T_1)/(T_0 - T_1)$ be the end temperature ratio and Q be the mass of fluid which has been recovered per unit fracture area (both surfaces) between the inlet and outlet positions. Referring to Section (42) we find that

$$Q = 2.8t^{\frac{1}{2}}/f(r) \quad (A.1)$$

where $f(r)$ is the inverse error-function. The water mass is here measured in 10^3 kg/m^2 and t in years. Relevant graphs are given in Section (45). The data are easily applied in the estimating of contact areas required to produce a given mass of water during a given time and with a given end temperature ratio. Further results of interest are also given in Section (45).

Again, the modeling of the flow pattern and heat recovery in a loop type multi-borehole setting from ultrathin sheet spaces is more complex and will generally require a numerical approach. Here, we are also interested in the production temperature history of a two-hole loop system. Based on the same assumptions as in the previous paragraph, using the same notation, and the development in Section (26) of the Supplement, we obtain for an ideal injection/production hole pair the

Figure A.7. Production temperature history of a loop well-pair in the thin-sheet setting. Formation temperature normalized to unity and injection temperature to zero.

results displayed in Figure A.7. The results concur with those published by Gringarten and Sauty (1975), which have been obtained for a slightly different case.

(6) Heat recovery by an array of pipe-like channels

Obviously, the thin-sheet model introduced above is an idealization that will rarely represent the actual situation in nature. In particular, the fluid flow along the sheet will frequently be non-uniform, and the theoretical/numerical aspects of the heat recovery are then more complex than portrayed above. Although a generalization to non-uniform flows does, in principle, not present major difficulties, we will at this stage of our investigations refrain from an elaborate discussion of such cases. The matter should preferably be taken up at a later stage when indications as to realistic field cases are available.

For the present purpose, we will limit ourselves to briefly considering a simple but useful model that provides an insight into the effects of non-uniform flow on the overall performance of sheet-like fluid conductors. This model involves the case where the sheet is replaced by a grid of parallel pipes as shown in Fig. A.8. Let the diameter of the pipes be d , their spacing s and we assume that $d \ll s$. Other conditions are assumed to be the same as above.

To obtain an approximation to the performance of the pipes, we first consider the conduction of heat out of a semi-infinite half-space which has an uniform initial temperature T_0 and a boundary temperature zero. A simple exercise in heat conduction theory (Carslaw and Jager, 1959) gives the conduction of heat per unit area out of the solid at

Figure A.8. Grid of pipe-like channels.

Figure A.9. Effective strip-width of a single infinitely long pipe as defined by equation (A.8).

time $t > 0$

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$$h = T_0 k (\pi a t)^{-\frac{1}{2}} \quad (\text{A.2})$$

where a is the thermal diffusivity.

We can rewrite this equation in the following form

$$h = T_0 C \quad (\text{A.3})$$

where

$$C = k/l_r \quad (\text{A.4})$$

is the contact conductance per unit area and

$$l_r = (\pi a t)^{\frac{1}{2}} \quad (\text{A.5})$$

is the thickness of the boundary resistance. This parameter is a measure of the penetration of the surface temperature condition into the solid.

Moreover, we will also consider the heat recovery by a single infinitely long pipe of diameter d embedded in an infinite space. Assuming again that the initial temperature of the space is T_0 and that the surface of the pipe is kept at temperature zero from $t = 0$ on, we can use a result by Carslaw and Jaeger (1959, page 334) to compute the heat uptake by the unit length of the pipe $H(t)$. Using an approximation which is valid for $t > 250d^2/a$ or $N > 10^3$ we find that

$$H(t) = 4\pi k T_0 / \ln(1.2N) \quad (\text{A.6})$$

where

$$N = 4at/d^2$$

We can now take the pipe to be embedded between two half-spaces that have been welded together and that $H(t)/2$ flows from each space. Comparing

this heat flow with the result for the semi-infinite space given by equation (A.2) above, we see that the instantaneous heat flow extracted by the pipe is equivalent to the heat flow out of a strip of width b along the surface of each of the semi-infinite spaces such that

$$2bkT_0/(\pi at)^{\frac{1}{2}} = 4\pi T_0 k/\ln(1.2N) \quad (A.7)$$

and hence

$$b = 2\pi l_r/\ln(1.2N) \quad (A.8)$$

which for most practical purposes can be approximated by $b=l_r$, that is, the strip width is about equal to the thickness of the boundary resistance defined by equation (A.5) above. This simple relation is not valid for $N < 10^3$. Based on numerical results by Carslaw and Jaeger (1959), more general data on the strip width b are plotted against time in Fig. A.9 for a number of values of d .

Considering the data in Fig. A.9, a number of practically relevant conclusions can be drawn. Continuing with our previous assumption that $s \gg d$, we conclude that the (instantaneous) effective strip width swept by a single pipe increases with time. At times such that $l_r > s$, the boundary resistance thickness tends to dominate the total heat flow resistance and pipe grids with such spacings achieve an efficiency of heat recovery that approaches the ideal thin-sheet case. In other words, inefficiencies resulting from flow non-uniformities tend to decrease with time.

As a matter of course, this subject can be discussed at almost any length. However, since we have no field examples for specific consideration, a further elaboration appears premature.

(III) PRODUCTION MECHANICS AND FIELD REALITIES(7) Well mechanics

Turning to the more hydrodynamical aspects of FGR systems, we face a number of important questions. These are related to drawdown, injection pressure, pumping power required and, in particular, to the question of whether uniflow or loop systems should be selected at given field situations.

To derive the pressure drawdown at a production well, the following relations are quite useful. Let the total mass flow of the well be M and the total pressure drawdown be Δp . At laminar flow conditions we relate these quantities by

$$M = A\Delta p \quad (A.9)$$

where A is the admittance or productivity index. The derivation of the admittance in a special case is given in section (26) of the Supplement. Applying elementary potential theory to the case of Darcy flow in infinite homogeneous and isotropic solids of fluid conductivity C , the following expressions are derived for the admittance

Table AIIIWell Admittances

<u>Three dimensional flow</u>	<u>Admittance</u>	
Well opening into:		
Spherical cavity of radius R	$A = 4\pi CR$	(A.10)
Flat disk cavity of radius R	$8CR$	(A.11)
Cylindrical cavity of radius R and length $L \gg R$	$2\pi CL/\ln(L/R)$	(A.12)

Table AIII (cont'.)

Two dimensional axisymmetric flow

Well of radius R penetrating a layer of thickness H	$2\pi CH/\ln(D/R)$	(A.13)
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where D is the (rather ill-defined) distance to the edge of the drawdown cone around the well. In field cases, D is orders of magnitude larger than R.

Since the flow from narrow fractures into boreholes tends to be turbulent, the above relations can not be applied to such cases. For the case of a flat fracture of width h placed in a plane perpendicular to the axis of a hole of radius R, we can easily obtain the following result (Bodvarsson, 1976a)

$$M = 9hR[\rho\Delta p/(1+fR/h)]^{\frac{1}{2}} \quad (A.14)$$

where ρ is the density of the fluid and f is a friction factor which is in the range 0.02 to 0.05.

For the present purpose, it is instructive to look into the significance of the above relations by inserting a few values of practical relevance. Having in mind a uniflow FGR system based on a well of radius $R = 0.1\text{m}$ we assume that it produces water of 100°C in axisymmetric Darcy type flow from a horizon of total thickness $H = 100\text{ m}$ and a permeability of 10^{-14} m^2 or 10 millidarcy. Applying by pumping a total drawdown of $p = 50\text{ bar} = 5\text{ MPa}$, we derive on the basis of equation (A.13) above, that the total flow would be $M = 10\text{ kg/s}$. Here, we have assumed $D = 10^3\text{ m}$.

Considering, on the other hand, the case of a fracture of width $h = 10^{-3}\text{ m}$, or one millimeter, and assuming $f = 0.03$, we find with the

help of equation (A.14) on the basis of the same drawdown that $M = 35$ kg/s. The velocity of the water at the outlet of the fracture is 60 m/s. These results illustrate quite clearly the flow potential of single fractures.

All relations above apply to reversed flows, that is, to fluid injection also. As will be discussed below, we have in the case of fractures to consider that the width h quite possibly may depend on the well pressure.

(8) Flow stimulation

Pumping can be applied to stimulate well flow by increasing pressure differentials and by fracturing. Most frequently, the free flow accepted by injection wells is insufficient and they have to be operated by pumping. A number of questions arise as to suitable drawdown, well flows and well head pressures.

In the case of intergranular Darcy type flows, flow/pressure relations can usually be obtained with the help of equations (A.10) to (A.13) given in section (7) above. Barring extreme conditions, it is unlikely that the formation fluid conductivity is much affected by enhanced pressure differentials.

The case of fracture flow requires more consideration. Quite clearly, an enhanced drawdown may lead to reduced fracture width and, alternately, an enhanced injection pressure is likely to increase the width of the fractures accepting fluids. The parameter h in equation (A.14) will thus depend on the pressure applied. Unfortunately, the relations are likely to be quite site-specific and general results are apparently not available. The following two remarks are of interest in this connection.

First, a very simple relation is available for estimating the elastance of simple circular fractures of uniform width in non-gravitating Hookean materials (see Sneddon, 1946; Bodvarsson and Bjornsson, 1976).

Assuming that initially the fracture is closed with a contact pressure p_c , we find that by applying an internal fluid pressure $p > p_c$, the width h of a fracture of radius R in common crystalline rocks can be estimated by

$$h = 3 \times 10^{-11} R(p - p_c), \quad \text{SI} \quad (\text{A.15})$$

or

$$h = 3R(p - p_c)$$

where in the latter case h , for convenience, is measured in millimeters, p in bars and R in kilometers.

Second, referring to Jaeger and Cook (1976), we find that the horizontal stress at a depth z in a Hookean gravitating half-space with $g = 10 \text{ m/s}^2$ is approximately equal to $10^4 z$ Pa. Consequently, horizontal stress in a perfectly Hookean earth should be about equal to hydrostatic pressure and only very small over-hydrostatic fluid pressure would suffice to maintain open vertical fractures. Obviously, this relation is of considerable interest in the geothermal sciences.

Although Hookean under stresses of short duration, all rock formation are characterized by a long-term rheidity, and actual horizontal stresses in the earth will therefore invariably be greater than hydrostatic. The over-stress depends on physical and temporal parameters. Clearly, the overstress can be greatly reduced by horizontal strain such as in the Great Basin Province (Nevada, Oregon, Idaho and Utah). The regional stress situation is consequently of very great interest in FGR.

(9) System type

In comparing the merits of the two FGR system types, that is, uniflow and loop systems, a number of factors have to be considered. These relate, in particular, to overall economics and system reliability or stability.

Clearly, in terms of investment capital, uniflow systems have the advantage that only production boreholes have to be drilled. Relative to loop systems, the reduction of total investment may amount to as much as 40% to 50%. In many cases, however, environmental constraints require subsurface disposal and a number of injection wells, may, nevertheless, have to be provided to maintain a satisfactory operation. On some projects, it is possible that the drilling of wells for disposal and pressure maintenance may be delayed until some time after full operation has started.

Moreover, since operating only production wells, uniflow systems should generally be able to apply larger drawdowns than loop systems where both production and injection wells are pumped. There is, however, a limit to the drawdown that can be applied without endangering operation reliability, in particular, the production temperature stability.

Difficulties of this nature can result from a number of potentially adverse flow and thermal phenomena that have to be considered in the siting and design of FGR systems. These are the rather intangible field realities that would introduce a considerable element of uncertainty into the operation of prospective FGR systems. The phenomena are inter-related, very site-specific and their combined effects difficult to estimate, even semi-quantitatively. A brief discussion will follow.

(10) Adverse flow and thermal effects

To simplify and abbreviate our discussion to follow, the adverse flow factors and their potential effects are listed in Table A.IV for the case of uniflow systems and in Table A.V for loop systems. Below, we will very briefly consider the individual factors.

(i) Flow non-uniformities. A semi-quantitative picture of the effects of flow channeling and other non-uniformities can be obtained with the help of the material given in section (6) above. Considering the thin-sheet model as a basis, the essential result is that the relative adverse effects of stationary (in time) flow non-uniformities tend to decrease with time. Since the reservoir dimensions of FGR systems have to be designed such that they can still meet the thermal power demand at the end of their functional life, that is, when the boundary distance l_r is approaching its maximum value, it is quite likely that rather substantial flow non-uniformities can be tolerated without major consequences. In other words, it is probable that the reservoir system design can with some confidence be based on the uniform flow thin-sheet model without risking substantial difficulties due to flow non-uniformities. It is, nevertheless, advisable to make provisions for some effects of this type by introducing an appropriate recovery efficiency factor in the design procedure.

In these considerations, we have assumed that the flow non-uniformities are stationary. As we shall see below, this assumption may not be well justified.

TABLE A.IV

ADVERSE FLOW PHENOMENA IN UNIFLOW SYSTEMS

<u>Type of Physical Phenomena</u>		<u>Potential Resulting Effects</u>
(1) Non-uniform fluid conductivity, flow channeling.	Inefficient heat recovery increased thermal resistance and temperature differential.	All three phenomena (1) to (3) promote premature reservoir degradation and decline of the water temperature.
(2) Thermoelastic strain.	Enhances channeling of water colder than the rock.	
(3) Buoyancy and convection.	Vertical temperature instability and downward channeling of colder water from higher levels.	Relaxation or stabilization times of temperature/pressure fields increase with decreasing reservoir fluid conductivity and increasing depth of production.

TABLE A.V

ADVERSE FLOW PHENOMENA IN LOOP SYSTEMS

<u>Type of Physical Phenomena</u>	<u>Potential Resulting Effects</u>		
	<u>Temperature Degradation and Inefficient Heat Recovery</u>	<u>Enhanced Injection Pumping Power</u>	<u>Enhanced Water Losses</u>
(1) Non-uniform fluid conductivity, flow channeling.	Potential major factor. Increased thermal resistance and temperature differential.	High pumping pressure may be required to overcome non-uniformity in thin-sheet conductors.	Can be a major factor in channeling injecting cold water out of the zone of heat recovery.
(2) Thermoelastic strain.	Enhances channeling of water colder than the rock.	Narrowing of fractures carrying water hotter than the rock requires increased pumping pressure.	May increase water losses by enhanced channeling.
(3) Thermobuoyancy.	Enhanced vertical temperature instability channeling in down-flow thin-sheet systems.		Downward convective penetration of cold water may enhance losses.
(4) Deposits.		Potential factor.	Potential factor.

(ii) Thermoelastic effects and thermoelastic/flow interactions. To obtain a measure of the quantitative effects of the thermoelastic phenomena, we will consider an homogeneous and isotropic Hookean half-space with a free surface and the thermal expansivity α . We assume Poisson's relations, viz., the Lamé constants are equal. At time $t = 0$, the half-space has zero temperature and the surface is kept at temperature T from $t > 0$ on. Heat is thus being conducted into the half-space causing an expansion of the material. Based on results of Bodvarsson (1976b) and the boundary conditions applied by Hanson (1978), the following simple relation is obtained for the resulting outward displacement of the surface at time t .

$$u = 1.9 \times 10^{-8} T t^{\frac{1}{2}} \quad (\text{A.16})$$

where we have assumed $a = 10^{-6} \text{ m}^2/\text{s}$ and $\alpha = 2 \times 10^{-5}/^\circ\text{C}$. To illustrate the magnitudes involved, values of the ratio (u/T) are plotted against time in Figure A.10.

Hanson (1978) has considered the thermoelastic displacement of the fracture walls in a thin-sheet heat recovery model at specific conditions. The assumptions and results are displayed in Figure (A.11).

Consider now a fracture of width w in simple rock which at time $t = 0$ has a uniform temperature T_r . A fluid of temperature T_f flows through the fracture and, for convenience, we assume that the flow density is so large that T_f is essentially constant. The rock/fluid interchange of heat causes thermoelastic effects which affect the width of the fracture. Obviously, we have two cases, (i) $T_r > T_f$ where the

Figure A.11. Thermoelastic displacement of the fracture walls in a thin-sheet heat recovery model (Hanson, 1978). The initial formation temperature is assumed to be 150°C, the water inlet temperature 30°C and the flow density 0.05 kg/ms.

Figure A.10. Thermoelastic displacement of the surface of a heated half-space.

cooling and contraction of the adjacent rock leads to an expansion of the fracture, and (ii) $T_r < T_f$ where there is the reverse effect. The magnitude of these processes can be estimated on the basis of relation (A.16) above.

To consider a relevant example, let $w = 2$ millimeters and $(T_r - T_f) = 100^\circ\text{C}$. An application of equation (A.16) shows that the width of the fracture will be doubled in about 10^6 seconds, that is, around 12 days. The reverse effect where $(T_f - T_r) = 100^\circ\text{C}$ leads to a closure of the fracture in the same time.

Moreover, there are more subtle effects. Let the width w be non-uniform and the flow density be moderate such that there are significant temperature changes along the flow. Consider, for example, the case where $T_r > T_f$ and there is a groove in the fracture wall parallel to the flow. The effect of the groove is to concentrate the flow, and hence, reduce the local fluid temperature increase. The groove will therefore carry a colder fluid and be exposed to a greater rate of thermoelastic expansion than the surrounding parts of the fracture. The total effect is to enhance the flow concentration and thereby lead to a distinct channeling of the flow.

We have the reverse effect when $T_r < T_f$. The groove will then carry a hotter fluid and suffer a greater rate of contraction than the surroundings. There is a tendency to reduce the concentration and smooth the flow density.

In laminar flow driven by a pressure gradient of dp/dx , a fracture of width w will carry a mass flow per unit length of (see Lamb, 1932):

$$q = -(w^3/12\nu)dp/dx \quad (\text{A.17})$$

where ν is the kinematic viscosity of the fluid. This equation indicates the great sensitivity of flow resistance to the fracture width. We will immediately surmise that thermoelastic/flow interaction are extremely important. They are likely to be a dominant evolutionary factor in fractured hydrothermal systems. Unfortunately, since these phenomena are on a very small scale that is unobservable from the ground surface, we are here confronting one of the most uncertain and intangible factors in the mechanics of FGR systems, and, as a matter of fact, in all geo-thermal system theory.

One important remark is that the assumption of stationary channels made in the previous paragraph may be subject to very considerable doubt.

(iii) Thermobuoyancy. Since the temperature of natural systems increases with depth, there is a vertical thermal instability that may lead to convection. The systems become unstable when their fluid conductivity exceeds a certain minimum determined by the critical Rayleigh number. There are no major difficulties in deriving the critical conditions in porous media where Darcy type conditions can be assumed, and there is already a considerable literature in this field (see e.g. Beck, 1974). No comparable results have been obtained in the case of formations where the fluid conductivity is dominated by irregular fractures. Moreover, it is clear that it will be very difficult to develop any sufficiently general theory.

Since the withdrawal of fluid at depth lowers the local pressure, fluid production by wells is likely to enhance any instability. This is

of particular interest in the case of uniflow systems where large pressure drawdown would be contemplated. The thermobuoyancy effects may become quite serious and lead to the downflow of colder fluids from the formations above the thermal reservoirs. Unfortunately, the conditions are very site-specific and the problem is greatly aggravated where there is a fracture dominated fluid conductivity. Such cases will have to be discussed on a site-specific basis. The amount and time development of the pressure drawdown in production zones is of relevance in this respect and below we will therefore present a short review of this topic.

(iv) Convective downward migration of fractures. The downward migration of fractures is another phenomena that falls into the category of thermoelastic/flow interactions. Cold water tends to sink to the bottom of existing fractures. Cooling of the adjacent rock results in thermoelastic contraction that widens the fracture and may also enlarge its extent downward. The process can continue on the basis of either free or forced convection within the fracture. This phenomena is no doubt of a very considerable importance in the evolution of natural geothermal systems and will also have to be considered in the case of FGR loop systems.

It is quite difficult to produce any reasonable estimates of the rate of convective downward migration of fractures. The subject has been discussed by Bodvarsson (1978a). Very approximate results indicate a rate of a few meters/year.

Another way to consider this question is to realize the quite substantial thermoelastic contraction of the reservoir formations

resulting from heat recovery. Take a unit volume of rock of density ρ , heat capacity c and having a thermal expansivity α . Removing $C_r = \rho c$ units of heat results in a contraction of the magnitude $\Delta V = \alpha$. In other words, in the case of common rock where $C_r = 2.5 \times 10^6 \text{ J/}^\circ\text{Cm}^3$ and $\alpha = 2 \times 10^{-5}/^\circ\text{C}$ we find that

$$\alpha/C_r = 8 \times 10^{-12} \text{ m}^3/\text{J} \quad (\text{A.18})$$

The rate of contraction in a system of thermal power P will thus be $8 \times 10^{-12} P \text{ m}^3/\text{s}$. Take a system of rather moderate power $P = 100 \text{ MWt}$, we find that the contraction is $8 \times 10^{-4} \text{ m}^3/\text{s}$ or about $2.5 \times 10^4 \text{ m}^3/\text{year}$. Considering the small fractures widths involved, this is a substantial rate of contraction and is likely to be quite important for the evolution of reservoir fluid conductivity. Obviously, much of the contraction may result in subsidence, but a notable fraction may open up new fracture spaces and thus promote fluid conductivity.

(v) Drawdown in uniflow systems. To obtain order of magnitude estimates without a lengthy development, we will resort to discussing the case of a semi-infinite homogeneous isothermal porous solid with Darcy type flow conditions and a free fluid surface. We assume that the free surface is initially in equilibrium and that at time $t = 0$ the production of a mass flow M of fluid is initiated from a small (compared with depth) source-region at a depth d below the equilibrium position of the free surface.

A sufficiently accurate solution of the problem involved can be obtained by linearizing the free surface conditions (Bodvarsson, 1977,

section (47) this report). The principal physical parameter in this case is the free fall velocity of the fluid in the porous medium $a = Cg/\phi$ where C is the fluid conductivity as defined in sections (7) and (26), g the acceleration of gravity and ϕ the porosity of the formations. On these premises, we find (section (47)) that the stationary drawdown above the source point is

$$D_s = M/2\pi\rho gCd \quad (A.19)$$

and the time to reach 1/2 of D_s is

$$t_{1/2} = d/a = d\phi/Cg \quad (A.20)$$

The magnitudes that may be obtained in uniflow systems drawing on deep reservoirs are of some interest. Let the average system (and fluid) temperature be 75°C such that $a = 4 \times 10^{-7} \text{ m}^2/\text{s}$, the permeability be 10^{-14} m^2 or 10 millidarcy, the porosity be 10%, the production depth be $d = 3 \text{ km}$ and the mass flow be $M = 10^3 \text{ kg/s}$. For this condition, we find that

$$a = 2.5 \times 10^{-6} \text{ m/s}, \quad D_s = 200 \text{ m}, \quad t_{1/2} = 38 \text{ years}$$

The interesting result is the very long half- or relation time for the system. An equilibrium cannot be reached during a normal useful system life which would amount to 20 or 30 years.

(vi) Water losses. The loss of circulating water is a major technological and economical concern in the case of loop systems. Water is a commodity of some value and mechanical energy is being applied to inject it into the reservoir formations. Losses of water therefore enhance the consumption of mechanical energy per unit heat produced. These implications are listed in Table A.V.

Unfortunately, in most cases of loop systems there are really no ways of finding quantitative a priory estimates of water losses. Data of this nature can only be obtained the hard way by extensive field testing.

In the following, we will discuss a number of economic data and parameters that are relevant to our investigations into the feasibility of FGR systems. To obtain a reasonably clear picture of the situation, conditions on the energy and capital market are to be reviewed and future trends estimated such that a reasonable basis might be developed for decision making on economic feasibility. At this juncture there is rationale for applying different financial parameters to energy recovery, distribution and user systems. In general, the distribution and user systems can be taken to be under separate ownership and are therefore subject to different financing procedures. The discussion in this section will mainly be relevant to the energy recovery systems. The parameters relevant to the latter systems will be taken up for consideration in later parts of this report.

(11) Energy prices

Based on data compiled by our group (G. Reistad) and a report by Paddison et al. (1979), the following data can be taken to be representative of energy costs for building heating in the East and West of the U.S. as of January 1979.

TABLE A.VI

Energy Costs for Building Heating

	Assumed furnace efficiency	Trenton, NJ		Portland, OR	
		\$/GJ	c/kWhr	\$/GJ	c/kWhr
Natural Gas	80%	3.80	1.40	4.10	1.50
Fuel Oil	75	4.80	1.70	4.40	1.60
Electricity	100	13.50	4.90	7.00	2.50

The table gives average market prices as rounded off to the second digit. It is to be noted that $\$/\text{MBtu} = 0.95 \text{ } \$/\text{GJ}$.

Because of various supply/demand and political problems, it is impossible to provide any accurate estimate of the trend of energy costs during the coming one or two decades. In a current authoritative paper on the economics of solar heating, Bezdek et al. (1979) apply the following escalation rates which may provide reasonable estimates.

TABLE A.VII
Escalation of Energy Costs

Electricity and Fuel Oil	7%/year
Natural Gas	10%/year

In the present context, it is convenient to transform costs/unit heat to value/unit mass of thermal water. The graphs in Figure A.12 are being provided for this purpose.

(12) Cost of well drilling and completion

Well costs are a dominant cost factor in all FGR systems. It is therefore important to provide some data on the costs of drilling and completion that can be expected in the case of FGR systems. Obviously, well costs are strongly dependent on location and a number of factors that are not readily amenable to a priory estimates. Based on a modification of data provided by Milora and Tester (1976) and Bodvarsson and Reistad (1976), we provide the estimates for 1979 given in Figure A.13.

(13) Financial scenarios and economic feasibility

All studies of economic feasibility involve the process of discounting, that is, the translation of cost/income functions in time. For this purpose,

Figure A.12. Value per unit mass of thermal water as a function of cost per unit energy and effective temperature differential utilized.

Figure A.13. Estimated drilling and completion costs for FGR systems. Modified version of data provided by Bodvarsson and Reistad (1976) given by solid line (a) and by Milora and Tester (1976) given by shaded region.

we have to select the proper discount or interest rate. There is no problem in a stationary economy, since we will then equate the discount rate to an appropriate market rate.

The discounting at non-stationary conditions involving non-uniform inflation is on the other hand, a matter that has to be given some consideration, in particular, in the case of capital intensive projects. Unless corrections are made for inflation and specific price escalations under such conditions, the discounting at a market rate would lead to grossly misleading results. Among the various methods of coping with this situation, we will here consider three scenarios.

(i) The present scenario (PS) where present prices and interest rates form the basis for all econometric computations. No attempt is made to account for non-stationary situations such as variable future rates and prices.

(ii) A realistic scenario (RS) where future inflation and price escalations are estimated and appropriate corrections are made in the discounting process. Considering the present (3/79) economic situation and the figures given in Table A.VII, we arrive at the following data as an appropriate basis for the RS.

TABLE A.VIII

Estimated Financial Parameters for a Realistic Scenario

Nominal cost of capital, average equity and depth	11%/yr
Inflation rate.	7
Real cost of capital.	$11 - 7 = 4$
Nominal escalation of energy prices, average fossil fuel & electricity.	8.5
Discount rate for energy.	$11 - 8.5 = 2.5$

(iii) A stationary scenario (SS) based on an appropriate real interest rate and neglecting inflation and price escalation. Here, we select the real rate of 4% as displayed in Table A.VIII. Although unrealistic from the microeconomical point of view, the SS is, nevertheless, of some relevance. It reflects the conditions in an ideal economy free of inflation. As a matter of fact, from the macroeconomical point of view, inflation is a perturbation that is external or unrelated to the technology of energy production. There is some rationale for optimizing production systems with regard to the SS. This approach is, in fact, applied in a recent paper on Hot Dry Rock energy extraction (Cummings et al., 1979).

Since actual cash flow takes place in the RS it is evident that economic feasibility should preferably be decided within such a framework. Clearly, the reliability of the estimates for the future trends of the financial parameters is then a matter of major concern.

(14) Econometric optimization

Practically all design requires some optimization or balancing of tradeoffs between variables. In the field of energy recovery there is a considerable number of problem settings related to system optimization that is more or less equivalent to the minimization of the cost per unit energy produced. In many cases the problems involved are complex, quite site-specific and a general discussion would be beyond the bounds of the present report. In the following, we will therefore limit our discussion of this topic to pointing out three fundamental problem settings that frequently arise in the context of resource utilization and energy recovery.

(i) Non-resistive resource. Consider first the case of a well-defined non-resistive resource of known finite magnitude that can be totally recovered at any chosen rate. In the present context this could, for example, be the amount of heat contained in a well-defined finite volume of isothermal fluid saturated porous rock where simple one-dimensional sweep theory (see section (4)) could be applied. Let the total amount of available heat be H and the net market value per unit heat be v such that the total resource value would be $F = Hv$. Our definition of net value is the gross market value reduced by all direct system O&M (operational and maintenance) costs as measured per unit heat delivered. Assuming that there is a sufficient market to absorb the heat at the value indicated, the question arises as to the optimal rate of recovery. In other words, how fast should the resource be utilized.

To simplify our development, we assume that the recovery proceeds at a constant rate or power P for a total time t_0 such that $H = Pt_0$. The yearly total net income is then Pv . Moreover, we assume that the total capital to be invested in a plant of power P is $C(P)$, and relying on some econometric empirics, we take that we can express $C(P) = BP^n$ where B and n are constants. In other words, the total plant costs are proportional to P^n . In the case of many energy related plants we can frequently take that $n = 1/2$ is a reasonable assumption. The most appropriate value of the exponent is, however, not of major concern here.

Let r be the interest rate and $D(r, t_0)$ be the discount factor that translates the total future net income during the total lifetime of the project to its present value. In the present context it is convenient to apply continuous discounting such that

$$D(r, t_0) = (1/t_0) \int_0^{t_0} \exp(-rt) dt = (1 - \exp(-rt_0))/rt_0 \quad (\text{A.25})$$

There is a choice among a number of criteria for econometric optimization. We will not dwell on this rather intriguing matter, but decide on the criterion that would appear to be most relevant to FGR systems, that is, the maximization of the present value of total system lifetime profits. Our econometric problem then consists in deriving the optimal t_0 that

$$\max_{t_0} [HvD(r, t_0) - B(H/t_0)^n] \quad (\text{A.26})$$

for given values of v , H , r , n and B . Provided that these values satisfy the condition $nC < Hv$ such that a maximum exists, that is, the project is feasible, a graphical illustration of this relation is given in Fig. A.14 below. The graphs illustrate the functional relationship and the position of the maximum is indicated. Generally, such maximums are quite flat. The maximization of (A.26) can be carried out with the help of graphical, analytic or numerical techniques.

(ii) Resistive resource. Our second example involves heat recovery from a resistive source at a rate P which is determined by market conditions and is taken to be constant during an operational time t_0 . This would, for example, be the case involving heat recovery by a loop FGR system from a thin-sheet structure. As indicated in Fig. A.7 the resistance to heat conduction in the adjacent rock results in a decline of the production temperature with increasing operational time. At a constant flow rate, the thermal power or rate of heat recovery declines with time. Hence, a major design consideration will be that the system can meet the power demand near the end of the prescribed period t_0 . Because of the decline characteristics, the amount of capital equipment, wells etc., required to maintain

Figure A.14. Optimization of the recovery period for a non-resistive resource.

Figure A.15. Optimization of the recovery period for a resistive resource assuming a fixed rate.

Figure A.16. Optimization of the depth of recovery.

the thermal power will increase with t_0 . Because of the decline characteristics, the amount of capital equipment, wells etc., required to maintain the thermal power will increase with t_0 . Hence, we have to assume that the total capital investment C is a function of t_0 . Here, it is again convenient to use the functional form $C(t_0) = Et_0^m$ where E and m are constants. The constant E is taken to include also the functional dependence of the capital on the power that was assumed in (A.26) above. The optimization is then equivalent to finding

$$\max_{t_0} [Pt_0 v D(r, t_0) - Et_0^m] \quad (A.27)$$

for the given values of P , v , r , m and E . Again, these parameters have to satisfy the condition $mrC < Pv$ such that a maximum exist and the project be feasible. The essential relations are illustrated in the graphs in Figure A.15 where also the position of the maximum or optimum is indicated.

(iii) Optimal resource depth. At normal upper crustal conditions with conduction dominated heat flow, the temperature rises approximately linearly with depth. The production temperature of FGR systems can thus be expected to rise approximately linearly with the reservoir depth. Moreover, since the enthalpy of water is approximately a linear function of temperature, we expect that the production enthalpy and thereby the water value will likewise be linear functions of the depth.

As indicated in Figure A.13, drilling costs, on the other hand, increase with depth at a rate that is faster than linear. Assuming other system parameters constant, there will consequently be an optimal production depth below which the gain in enthalpy and water value will be more than

offset by the increase in well costs. The optimal resource or production depth is obviously a concept of importance in FGR system design. Below, we will give a brief method of estimating this optimum.

Consider a FGR system that produces water at a constant temperature and at a constant rate for a period t_0 . Let the total mass produced during t_0 be G and the net value per unit mass be expressed by $b(z-z_0)$ where z is the production depth, b is a constant and z_0 is a limiting depth above which the water is of no value. Moreover, let the total system costs be expressed by a quadratic function in depth (see Bodvarsson and Reistad, 1976)

$$(d + ez + fz^2) \quad (A.28)$$

Applying the same procedure and notation as above, the problem now consists in deriving

$$\max_z [Gb(z-z_0)D(r,t_0) - (d + ez + fz^2)] \quad (A.29)$$

The derivation of the depth that maximizes the present value of profits is elementary and provided a positive maximum exists the result can be expressed by the simple relation

$$z_{opt} = (GbD(r,t_0) - e)/2f \quad (A.30)$$

Obviously, the numerics of this relation will be very site-specific and will have to be discussed on a case basis. The expression (A.29) is illustrated in Fig. (A.16).

(15) Net energy and the energy loop

All energy producing systems consume an amount of energy for internal purposes. In the case of FGR systems, the internal consumption is mainly

in the form of mechanical energy for pumping of wells and fluid transport. The systems can thus only produce a net output and it is important to consider the economic implications, in particular, because the mechanical energy is in most cases derived from thermal plants where the conversion efficiency is severely limited by the second law of thermodynamics. We will briefly look into the total energy balance of FGR systems where the total thermal energy expended for internal purposes is also considered.

The elementary flow sheet of an FGR system is portrayed in Figure A.17 below. Cold water is being pumped into a reservoir where it is heated to a suitable temperature and distributed to the market. To account numerically for the total internal consumption, we assume that for each unit heat gross an amount of heat x has to be expended to provide the mechanical energy for pumping. In our total balance, where we ignore (temperature) quality, this amount of heat is taken to be equal to the heat consumed at the thermal power plant supplying the mechanical power. The net heat output from the FGR plant is then $(1-x)$ for each unit heat gross produced.

Figure A.17. The energy loop of FGR systems. For each unit heat produced, x units are used for pumping.

Let the cost of the unit power gross in the FGR plant be C . The total costs per unit power net will then be

$$C_{\text{net}} = C/(1-x) \quad (\text{A.31})$$

This very simple expression portrays the economic implications of the energy loop sketched in Figure A.17. Since the overall efficiency of thermal power plants is 0.25 to 0.35, it is quite obvious that the internal consumption may be a significant factor. To take an example, let an FGR system produce thermal water at 85°C and assuming that a temperature differential of 40°C is being utilized, the useful energy content of the water is 0.17 GJ/10³kg. If the total FGR pumping head is 100 bar, that is, 10 MPa, the total mechanical energy expended will be 0.01 GJ/10³kg. Assuming an overall thermal power plant efficiency of 0.3, we obtain a value $x = (0.01/0.3)/0.17 = 0.2$ and hence $1/(1-x) = 1.25$. The internal energy consumption has therefore significant implications.

At this juncture, a substantial lack of field and economical data prevents us from direct practical applications of the relations set forth in section (14) and (15) above. The results are, nevertheless, of conceptual importance and help to clarify the econometrics of FGR systems.

(V) MINIMAL SYSTEMS AND DESIGN EXAMPLES(16) Minimal systems

Since the capital costs of FGR systems include components that are largely independent of the thermal power, it is clear that there is a definite lower economical limit to the capacity of all types of systems. The dimensions of the minimal systems are parameters of considerable interest to FGR technology, and this topic will therefore be explored to some extent. In the following, we will provide estimates of the minimum power and source dimensions of various types of FGR systems.

We will continue using the notation introduced in section (14) above. Moreover, let ϵ be the system load factor, M the peak mass flow, G the total mass of thermal water produced during the lifetime t_0 and therefore $G = \epsilon M t_0$. If ΔT is the temperature differential utilized by the consumer, then $P = s M \Delta T$ and the value of the water is given by $b = s v \Delta T$.

In the case of porous intergranular flow reservoirs, V will be taken to be the total contact volume required to produce the mass G , that is, assuming simple sweep-theory $V = s G / C_r$.

Turning to thin-sheet systems, Q will be taken to be the mass of water that can be obtained from the unit contact area during t_0 at some prescribed end temperature ratio. This quantity is given by equation (A.1) in section (5) above. Moreover, let A be the total contact area required for system operation during the time t_0 and hence $A = G / Q$.

Let C again be the total capital costs of a FGR system and P be the (constant) minimum economic thermal power that must be sustained during a time period t_0 to amortize the capital invested. Taking the discount factor as defined by equation (A.25), our basic equation is then

$$\epsilon P t_0 v D(r, t_0) = C \quad (A.32)$$

Given the net value of the heat v , the load factor ϵ , the total lifetime t_0 and the interest rate r , this equation defines the minimum power P . Assuming a load factor of unity and a lifetime of $t_0 = 25$ years, equation (A.32) is illustrated graphically in Figure A.18, where the power P is plotted against the capital costs C and the heat value v with the interest rate as a parameter. A similar plot of the flow M against the capital costs and value b per unit mass of water is given in Figure A.19. Finally, the plot in Figure A.19 is rearranged in Figure A.20 to illustrate the water value b as a function of M and C .

The case of porous intergranular flow reservoirs is taken up in Figure A.21 where the total contact volume required to operate the system for $t_0 = 25$ years is plotted against the capital investment and the water value b . Moreover, along the same lines, the total contact area needed in thin sheet-sheet reservoirs is plotted in Figure A.22.

(17) Design examples

To illustrate the order of magnitude of the surface dimensions of simple FGR systems of some economical significance, we have chosen to sketch hypothetical designs of the two types discussed above, each producing water at 70°C for building heating. The systems are taken to generate an effective power of 6 Mwt, which at an availability or load factor $\epsilon = 0.5$, is sufficient to meet the base heating demand (about 80% of total) for a community of about 4×10^3 inhabitants located in the Pacific Northwest of the United States of America. The systems operate in an

environment where the average surface temperature is 10°C and the geotemperature gradient is assumed to be 31°C/km.

The porous-slab system sketched in Figure A.23 recovers heat from a porous horizon of 0.2 km thickness embedded between the depths of 1.9 and 2.1 km. The total effective contact volume required for 25 years of operation is $5 \times 10^7 \text{ m}^3$. The flow $M = 50 \text{ kg/s}$.

The thin-sheet system sketched in Figure A.24 is supposed to recover heat from a quasi-vertical fault zone or dike of sufficient natural or artificially induced fluid conductivity. The system has two injection production borehole pairs flowing 50 kg/s and the total effective contact area required for an operational period of 25 years is 1.2 km^2 .

A considerable amount of work on FGR minimal systems has been carried out by Hanson (1978). His results show minimal contact areas and optimal depths for a range of assumed field conditions.

Figure A.18. Minimum economic thermal power of FGR systems that are operational for 25 years as a function of invested capital, net heat value and interest rate.

Net heat value v is defined as the price of unit effective heat to the production system reduced by the operational and maintenance costs of the FGR system as measured per unit heat produced.

Figure A.19. Minimum economic mass flow of FGR systems that are operational for 25 years as a function of invested capital, net water value and interest rate.

Net water value b is defined as the price of the unit mass thermal water to the production system reduced by the operational and maintenance costs of the FGR system as measured per unit mass water.

Figure A.20. Minimum economic net water price for FGR systems that are operational for 25 years as a function of invested capital, mass flow and interest rate. The yearly load factor is taken to be equal to unity.

Figure A.21. Minimum economic contact volume for porous slab FGR systems that are operational for 25 years as a function of invested capital, net water value and interest rate.

Net water value b is defined as the price of the unit mass thermal water to the production system reduced by the operational and maintenance costs of the FGR system as measured per unit mass water.

Figure A.22. Minimum economic contact area for thin sheet FGR systems that are operational for 25 years as a function of invested capital, net water value and interest rate.

Net water value b is defined as the price of the unit mass thermal water to the production system reduced by the operational and maintenance costs of the FGR system as measured per unit mass water.

Figure A.23. Experimental design of a (minimal) porous slab FGR system to operate in the Pacific Northwest.

Figure A.24. Experimental design of a (minimal) quasi-vertical thin-sheet FGR system to operate in the Pacific Northwest.

(VI) PROSPECTIVE RESOURCE AREAS

In searching for prospective FGR resource areas in the USA, we have relied on the concepts and material set forth in section (3) and (5) above. Such source structures as sedimentary basins, flood-basalt areas, fracture zones etc., are obviously of central interest. In our search, we have concentrated on the Pacific Northwest and the state of Oregon, in particular, but have also made a first preliminary survey of the northern parts of the USA. As far as sedimentary basins are concerned, we have limited our initial targets to basins that are deeper than about 3 km.

Mr. Greg Mack, graduate research assistant, Department of Geology, OSU, has been mainly responsible for our search of prospective resource areas.

(18) Resource areas in the Pacific Northwest

The sedimentary basins and flood-basalt areas of FGR interest in the states of Idaho, Oregon and Washington are displayed in Figure A.25. The same figure also shows the Klamath Basin which is a graben structure of rather different nature than the sedimentary basins. This graben is of considerable interest. It is bounded by very conspicuous master faults and harbors one well-known KGRA at Klamath Falls. Some heat-flow and temperature data for Oregon supplied by Dr. David Blackwell, SMU, are displayed in Figure A.26 and A.27.

Further geological data on the Willamette and Lower Columbia Basins are given on inserts at the end of this report.

A discussion of the geological/technological specifics of the individual resource structures is beyond the bounds of the present project. Since

thermal water can for economical reasons be transported only over relatively short distances, market availability and economics is an important consideration. The structures that underlie or are close to major heat markets such as the Willamette and Lower Columbia Basins are obviously of major interest.

(19) Middle and northern USA

In our search for resource areas over the USA, we have concentrated on the middle and northern parts where there is substantial interest in FGR systems for building heating. Since the market is much more limited in the South and Southeast, we are not including data for these areas. The results of our efforts are shown on insert maps at the end of part A of this report. Because of the particular relevance of major fracture zones to thin-sheet FGR systems, we are including the two Figures A.28 and A.29 that have been copied from the paper by Thompson and Burke (1972) on the geology and geophysics of the Great Basin.

Figure A.25. Deep Basins And Flood Basalts Of The Pacific Northwest

Figure A.26. Average heat flow map of Oregon. Average heat flow values (mW/m^2) for each 1° square block of Oregon are shown. The first figure below the heat flow value is the standard error of the heat flow average and the last figure is the number of data points included in each 1° block. The average values have been contoured at 10 mW/m^2 (0.25 HFU) intervals. Physiographic provinces boundaries are shown for reference. Data provided by Dr. David Blackwell, Southern Methodist University, Dallas, Texas.

NORTHERN OREGON CASCADES

Figure A.27. Geothermal gradient, heat flow, interpreted crustal temperatures, and regional Bouguer gravity anomalies for the western part of the northern Oregon Cascade Range (gravity data are from Couch and Baker, 1977). Heat flow data between latitudes 43°15'N and 45°15'N are projected to the profile. The zero distance reference is the mean location of the Western Cascade Range-High Cascade Range boundary. Data provided by Dr. David Blackwell, Southern Methodist University, Dallas, Texas.

Figure A.28. Predominately normal (Basin and Range) faults of late Cenozoic age in the western United States. From Thompson and Burke (1972).

Figure A.29. Cross section of Dixie Valley, Nevada. The subsurface structure to the depth of the sedimentary fill (stippled) is based on geophysical exploration. Dike at depth is hypothesized to accomodate surface extension, as shown by arrows. From Thompson and Burke (1972).

(VII) EXPLORATION AND TESTING

(20) Geophysical exploration

Data and information obtained by geophysical exploration methods will obviously be important in the siting and design of FGR system. It is convenient to divide the geophysical methods of interest into two classes, that is, the structure probing and the temperature sensing methods. The first class of methods including most of the conventional techniques such as gravity, magnetic, seismic, electric, etc., serve to delineate geological structure, determine depth and dimensions of prospective FGR reservoirs. The second class of methods furnishes data on the subsurface temperature field that are applied and/or extrapolated to estimate the reservoir temperature distribution. The methods applied for this purpose are mainly direct thermal, electrical and chemical/isotropic methods.

There is already a very considerable literature on geophysical techniques as applied to the exploration of geoheat resources (see e.g., Goldstein et al., 1979). Any in depth review or discussion of this topic would be impossible within the bounds of the present project. The purpose of our brief discussion here is mainly to underline the importance of this subject and to point out two somewhat non-conventional aspects of the thermal techniques particular to the problems encountered in work on FGR systems.

First, a great number of the prospective FGR resource areas listed in chapter (VI) above can be characterized as thermally non-active and conduction dominated areas with stationary or quasi-stationary temperature fields such as, for example, the great sedimentary basins. Shallow-hole

temperature and heat flow data obtained in such areas can generally be extrapolated or downward continued to a considerable extent. In this context it is quite important to realize that broad small-amplitude surface heat-flow anomalies can be rather inconspicuous surface expressions of quite important temperature anomalies at depth. Quantitative data on the field at depths of FGR interest can be obtained by analytical/numerical downward continuation methods for stationary potential fields. There are several methods available for this purpose. Here we will call attention to an analytical type of method that was developed by Bodvarsson (1971) for gravity/magnetic fields and later extended to stationary purely conductive temperature fields (Bodvarsson, 1973). The method was tested, applied and extended by Eggers (1975). A copy of the 1973 paper is inserted as section (48) of the Appendix.

The second topic that we feel should be stressed here concerns the evolutionary or temporal aspects of conductive temperature fields in more active areas such as, for example, the horst/graben structures of the Great Basin. Bodvarsson (1978a) has presented arguments to the effect that many of the present geothermal systems in this region may not have been active for more than a few 10^4 years. In many locations the scale of temperature field evolution may therefore be quite short. Relying on very simple conduction temperature field arguments (see section (6) above), we find that the half-depth penetration of a conduction field into a homogeneous solid is given by $(at)^{1/2}$ where a is the thermal diffusivity that is usually equal to about $10^{-6} \text{ m}^2/\text{s}$. The half-depth corresponding to a time interval of 3×10^4 years is thus only about one kilometer. It is

therefore quite clear that conduction dominated thermal processes initiated only 10^4 to 10^5 years ago at depth of the order of a few kilometers will not yet have produced a stationary type signature at the surface. Under such conditions, downward continuation may lead to erroneous results.

(21) Reservoir testing

Long term reservoir performance is a matter of primary interest in all FGR projects. The developing of well test methods that provide the maximum amount of data on fluid conductivity, dimensions, etc., is therefore of great importance. No doubt, the techniques of reservoir testing are even more fundamental to FGR development than in the petroleum industry where such methods are widely used to test well performance and reservoir properties.

Obviously, the techniques that have been developed by the petroleum industry (Matthews and Russel, 1967; Earlougher, 1977) are very frequently applicable to geothermal and FGR reservoirs in porous intergranular flow media. The methods of pressure transient analysis for geothermal wells have been discussed at considerable length by Ramey (1976). Some aspects of the testing of porous FGR reservoir are also discussed by Bodvarsson (1978b to 1978d) in papers that are reproduced in the Supplement.

In the case of loop systems, the FGR industry will be particularly interested in well test methods that furnish data on the width and extent of large fractures that may either open into single wells or connect two or more wells. Test methods for this purpose have been considered at some length on the present project. The results that have been obtained are discussed in four papers that are reproduced in sections (29) to (32) in the Supplement. The papers are largely self-explanatory and we refer to them.

Oscillatory or transient pressure well test methods are recommended for inter-well tests (see Bodvarsson (1978e): Pressure Field Propagation and Density Currents, section (32)). Data on phase velocity propagation and skin-depth are given in Figure 1 and 2 of this paper.

It is of interest to compare the dynamical responses of single fractures of width h and Darcy type porous media of permeability β . Assuming a fixed test frequency of 10^3 s equivalence with regard to skin depth is obtained for the values in the following table.

TABLE A.IX

Equivalent Skin-Depths

Single Fracture	Darcy Type Media
width h	permeability β
0.1 mm	0.02 Darcy
1	2.0
10	200

Helmholtz type hydroelastic resonance modes are recommended for the testing of the dimensions of fracture spaces connected to single wells. The underlying theory is given on displays in section (33) of the Supplement. Numerical data on resonant periods are furnished there.

(VIII) HEAT STORAGE IN FGR LOOP SYSTEMS

(22) Storage of solar heat

Loop FGR systems furnish facilities to inject hot water into the subsurface where the heat content can be stored and produced again at a later date. This matter is of particular interest for the solar energy industry where there is a great need for long term heat storage facilities. The concept of combined FGR/solar systems has been considered on the present project. We will emphasize the following aspects.

The storage temperature differential. One of the principal aspects of storing heat in rock, and other materials for that matter, is that a temperature differential is required for both storage and retrieval. In other words, to store heat by injecting hot water into the ground, the water has to have a higher temperature than the accepting formations and the situation has to be reversed on retrieval. Both differentials add up and may in some geological situations result in a considerable loss of temperature in the storage process. Moreover, any leakage of heat from the storing formations can aggravate the situation. In the following, we will refer to the total temperature loss during storage as the storage temperature differential.

It is important that the two main types of FGR reservoir structures, that is, the porous slab and the thin-sheet types, behave quite differently with regard to the storage temperature differential. In ideal homogeneous intergranular flow where the sweep process applies (see section (4)), the differential should be negligible. Even at the most ideal conditions in fracture flow there will, on the other hand, always be a finite temperature

differential (see section (44)). This is most easily seen by considering a fracture with a constant mass flow and a square wave inlet temperature. The high temperature inlet period can be taken to be for the storage of heat and the low temperature period for retrieval. The output of the fracture is then an attenuated temperature oscillation. In the case of a sufficiently large contact area, the outlet temperature will be practically constant and equal to the average inlet temperature. Hence, neglecting losses, the storage temperature differential will in this case be equal to 1/2 of the total high/low inlet temperature differential. We can therefore conclude that porous intergranular flow formations are more favorable with regard to heat storage. In practical situations involving such formations, the potential temperature losses result from flow dispersion and other flow non-uniformities such as fractures.

Storage efficiency and economics. Solar heat collectors are capital intensive. Unfortunately, published data on performance and costs vary greatly, and it is difficult to come to reliable conclusions. According to data at our disposal (Roseen, 1978; Larson, 1978) medium area collectors cost about 200 \$/m² and deliver at isolation conditions in the Pacific Northwest about 1.2 GJ/m² year. Assuming capital and O&M costs of 12%/year, we arrive at a total collector costs of the order of 20 \$/GJ. Comparing this figure with the data given in Table A.VI above, we conclude that the costs of solar heat collection are quite high.

When solar heat storage is applied, the costs of the storage and of losses during storage have to be added to the above figure. Based on data worked out on the present project, it appears unlikely that net

storage costs can be much less than 2 \$/GJ and storage efficiency is unlikely to be much in excess of 80%. It is therefore to be concluded that the total costs of stored solar heat will most probably exceed 22 \$/GJ. This figure is very considerably in excess of the present cost of heat from alternate sources.

As of now, our results on the storage of solar heat in FGR systems are therefore negative. Only greatly reduced costs of solar heat collection and/or a very substantial increase in the costs of heat from alternative sources could reverse our conclusions.

(23) Storage of waste heat

In some locations, waste heat may be available from power plants and other industries at a relatively very low cost. Values of the order of 1 to 2 \$/GJ are possible. Clearly, the conclusions set forth in section (22) above would be fundamentally different at such conditions. Using the same figures on storage costs and efficiency, the cost of the heat stored in FGR type systems could then amount to the order of 5 \$/GJ. Storage would be economically feasible and in some cases attractive.

The combination of FGR with heat storage leads to a number of new aspects with regard to design, operation and economics. Since this is a separate topic, a further investigation is not contemplated here. We will, however, remark that a brief study of the situation leads us to suggest that on a combined FGR/storage scheme, the two operations should be carried out in two separate reservoirs. For the reasons given above, porous formations with intergranular flow are to be preferred, where storage and FGR are performed at two different hydrologically separated

levels. Storage might be contemplated at a shallow to medium depth level and FGR at a deeper level. The advantage of a combined operation of this type consists mainly in the integrated use of the equipment. This leads to considerable savings in operational costs.

(IX) RECENT FGR DEVELOPMENT

(24) FGR development in Europe

There is substantial interest and activity in FGR in Europe. Work closely related to the OSU program is being carried out in France, Southern Sweden, and Denmark. In each of these countries, there are vigorous geothermal energy development plans, with the goal of producing 50 to 125°C fluid (more usual, however, are 60 to 80°C fluids) from natural permeable sedimentary horizons at a depth of up to 4 km (usual depths are 1.5 to 2.5 km). The fluid is to be used for heating with the cooled fluid returned to the same horizon, some distance away, so it can be reheated and produced again.

The French program is leading the way in these developments. In fact, it appears that it is becoming routine in certain regions in France to drill a production-injection pair of wells (a doublet) and connect up several thousand apartments to it for space and/or water heating. There are presently six main geothermal applications in France; at least four of these are of the FGR type (Melun l'Almout, 1970; Villeneuve-la-Garenne, 1976; Creil, 1976; and Melun Mee Sur Siene, 1978). Moreover, the French doublet systems are using only 60 to 70°C source temperature fluids and consequently are also leading the way in how to use these lower temperature fluids in district-building heating systems in order to minimize the overall cost of heating. Developments in this area are the coupling of heat pumps with the geothermal resources and the dual use of radiant floor panels and wall convectors.

The Swedish program is presently in a stage of resource testing with

pumping from an old oil well that has been used in other phases of their program. User system studies, including heat pump system coupling, are also being considered.

The Danish program is also in its initial phases, however, they are planning developments along the same lines as in France.

(X) SUPPLEMENT(25) Temperature front dispersion in the sweep process

To illustrate temperature front dispersion in the sweep process, we consider an initial value sweep problem where macro-conduction is taken into consideration. We assume a fluid saturated homogeneous and isotropic porous solid of infinite extent with intergranular mass fluid flow m in the direction of the positive x -axis. Let the initial temperature distribution at $t = 0$ be $T(x,0) = T_0 U(x)$ where T_0 is a constant and $U(x)$ is the unit step function. For $t > 0$, the percolating fluid translates the temperature front along the x -axis and a front smoothing or dispersion will result from the macro-conduction of heat in the same direction. Assuming no heat sources and using the same notation as in section (4) above, this case is governed by the one-dimensional heat transport equation (see section (45)),

$$C_r \partial_t T + sm \partial_x T = k \partial_{xx} T \quad (A.33)$$

where k is the thermal macro-conductivity. The initial value problem is easily solved with the help of an elementary transformation, viz.,

$$T(x,t) = (T_0/2)[1 + \text{erf}((x-ut)/2\sqrt{at})] \quad (A.34)$$

where $u = sm/C_r$ is the sweep velocity and $a = k/C_r$ is the thermal diffusivity. This result shows that the center point F of the front where $(x-ut) = 0$ and hence, $T = T_0/2$ is translated or swept along the x -axis with the sweep velocity u . Moreover, the steepness of the front at F is found to be

$$(dT/dx)_F = T_0/2(\pi at)^{1/2} = T_0/2l_r \quad (A.35)$$

where $l_r = (\pi a t)^{1/2}$ is the boundary resistance thickness defined in section (6) above. As shown in Figure A.30, we can use the steepness at F to define a front width b . The result given by (A.35) shows then that the width is independent of u and is given by $b = 2l_r$. Assuming $a = 10^{-6} \text{ m}^2/\text{s}$, we find that the unit-step front develops a width of 60 m in about 10 years.

Figure A.30. Development of a unit step temperature front.

(26) Well admittance and breakthrough time in Darcy type flow

Consider a homogeneous and isotropic fluid saturated space with Darcy type flow. Let the fluid be incompressible, the fluid pressure be p

and the fluid conductivity be C . The mass flow of the fluid is then given by Darcy's law,

$$\vec{m} = -C\nabla p \quad (A.36)$$

Moreover, let the fluid source density be f such that conservation of mass requires

$$\nabla \cdot \vec{m} = f \quad (A.37)$$

and hence by inserting (A.36) into (A.37) we obtain the potential equation for the fluid pressure

$$\nabla^2 p = f/C \quad (A.38)$$

where $\nabla^2 = -\nabla^2$ is the Laplacian operator. Assuming that f is a delta type source density of total strength M , we find that the solution of (A.38) is

$$p = M/4\pi rC \quad (A.39)$$

where r is the distance from the source to the field point. Obviously, because of spherical symmetry, this solution will also apply to the exterior of a spherical source cavity of radius R and total strength M . If the source pressure is Δp , we obtain by setting $r = R$ the relation

$$M = A\Delta p \quad (A.40)$$

where $A = 4\pi CR$ is the admittance.

To obtain a simple approximation for cold water breakthrough time t_b between a point-like source and a point-like sink of spacing D and of

strength M in a homogeneous and isotropic Darcy type flow situation, we place the x -axis through the pair with the origin half-way between the source points. On the basis of (A.36) and (A.39), we find that the mass flow density along the x -axis is

$$m = (M/4\pi)[((D/2)-x)^{-2} - ((D/2)+x)^{-2}] \quad (\text{A.41})$$

Referring to section (4), we obtain the sweep velocity as $u = sm/C_r$ and the breakthrough time is then

$$t_b = \int_{D/2}^{-D/2} (1/u) dx = 0.75D^3 C_r / sM \quad (\text{A.42})$$

(27) Generalizations of the thin-sheet model

The results obtained for the single fracture model set forth in section (45) of the Appendix are obtained for the case where the initial temperature distribution is constant and equal to T_0 . It is a simple matter to generalize this to cases where the initial temperature varies as $f(x)$ along the fracture. Limiting ourselves to the case $f(x) = (b + gx)$ where b and g are constants, we obtain the result (see Bodvarsson, 1976a)

$$T(x,0,t) = (b+gx)\text{erf}(\alpha x/2\sqrt{at}) - (2g/\alpha)\sqrt{at}/\pi[1-\exp(-\alpha^2 x^2/4at)] \quad (\text{A.43})$$

where the notation is as in (45).

Moreover, the basic single fracture model that is set forth in section (45) of the Appendix assumes uniform/unidirectional flow along the fracture. This model is not applicable to fractures with varying transverse dimensions as, for example, in the case of flow between two streamlines where the

distance between the lines varies along the flow. This situation is obviously of importance in computing the temperature of the water produced by loop systems drawing on thin-sheet reservoirs. We can then proceed as follows.

Retaining the notation and other assumptions made in section (46) the problem involves the case where the mass flow density $q(x)$ is a function of a coordinate x defined in a convenient way along the steam channel. The boundary condition (12) in section (46) retains its form

$$\partial T_x = \alpha(x) \partial T_y \quad (\text{A.44})$$

but $\alpha(x)$ is now a function of x . We introduce the integral

$$A(x) = \int_0^x \alpha(x') dx' \quad (\text{A.45})$$

and rewrite solution (13) in section (46)

$$T(x,y,t) = T(A(x) + y) \quad (\text{A.46})$$

The results set forth in section (46) follow easily, but are now limited to individual channels between two steamlines. To obtain good results, a sufficiently large number of channels have to be chosen.

(28) Darcy type flow in a layered half-space with a free fluid surface

Using the technique of linearization, Bodvarsson (1977) see section (47) of the Appendix) has derived solutions to the problem of small amplitude Darcy type flow in homogeneous/isotropic half-spaces with a free fluid surface. With regard to the development in section (10.v) it is of interest to generalize these results to layered spaces.

In principle, the problem setting is not too different from section (47). We have to solve the potential equation for an inhomogeneous half-space in $z > 0$

$$-\nabla \cdot (C \nabla p) = f \quad (\text{A.47})$$

with the boundary condition at the equilibrium free surface

$$\partial_t p - a \partial_z p = 0, \quad z = 0 \quad (\text{A.48})$$

A difficulty arises because of the generalization in that we can not construct a solution of the form $p(x, y, z + at)$ as was possible in the simple case. We have not devoted any major effort to investigating the most convenient methods of solving the problem. It does, however, appear that in many cases, one will have to resort to numerical methods of the finite-element or finite-difference type.

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(1) Introduction

In evaluating geothermal resources we are primarily interested in data on the distribution of temperature and fluid conductivity within the reservoir, the total volume of the productive formations, recharge characteristics and chemical quality of the thermal fluids. While geophysical exploration by surface methods may furnish some data on the temperature field and give indications as to the reservoir volume, they furnish practically no information on the fluid conductivity and production characteristics. Such information will generally have to be obtained by tests performed within the reservoir, primarily by production tests on sufficiently deep wells. Reservoir testing is therefore one of the most important tasks in a general exploration program.

In principle, reservoir testing has much in common with conventional geophysical exploration. Although the physical fields applied are to some extent different, we face the same type of selection between controlled and natural drives, forward and inverse problem setting, etc. The basic philosophy (Bodvarsson, 1966) is quite similar.

In the present paper, we will discuss some fundamentals of the theory of reservoir testing where the fluid conductivity field is the primary target. The emphasis is on local and global aspects of the forward approach to the case of liquid saturated (dominated) Darcy type formations. Both controlled and natural driving pressure or strain fields are to be considered and particular emphasis will be placed on the situation resulting from the effects of a free liquid surface at the top of the reservoir.

(2) Relations governing the pressure field in Darcy type formations

Let $p(t,P)$ be the pressure field at time t and at the point P in a Darcy type domain B with the boundary surface Σ . Consider a general setting where the permeability k is a linear matrix operator and the kinematic viscosity of the fluid ν is also taken to be variable. It is convenient to introduce the fluid conductivity operator $c = k/\nu$ and express Darcy's law

$$\vec{q} = -c\nabla p \quad (1)$$

where $\vec{q}$ is the mass flow density. Moreover, let ρ be the fluid density, s the capacitivity or storage coefficient of the formation and f be a source density. Combining (1) with the equation for the conservation of mass, we obtain the diffusion equation for the pressure field

$$\rho s \partial_t p + \pi(c)p = f \quad (2)$$

where $\pi(c) = -\nabla(c\nabla)$ is a generalized Laplacian operator. Appropriate boundary

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conditions that may be of the Dirichlet, Neumann, mixed or more complex convolution type, have to be adjoined to equation (2). The case of a homogeneous/isotropic/isothermal formation results in the simplification $\Pi(c) = c\Pi = -c\nabla^2$ where c is a constant. Moreover, stationary pressure fields satisfy the potential equation

$$\Pi(c)p = f. \quad (3)$$

The eigenfunctions $u_n(P)$ of $\Pi(c)$ in B satisfy the equations

$$\Pi(c)u_n = \lambda_n u_n, \quad n = 1, 2, \dots \quad (4)$$

where the constants λ_n are the eigenvalues and the boundary conditions on Σ are homogeneous of the same type as those satisfied by $p(t, P)$ in (2) and (3).

(3) Types of solutions

It is of interest to consider some general expressions for the solutions of equations (2) above. The key to the equation is the causal impulse response or Green's function $G(t, P, Q)$ which represents the pressure response of the causal system to an instantaneous injection of a unit mass of fluid at $t = 0+$ at the source point Q . This function satisfies the same boundary conditions as the eigenfunctions $u_n(P)$. Solutions to (2) in the case of a general source density $f(t, P)$, non-causal initial values and general boundary conditions can then be expressed in terms of integrals over the Green's function (Duff and Naylor, 1966).

Two fundamental types of expressions for the Green's function are available. First, in the case of simple layered domains B with a boundary Σ composed of a few plane faces, $G(t, P, Q)$ can be expressed as a sum (or integral) over the fundamental source function

$$p = (8\rho s)^{-1}(\pi at)^{-3/2} \exp(-r_{PQ}^2/4at) U_+(t) \quad (5)$$

and its images. The symbol $U_+(t)$ is the causal unit step function and r_{PQ} is the distance from Q to P . Whenever applicable, sums of this type represent the most elementary local and/or global expressions for $G(t, P, Q)$.

Second, the Green's function can be expanded in a series (in integral) over the eigenfunctions of $\Pi(c)$. If ρ and s are constant, then

$$G(t, P, Q,) = (1/\rho s) \sum_n u_n(P) u_n(Q) \exp(-\lambda_n t/\rho s). \quad (6)$$

The series expansion (6) is of a more general applicability than solutions of the type based on the fundamental source function (5). However, because of quite poor convergence properties, (6) is largely of a more global long-term relevance. It is less suited for the computation of local values. The formal link between the two types of solution (5) and (6) is provided by the Poisson summation formula (Zemanian, 1965).

A different type of solution of (2) that is of interest in the present context can be obtained by operational methods. Limiting ourselves to the pure initial value problem with $p(0, P) = p_0(P)$ in the case of an infinite domain, we can, since ρ , s and $\Pi(c)$ are independent of t , formally express the solution of the homogeneous form of (2) as

$$p = \exp[-t\Pi(c)/\rho s]p_0 \quad (7)$$

where the exponential operator is to be interpreted as a Taylor series in the operator $\Pi(c)$

$$\exp[-t\Pi(c)/\rho s] = 1 - [t\Pi(c)/\rho s] + (1/2)[t\Pi(c)/\rho s]^2 - \dots \quad (8)$$

The series represents an iteration process where the convergence is limited to (properly defined) small values of t . The practical applicability is therefore fundamentally different from (6). Moreover, it is of considerable interest that rather general situations with regard to $\Pi(c)$ can be admitted in (7) and (8).

Three simple but fundamental physical parameters are associated with processes governed by the diffusion equation (2). First, the local diffusivity $a = c/\rho s$. Second, the skin depth $d = (2c/\rho s\omega)^{1/2}$ which is a measure of the penetration of a wave of angular frequency ω (Bodvarsson, 1970). Finally, the relaxation time $t_0 = 1/ak^2$ which is a measure of the attenuation in time of a one-dimensional wave like pressure field of wave number k . The time t_0 is the time during which the wave amplitude decreases from unity to $1/e$. This parameter is obtained by inserting a solution of the form $\exp[(-t/t_0) + ikx]$ into the one-dimensional form of (2).

(4) Effects of a free liquid surface

The presence of a free liquid surface in a reservoir requires the introduction of a rather complex surface boundary condition. Let Σ now represent the free liquid surface at equilibrium and Ω be the free surface in a perturbed state. The boundary Ω is a surface of constant pressure which without loss of generality can be taken to vanish. The free surface condition (Lamb, 1932) is then expressed

$$Dp/Dt|_{p=0} = 0 \quad (9)$$

where D/Dt is the material derivative. This is an essentially non-linear condition which leads to a much more complex problem setting. Losing the principle of superposition the construction of solutions to the forward problem becomes a difficult task.

Bodvarsson (1977a) has shown that when Ω deviates only little from Σ , (9) can be simplified and linearized. For this purpose we place a rectangular coordinate system with the z -axis vertically down such that the (x, y) plane coincides with Σ . Moreover, let the amplitude of Ω relative to Σ be $\bar{u}$ and the scale of the undulation of Ω be L . Then provided $|\bar{u}/L| \ll 1$, the condition (9) can be replaced by the approximation

$$(1/w)\partial_t p - \partial_z p = 0, \quad (10)$$

where $w = cg/\phi$ is a new parameter, namely, the free sinking velocity of the pore liquid under gravity (g = acceleration of gravity). Under these circumstances, the solution of the forward problem is obtained by constructing a solution to (2) which satisfies (10) at the free surface and appropriate conditions at other sections of the reservoir boundary.

The presence of a first order derivative with respect to time in the free-surface condition (10) obviously leads to an additional relaxation process analog to the purely diffusive phenomena associated with the first order time derivative in the basic equation (2). As we shall conclude below, the individual time scales of the two phenomena are, however, quite different.

For the sake of brevity, we shall limit the present discussion to the simplest but practically quite relevant case of the semi-infinite liquid saturated homogeneous, isotropic and isothermal half-space. To consider the pure free-surface related phenomena, we eliminate pressure field diffusion by neglecting the compressibility of the liquid/rock system. In this setting we can combine the potential equation (3) and the surface condition (10) in one single equation confined to the Σ plane (Bodvarsson, 1978a), which expressed in terms of the fluid surface amplitude $u(t,x,y) = p/\rho g$ takes the form

$$(1/w)\partial_t u + \pi_2^{\frac{1}{2}} u = f/\rho g c \quad (11)$$

where $\pi_2^{\frac{1}{2}} = (-\partial_{xx} - \partial_{yy})^{\frac{1}{2}}$ is the square root of the two-dimensional Laplacian and f is an appropriately defined source density. To obtain the pressure field in the space $z > 0$, the boundary values derived from (11) have to be continued into the lower half-space on the basis of standard potential theoretical methods. The fractional order of the Laplacian in (11) is quite unusual, but the operator is well defined and poses no mathematical problems. For a further discussion of such operators in a slightly different setting, we refer to a paper by Bodvarsson (1977b).

Consider the attenuation of a wave formed pressure field of the form $\exp[-(t/t_0) + ikx]$ where t_0 is the relaxation time and k is the wave number. Inserting into equation (11), we find that $t_0 = 1/wk$. Comparing this result with the case of the purely diffusive pressure field we find that the ratio of the free surface/diffusion relaxation times is $ak^2/wk = k\phi/g\rho s$. The assumptions of waves of lengths 10 to 10^3 meters and porosities of 10^{-2} to 10^{-1} , results in ratios ranging from about 10^2 to 10^5 . The relaxation times of diffusion phenomena are therefore orders of magnitude shorter than for free-surface phenomena of a comparable spatial scale. As a result, we can conclude that in most cases of practical relevance, the two phenomena can be separated and treated individually.

Some solutions of equations (11) of practical interest have been obtained by Bodvarsson (1977a). Confining ourselves again to the simple semi-infinite half-space, the most important result is given by the causal impulse-response function $G(t,S,Q)$ which represents the response of the surface amplitude at the point $S = (x,y)$ in Σ and time $t > 0+$ to an instantaneous injection of a unit mass fluid at a point Q in the half-space at time $t = 0+$. The system is assumed to be in equilibrium for $t < 0$. Let $Q = (0,0,d)$, the resulting expression for the surface amplitude is

$$G(t,S,Q) = (1/2\pi\phi\rho)(wt+d)[x^2+y^2+(wt+d)^2]^{-3/2} u_+(t) \quad (12)$$

where $U_+(t)$ is the causal unit-step function. The impulse response is essentially the key to the solution of (11) for more general conditions. The pressure field in the half-space is obtained from (12) by a simple continuation technique where the singularity at Q has to be taken into consideration. The long term response of the surface amplitude to a periodic source function at Q is of particular interest in the present context. Let the mass flow injected at $Q=(0,0,d)$ take the form $\exp(-i\omega t)$. The amplitude of the frequency response is then obtained by

$$F(S,Q,\omega) = \int_0^\infty G(S,Q,\tau) \exp(i\tau\omega) d\tau \quad (13)$$

The present results on the dynamics of the free surface amplitude provide the basis for a technique of reservoir probing and testing which yields results on c and ϕ that are supplementary to the conventional well test techniques (see Bodvarsson and Zais, 1978, this volume).

(5) Testing with controlled signals

Local. Reservoir tests with controlled drive yielding mostly local parameter values include primarily the driving point tests which are usually referred to as pressure buildup and/or drawdown tests on single wells. Pioneering work on the development of this technique has been carried out at Stanford, and there exists considerable literature (see e.g. Ramey, 1976). Interpretation is based on appropriate solutions of equation (2).

Interference. The spatial scale of well-to-well interference tests depends on the distances involved. Short distances tend to yield only local parameter values whereas long distances may lead to results of a more global nature. In the case of simple systems of sufficient extent, the interpretation is to be based on the following concentrated source unit-step responses obtained on the basis of equation (2) (Carslaw and Jaeger, 1959).

axi-symmetric two-dimension	point-symmetric three-dimension	
$-(m/4\pi c)Ei(-F^{-1}),$	$(m/4\pi Cr)\operatorname{erfc}(F^{-\frac{1}{2}})$	(14)

where $F = 4at/r^2$ is the Fourier number and m is the appropriately defined (constant) mass flow applied. Again, there is very considerable literature on the subject (Mathews and Russel, 1967; Earlougher, 1977) mostly emphasizing the two-dimensional axi-symmetric situation.

It is important to note that in the above expressions, the complementary error function (erfc) and the exponential integral (Ei) will in the interval $0 < F < 0.5$ yield very similar values when taken as functions of time at a fixed field point. The short-term well interference test is therefore largely "blind" with regard to the space dimensions involved. Although the value of the amplitude factor is observable, its structure depends critically on the space dimension and this data does therefore not convey any information unless strong assumptions are made with regard to the underlying model. Considerable caution is therefore called for in the interpretation of well interference data, and it would appear that too much confidence has been placed in the applicability of the axi-symmetric two-dimensional Theis-type solution.

Global. Tests of this nature can be carried out only when there is sufficient data on the global characteristics of the pressure/flow field. An important case consists in the use of global free liquid surface data. A brief review of the theory involved has already been given in section (5) above. Forward solutions based on the type of Green's function expression given by (6) above are of particular relevance in global work.

(6) Testing with natural signals

Types of drive. Available natural driving strain or force fields are of the following LF (low-frequency) to ULF (ultra-low-frequency) types (period range in parenthesis): seismic strain (1 to 10^3 s), hydroelastic oscillations and noise (two-phase flow, etc.) (10 to 10^5 s), tidal strain (10^4 to 10^6 s), atmospheric pressure variations (10^4 to 10^6 s), precipitation load (10^4 to 10^6 s) and seasonal water-level variations (10^6 to 10^8 s).

Local. The most obvious applications of natural drive are to the local type of testing. For the sake of brevity, we will limit our attention to VLF and ULF test signals where the mass forces on liquid columns in boreholes can be ignored. Moreover, in the single borehole case the essential results are obtained by deriving the pressure amplitude in an open hole (free liquid surface) to a homogeneous harmonic formation dilatation drive of amplitude b and angular frequency ω . Responses to other types of signals can then be easily derived with the help of a Fourier transform analysis. Under some further plausible simplifying assumptions, the following essential results for the pressure amplitude p in a single borehole of cross section f were presented at the 1977 Stanford Symposium (Bodvarsson, 1977c and 1978a), namely,

$$p = p_0 T / (1 + T), \text{ where } p_0 = \epsilon b / s, \text{ and } T = -4i\pi g r_0 c / \omega f = -iAS / \omega. \quad (15)$$

Here, p_0 is the static pressure amplitude, ϵ the formation matrix coefficient characterizing the relation between the imposed strain and the porosity, r_0 the radius of the (spherical) well cavity, $A = 4\pi r_0 c$ the admittance of the cavity and $S = dp/dm = g/f$ is the mass stiffness of the well. The first two relations in (15) are general, but the third one is obtained on the basis of the assumption that $d/r_0 \gg 1$ where d is the skin depth of the formation at tidal frequencies.

The case of pressure oscillations of tidal nature in closed well-reservoir systems has been discussed recently by Arditty, Ramey and Nur (1978). By a proper definition of the well mass stiffness S , the relations (15) would also be applicable to systems of this type.

The application of seismic signals in reservoir testing offers interesting possibilities. Mainly because of vertical displacement oscillations, the forward theory for this case is more complex than the results given above and can therefore not be discussed in this brief note. The subject has been investigated by Bodvarsson (1970). Forward solutions based on the interactive type of series given by (8) are of particular interest in the interpretation of local tests based on natural drive.

Interference and global. More global type interference tests can, in principle, be carried on the basis of natural pressure or strain signals. Because of the well/well pressure field scattering processes involved, the theory cannot be discussed within the framework of this short note.

(7) Fractured reservoirs

The discussion above has been devoted entirely to formations which are of the Darcy type or can be approximated by such media. Largely fractured reservoirs have not received any attention. The theory of such cases differs from the material presented above and will not be discussed here. It is of interest to note that the mechanism of pressure field propagation in fractures with elastic walls has been discussed by Bodvarsson (1978b).

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(30) A FIELD EXAMPLE OF FREE SURFACE TESTING*

by

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Introduction

Theoretical results on free liquid surface dynamics presented by Bodvarsson (1978, this volume), provide the basis for a technique of reservoir probing and testing which can yield results that are supplementary to conventional well testing data. The Laugarnes geothermal area in Iceland which is one of the sources of the Reykjavik District Heating System is a case where both methods are applicable and appear, interestingly, to yield quite different results. A brief account of the free surface results will be presented below.

The Laugarnes geothermal source area

The Laugarnes geothermal area (see Fig. 1) has been described in some detail by Thorsteinsson and Eliasson (1970). The active reservoir underlies an area of 5 km² within the city of Reykjavik and has a base temperature about 145°C. The reservoir is embedded in a flood basalt series of more than 3 km thickness. Fluid conductivity is mainly along the contacts of lava beds and up through dikes and fracture zones. Evidently, the permeability is quite heterogeneous and anisotropic.

Several dozen production wells have been drilled in the area during the past decades. The maximum depth is now of the order of 3 km. The productivity of individual wells obtained with the help of submerged pumps placed at depths up to 100 meters varies from 1 to 50 kg/s with well-head temperatures mostly in the range of 125°C to 135°C. The main production is obtained from an aquifer extending between the depths of 730 and 1250 meters. The pumping load is governed by the demand on the heating system during the course of the annual cycle and varies from about 100 to 300 kg/s. As a consequence of the varying production rate, the elevation of the piezometric surface fluctuates in a quasi-periodic way with the year as a basic period. Thorsteinsson and Eliasson (1970) have during the period 1965 to the end of 1969, collected a considerable amount of water level data from 60 observation wells in the area. Fig. 2 gives an example of their water level data on a day in November of 1967. Moreover, Fig. 3 illustrates the relation between the integrated production rate and the water levels as observed in two centrally located wells. These data furnish a quite interesting picture of the hydrological characteristics of the reservoir.

Very few quantitative data are available on the permeability and porosity characteristics of the Laugarnes reservoir. Using conventional well interference test techniques in field experiments of 10 to 20 hours duration, Thorsteinsson and Eliasson (1970) have estimated the permeability of the reservoir to be of the order of 10 darcys.

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Bodvarsson (1975) arrived on the basis of water level recovery data from one well at a permeability value of a few darcy. No results were obtained on the porosity but field observations on outcrops indicate very low values, perhaps a few parts per thousand.

Relevant theoretical results presented by Bodvarsson (1977a & b, 1978) permit an analysis and interpretation of the available observational data in terms of estimates of the more global permeability and porosity characteristics of the reservoir. Two different procedures are available for carrying out this analysis, namely, 1) the production data can be taken to represent a periodic process with an approximately sinusoidal input/output, or 2) short sections of the graphs can be analyzed individually as independent processes.

On the first approach, input-output amplitude and phase relations for the annual cycle can be estimated with the help of the production rate and water level data in Fig. 3. Unfortunately, the present observational material is deficient in that the peak-to-peak input-output phase lags are small and quite poorly defined. Nevertheless, on the available data, estimates of roughly 1.5 months equivalent to a phase angle of 45 degrees are indicated.

Carrying out a numerical evaluation of the complex integral for the frequency response as given by equation (13) in the paper by Bodvarsson (1978, this volume) for the case of various values of the sinking velocity parameter w , and comparing the results with the observational data, we obtain on the basis of the phase difference a best fit for a value of $w = 4 \times 10^{-4} \text{ m/s}$. With the help of the amplitude ratio, permeability estimates of roughly 10 millidarcy and porosity estimates of 10^{-3} are obtained.

An alternative approach to the periodic input/output data based on a simple lumped system model is discussed in the Appendix. The resulting estimates of the permeability and porosity are of the same order of magnitude as the data given above.

On the individual event analysis of the water level responses to the changes in the production rates, we obtain quite similar results. The theory is based on the following results by Bodvarsson (1977b) for the response of the free water surface to sinks at depth in homogeneous and isotropic Darcy type solids. First, let the initial free surface be at equilibrium and a point-sink of volume rate V be placed at the depth d and start production at $t = 0$. The initial rate of drawdown of the free surface vertically above the sink is then

$$u = V/2\pi\phi d^2 \quad (1)$$

where ϕ is the porosity. Moreover, let k be the permeability of the solid, ν the kinematic viscosity of the fluid and therefore $c = k/\nu$ the fluid conductivity. The long term stationary value of the free surface drawdown vertically above the sink is then found to be

$$h_s = V/2\pi g c d \quad (2)$$

where g is the acceleration of gravity.

We apply these results to the production event from September 1968 to March 1969 and assume that the point source model can give reasonable estimates of the parameters of interest. During the event in question, the flow rate was increased quite abruptly from 2.5 to $7 \times 10^5 \text{ m}^3/\text{month}$, that is, by about $0.17 \text{ m}^3/\text{s}$. To correct for local precipitation we assume that the increased input flow to the local reservoir is $0.15 \text{ m}^3/\text{s}$. From the initial slope of the water level graph given in Fig. 3, we derive an initial rate of drawdown in response to the increased production of $u = 1.1 \times 10^{-5} \text{ m/s}$. Assuming that the production depth is about 10^3 m we find on the basis of equation (1) an estimate of the porosity of about $\phi = 2 \times 10^{-3}$.

Since equilibrium was not approached during the present event, we are unable to apply equation (2) to obtain a numerical estimate of the fluid conductivity c . However, since the graph in Fig. 3 furnishes us with a lower bound h_m for the stationary drawdown h_s , we can convert equation (2) to an inequality

$$c \leq V/2\pi g h_m d \quad (3)$$

and obtain an upper bound for c . Taking on the basis of the graph $h_m = 60 \text{ m}$, we obtain the upper bound of $4 \times 10^{-8} \text{ s}$. Assuming the kinematic viscosity to be $3 \times 10^{-7} \text{ m}^2/\text{s}$ (100°C) we obtain that the permeability $k \leq 1.2 \times 10^{-14} \text{ m}^2 = 12 \text{ millidarcy}$.

The above estimates of the global permeability turn out to be two to three orders of magnitude lower than the values quoted above as the results of the short-term well interference tests. There appears to be an inverse relation between the time scale of the test signal and the magnitude of the estimate. The longer the time scale, the lower the estimate.

Although a much more elaborate analysis of the Laugarnes data is indicated, the above discrepancies may be quite real and reflect the very considerable heterogeneity and fracturing of the reservoir. Due to local interconnection by fractures, the short-term interference tests performed on adjacent wells give much higher permeability estimates than the more integrated global values obtained with the help of the total production rate and well data. The result indicates that considerable caution is called for in the interpretation of relatively short-term well interference tests on complex reservoirs.

Appendix

In processing the periodic data, we can also base our estimates on a lumped model as shown in Fig. 4. The model is characterized by a single input conductance K and a single capacitance S . In the physical sense, the capacitance simply represents the effective pore area of the container shown in Fig. 4. Let f be the volume rate produced from the container, h be the average liquid level in the container counted positive down and assuming that the ambient water level is zero, we arrive at the following equation governing the lumped system

$$S(dh/dt) + Kh = f \quad (4)$$

In the case of periodic flow $f = F \exp(i\omega t)$ where F is the amplitude and ω the angular frequency. Let the response of the liquid level be $h = H \exp(i(\omega t - \alpha))$, and inserting in equation (4) the resulting output-input amplitude ratio is found to be

$$H/F = (K^2 + S^2\omega^2)^{-\frac{1}{2}} \quad (5)$$

and the phase angle

$$\alpha = \tan^{-1}(S\omega/K) \quad (6)$$

From the graphs in Fig. 3, we find that we can on the average take $F = 0.07 \text{ m}^3/\text{s}$, $H = 19\text{m}$ and $\alpha = 0.78$ radians. Solving equations (2) and (3) for the system parameters we obtain

$$K = 2.7 \times 10^{-3} \text{ m}^2/\text{s} = 2.5 \times 10^{-4} \text{ Kg/sPa}, \quad S = 1.4 \times 10^4 \text{ m}^2 \quad (7)$$

To translate these results into estimates of the average permeability k and average porosity ϕ we observe that the ground water level depression in Fig. 2 has the shape of a slightly elongated flat disk with an area of approximately $A = 4 \text{ km}^2$. For the present purpose we replace this disk by a circular one with a radius $R = 1.13 \text{ km}$. On the basis of simple potential theoretical relations (Sunde, 1968), we find that the contact conductance of a flat circular disk of radius R immersed in a porous medium of fluid conductivity c is simply $8cR$. In the present case, where the disk is placed on the surface of the half-space the contact conductance is consequently $4cR$. Since the value of K given in (4) above is to be taken as an observed value of the actual contact conductance, we obtain the estimate for c as

$$\bar{c} = K/4R = 2.5 \times 10^{-4}/4 \times 1.13 \times 10^3 = 5.5 \times 10^{-8} \text{ s} \quad (8)$$

Since $c = k/\nu$ where k is the permeability and ν the kinematic viscosity, and moreover, the porosity $\phi = S/A$, we obtain by assuming $\nu = 3 \times 10^{-7} \text{ m}^2/\text{s}$ (100°C) the following estimates

$$k = 1.7 \times 10^{-14} \text{ m}^2 = 17 \text{ millidarcy and } \phi = 3.5 \times 10^{-3} \quad (9)$$

which is of the same order of magnitude as the results given above.

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Figure 1. Geological map of southwest Iceland with index map.

From: Tomasson and Thorsteinsson (1976).

Figure 2. Elevation of the piezometric surface in the Laugarnes hydrothermal system on November 15, 1967.

From: Thorsteinsson and Eliasson (1970).

Fig. 3. Hydrographs of wells G7 and G16 and monthly withdrawals of water from 1965 to 1969.

From: Thorsteinsson and Eliasson (1970).

Fig. 4. Lumped model of input conductance K and capacitance S .

by

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Introduction

The theory of pressure and water level oscillations of tidal origin in Darcy type aquifers and petroleum reservoirs has been discussed in a number of recent publications (see for example, Bredehoeft, 1967; Bodvarsson, 1970, 1977, 1978a, 1978b; and Arditty et al., 1978). There is a general agreement that observational data on the tidal pressure phenomena may be applied to obtain useful estimates of important reservoir parameters such as the permeability.

A Simple Basic Model

In the simplest setting involving a single open well connected by a small spherical cavity to a large homogeneous and isotropic reservoir, the mechanism of the tidal well test is easily comprehended on the basis of the model illustrated in Fig. 1 below. Let the permeability of the porous medium be k , the density of the fluid by ρ , its kinematic viscosity be ν and hence the fluid conductivity of the medium be $c=k/\nu$. Moreover, let s be the hydraulic capacitivity or storage coefficient of the medium and the diffusivity therefore $a=c/\rho s=k/\mu s$ where μ is the absolute viscosity of the fluid. The skin depth of the medium at an angular frequency ω is then $d=(a/2\omega)^{1/2}$ (Bodvarsson, 1970). For the present purpose, concentrating first on cases where boundary effects can be ignored, we assume that the skin depth of the reservoir material at tidal frequencies is smaller than the extent of the reservoir including the depth of the well. In other words, the reservoir can be assumed to be infinite as viewed from the well-cavity. Introducing a spherical coordinate system with the radial coordinate r and with the origin placed at the center of the cavity, the fluid pressure field $p(r,t)$ in the porous medium is governed by the diffusion equation (Bodvarsson, 1970).

$$\partial_t p - a[\partial_{rr} + (2/r)\partial_r]p = -(\epsilon/s)\partial_t b \quad (1)$$

where t is time, $b(t)$ the tidal dilatation of the medium and ϵ is the formation matrix coefficient. Let r_0 be the radius of the cavity, f the cross section of the well and g the acceleration of gravity. The boundary condition at $r = r_0$ is then

$$(f/g)\partial_t p - Fc\partial_r p = 0, \quad (2)$$

where $F = 4\pi r_0^2$ is the surface area of the cavity.

The expression for the oscillations of the water level in the well in response to the dilatation is obtained by solving equation (1) with the

*Paper given at the Fourth Workshop on Geothermal Reservoir Engineering, Stanford University, December, 1978.

boundary condition (2) and deriving the pressure at the cavity which is equal to the pressure at the well bottom. To simplify our results without any appreciable loss of generality, we can in most cases assume that the skin depth of the medium is much larger than the dimensions of the cavity, that is, $d \gg r_0$. Assuming therefore an infinite medium and that b and $p \propto \exp(i\omega t)$, the solution of (1) in terms of amplitudes is (Bodvarsson, 1970)

$$p = (B/r)\exp[-(1+i)r/d] - (\epsilon b/s), \quad (3)$$

where B is a constant to be determined by the boundary condition (2). Inserting (3) into (2), we finally obtain for the amplitude of the water level in the well

$$h = -(\epsilon b/\rho g s)T/(1+T), \quad (4)$$

where b is the dilatation amplitude and T is the tidal factor,

$$T = -4i\pi g s c r_0 / f\omega, \quad (5)$$

An elementary potential theoretical argument shows that the admittance or conductance of the cavity is

$$A = 4\pi c r_0, \quad (6)$$

and we can define the mass stiffness of the well

$$S = dp/dm = g/f, \quad (7)$$

This quantity measures the increase in well bottom pressure when an unit mass of liquid is added to the well. Using these expressions, the tidal factor can be expressed

$$T = -iAS/\omega \quad (8)$$

which along with (4) is our final result for the above simple model illustrated in Fig. 1.

It is to be noted that the above expression (8) will also hold for a closed well situation. We have then only to redefine the mass stiffness

$$S = dp/dm = 1/\beta M \quad (9)$$

where M is the liquid mass in the well and β is the compressibility of the liquid. In the case of a gas cap, (9) will have to be adjusted accordingly. In the case of a closed well equation (4) will have to be expressed in terms of the well-head pressure rather than a water level.

Interpretation of Well Data

In the relatively simple situation described above, the interpretation of well data is based on equations (4) and (8). Invariably, ρ and f can be

taken to be known. Since in most practical cases, the effective dilatation e_b and formation capacitivity s are of less interest than the formation fluid conductivity c , the latter quantity is generally the primary target of any interpretation of observational tidal well data. Equations (4), (8) and (6) show that c has to be derived from the tidal factor T and that this factor can be separated if we are able to observe the water level amplitude at two different tidal frequencies. Since the tidal force field includes a number of frequencies this will generally be possible. Being, in principle, able to obtain T and thus on the basis of (8) the admittance A , the fluid conductivity will have to be derived with the help of (6). In the rather idealistic situation with a spherical well-cavity of known radius r_0 , we are therefore, in principle, able to reach our goal of obtaining a numerical estimate of c .

From the practical point of view, the procedure will, however, break down if $T \gg 1$. The factor $T/(1+T)$ is then approximately equal to unity and the water level amplitude h will be independent of the fluid conductivity. In practice, we can expect this difficulty to become serious when about $T > 3$. Since in most cases the factor $4\pi g/\omega$ will be of the order of 10^7 (MKS), we see that the above inequality implies $r_0 c > 3 \times 10^{-7}$ (MKS). For water at 100°C with $\nu = 3 \cdot 10^{-7} \text{ m}^2/\text{s}$ we obtain then in terms of permeability $r_0 k > 3 \times 10^{-7} \times 3 \times 10^{-7} \approx 0.1$ darcy-meters. Therefore, taking, for example, $r_0 = 0.5$ m, we find that the above difficulty becomes serious for permeabilities in excess of 200 millidarcy. In other words, the tidal test based on open well situations is sensitive only to small to medium permeabilities. Due to increased stiffness S , the applicability in the case of closed wells is more restricted.

Deviations from the basic model

Non-spherical well-reservoir connection. The assumption of a spherical cavity is perhaps to most obvious idealization in the above basic model. Unfortunately, the symmetry of the pressure field will be broken in the case of a non-spherical cavity, and the above simple relations may, in principle, not apply. However, provided the dimensions of a non-spherical cavity are much smaller than the skin depth d of the medium, and this will mostly be the case, the difficulties arising are not too important from the more global point of view. The global pressure field at some proper distance from the cavity will be approximately spherically symmetric and the above analysis will largely be valid. The most serious casualty is that the cavity admittance is not given by the simple relation (6) and other analog relations have to be relied on. In practical cases, there may be difficulties in establishing the form of the cavity. Most frequently, however, the well-reservoir connection consists of an open section of the well. Let the radius of the well be r_1 and the length of the open section be L . An elementary potential theoretical exercise shows that when $L \gg r_1$ the admittance can then be (Sunde, 1968) approximated by

$$A = 2\pi c L / \ln(L/r_1) \quad (9)$$

It is of interest to point out that an open section of $L = 10\text{m}$ and $r_1 = 0.1\text{m}$ has approximately the same admittance as a spherical cavity of $r_0 = 1.1\text{m}$.

Multi-well setting. Another important deviation from the basic model involves cases where there is more than one well opening into the reservoir. This situation may lead to a well-well interaction and pressure field scattering. The practical criterion for interaction is obtained by comparing the well-well distance to the skin depth d of the medium. In general, two wells will interact noticeably if the distance between the well-reservoir cavities is approximately equal or less than the skin depth at tidal frequencies.

The analysis of multi-well situations is more complex than the results given above. In the case of spherical cavities, the solution for the pressure amplitude field will then have to be constructed as a sum over solutions of the type (3), that is

$$p = \sum_j (B_j/r_j) \exp[-(1+i)r_j/d] - (\epsilon b/s), \quad (10)$$

where the j^{th} summand is centered at the j^{th} well-cavity, r_j is the distance from the field point to the center of the j^{th} cavity and the B_j s are integration constants. A boundary condition of the type (2) applies at each well-cavity and the constants B_j are obtained by solving a set of linear algebraic equations. An estimate for the fluid conductivity can then be obtained along similar lines as indicated above. We will, however, refrain from a further discussion. Obviously, neglecting well-well interaction in multi-well situations leads to an underestimate of the formation fluid conductivity c .

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Figure 1. Single well model.

Duf
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(32) PRESSURE FIELD PROPAGATION AND DENSITY CURRENTS*

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The injection of fluids into the subsurface results in pressure and flow transients which propagate through the formations. At moderate pressure amplitudes, the pressure field propagation in Darcy type porous media is governed by the well known simple diffusion equation with the diffusivity $a = b/\mu c$ where b is the permeability of the formation, μ the absolute viscosity of the fluid and c the total compressibility of the fluid saturated formation. The primary physical parameter involved in the diffusion of pressure fields of angular frequency ω in such media is the skin depth that is given by $d_s = (2b/\mu c \omega)^{1/2}$ (Bodvarsson, 1970).

The propagation of pressure fields with wave numbers k in a single fluid filled plane fracture of width h , where the inequality $hk \ll 1$ is satisfied, is governed by the equation

$$\rho(1 + \kappa h S)(\partial_{tt} + R \partial_t)p - h \nabla^2 p = S(\partial_t + R)f \quad (1)$$

where p is the fluid pressure in the fracture, ρ the density of the fluid, κ the compressibility of the fluid, R a resistance operator, S the stiffness operator for the half-space bounding the fracture, f is a source term and $-\nabla^2$ is the two-dimensional Laplacian. In the case of laminar flow regimes $R = 12\nu/h^2$, where ν is the kinematic viscosity of the fluid, and for Hookean half-spaces of infinite extent, the stiffness operator is defined by the somewhat unusual expression

$$S = (G/2(1-\sigma))(-\nabla^2)^{1/2} \quad (2)$$

where G is the shear modulus, and σ the Poisson ratio of the material.

Considering the homogenous form of equation (1), pressure fields of wavelength L and assuming that

$$h \ll (1-\sigma)L/\pi \kappa G, \quad (3)$$

such that the compressibility of the fluid can be neglected, we can distinguish between two different types of regimes of pressure propagation. In the case of oscillating fields with the angular frequency ω , the condition

$$\omega \ll 12\nu/h^2 \quad (4)$$

implies a resistance dominated or diffusive field propagation with the skin depth (Figure 1)

$$d = h[G/3\mu\omega(1-\sigma)]^{1/3} \quad (5)$$

whereas, on the other hand, the condition

$$\omega \gg 12\nu/h^2 \quad (6)$$

*Paper given at the Second Invitational Well Test Symposium, Berkeley, October, 1978.

implies an inertia dominated wave propagation with the phase velocity (Figure 2)

$$v = [hkG/2\rho(1-\sigma)]^{\frac{1}{2}}. \quad (7)$$

Moreover, assuming that both (3) and (4) hold, equation (1) can be simplified to

$$\partial_t p - (h/\rho R) S \nabla^2 p = (1/\rho) S f \quad (8)$$

which is a diffusion type equation for the pressure field.

Density currents are of particular interest in Darcy type porous media. Consider the case of a fluid-saturated half-space at temperature T containing a spherical thermal anomaly at zero temperature. This situation can result from the injection of cold water into the half-space. Because of gravity, the spherical anomaly will sink with an initial velocity (SI-units) of

$$w = 2\alpha bgTC_f/C_r(v_i + v_e) \quad (9)$$

where α is the thermal expansivity of the fluid, g the acceleration of gravity, C_f and C_r the volume heat capacities of the fluid and rock formations respectively, and v_i and v_e are the kinematic viscosities of the fluid inside respectively outside the thermal anomaly. The spherical anomaly will be deformed during descent.

Reference

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FIGURE 2

v = phase velocity for pressure waves
in a fracture of width h
when $\omega \gg 12v/h^2$

(33) Hydroelastic Helmholtz type borehole-cavity oscillators

The subject of Helmholtz type borehole-cavity oscillations was discussed in a paper by Bodvarsson and Bjornsson (1976) where also some field data were presented. The following sketches and equations from a paper given at the Hot Dry Rock Workshop, Los Alamos, New Mexico, May 1978, display some generalizations of the previous results. The material is self-explanatory.

The simple borehole-cavity resonator with a surface basin

large basin with constant fluid level

Figure 1

ρ = density of fluid

V = volume of cavity

p = pressure in cavity (constant)

$e = dV/dp$ = elastance of cavity

d = depth of borehole

a = cross section of borehole

u = oscillation velocity in borehole (small amplitude)

q = impressed mass flow source term

Linearized equation of small amplitude motion (attenuation neglected):

$$\rho dDu = V/e$$

Kinematic condition:

$$DV = -au + (q/\rho)$$

System equation:

$$\underline{D^2u + \omega_0^2u = (q/\rho ed)}$$

where $D = d/dt$

resonant frequency:

$$\underline{\omega_0 = (a/\rho ed)^{1/2}}$$

Figure 2
Elastance of the penny-shaped cavity
 (Sneddon, 1946)

$$w \ll R,$$

G = shear modulus

E = Young's modulus

$$\text{elastance } e = dV/dp = 16(1-\sigma^2)R^3/3E$$

$$\text{or for most rocks } e \approx 2R^3/G$$

hence for simple borehole-cavity system

$$\omega_0 = (aG/2\rho R^3 d)^{\frac{1}{2}}$$

and in common rock

$$\omega_0 = (700/R)(a/Rd)^{\frac{1}{2}}, \quad \text{MKS}$$

Examples of resonant periods when $a = 0.05 \text{ m}^2$ and $d = 2 \times 10^3 \text{ m}$

	$R = 10$	30	100 m
period	57	330	1800 s

Figure 3

Forced oscillations of the simple
borehole-cavity system with a surface basin

$$\omega_0 = (a/\rho e d)^{\frac{1}{2}},$$

$$u = u_0 \exp(i\omega t)$$

$p = p_0 \exp(i\omega t)$ = pressure at the surface
of basin

p_0 = pressure amplitude

Equation of motion:

$$\rho d D u = (V/e) - p$$

hence

$$D^2 u + \omega_0^2 u = -(1/\rho d) D p = -(1/\rho d) i \omega p_0 \exp(i\omega t)$$

$$u = \frac{i \omega p_0}{\rho d (\omega^2 - \omega_0^2)}$$

The simple open borehole-cavity resonator

h = oscillation amplitude of water level

$$Dh = u$$

Equation of motion:

$$\rho dDu = (V/e) - gph$$

hence

$$\omega_0 = [(a/\rho ed) + (g/d)]^{\frac{1}{2}}$$

Figure 4

Simple borehole-cavity resonator with a surface basin and constant mass flow

mass flow $q_0 = \rho av$ (constant)

Equation of motion:

$$D^2u + (v/d)Du + \omega_0^2u = (q/\rho ed)$$

q = source term, impressed oscillatory mass flow

Figure 5

Major Sedimentary Basins of the Pacific Northwest

Contour Indicates
3 km. depth

Geology of The Willamette River Basin And Part of The Lower Columbia River Basin, Oregon

From: F.G. Wells and D.I. Peck (1961) Geologic Map of Oregon West of The
121° Meridian, U.S. Geol. Survey, Miscellaneous Geologic Inv.
Map I-925

Scale
1:50,000

Symbols
Dashed where approximately located
--- Faults
--- Centrif
--- Anticline
--- Syncline
Wells
Oil wells
Water wells

Qpln: Recent terrace deposits

Qtlb: Beach and fluvial; bar and levee

Tpfl: Tertiary, fluvial, bar and levee

Tpml: Tertiary, marine, low energy, bar and levee

Tpml, beach

Tpml, beach: Columbia River mouth, Seaside

Tpml, beach: Marine, low energy, bar and levee

Tpml, beach: Marine, low energy, bar and levee

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Tpml, beach: Marine, low energy, bar and levee

Scale: not the same as the map
Horizontal 1:250,000
Vertical 1:16,000

Well depth in feet from the surface

References:
New to N.Y.C. (1969) Subsurface
Geology Of The Lower Columbia
And Willamette Basins, Oregon;
State Of Oregon, Dept. of Geol.
And Min. Industries, Oil And Gas
Investigations No. 2

Major Sedimentary Basins of the Pacific Southwest

Contour indicates 3 Km. depth

Major Sedimentary Basins of the Northeast

Contour indicates
3 Km. depth

PART (B): UTILIZATION OF GEOTHERMAL FLUIDS IN THE TEMPERATURE RANGE OF 15°C TO 150°C FOR BUILDING HEATING

This part of the report examines the FGR system from the user end. The objective is to evaluate the value of the geothermal fluid to a user and investigate the type of user system. The major emphasis is on fluids in the temperature range at the lower end of the 15°C to 150°C spectrum because so much previous work has considered applications at about 65°C and above. Furthermore, building heating is treated exclusively because, in general, if industrial processes are available that can extract of the order of 20 to 30°C from the geothermal fluid they will have much better economic feasibility and in that sense, the district heating represents a limiting case on the evaluation of direct use at the temperature range considered here.

This part of the report consists of four main sections. First, conceptual designs of overall FGR district heating systems are presented. Next, the type of terminal unit, the in-building energy conversion device, is considered. In the third main section the problem of meeting peak heating requirements is addressed. In the final section, the worth of the geothermal fluid as a function of temperature is considered at two levels--that of the building operator and that of the district heating association.

(XI) CONCEPTUAL SYSTEM LAYOUTS

There are a variety of system configurations that can be used in geothermal heating and the optimal scheme is dependent on a large number of factors. The major concerns in this section are to illustrate, conceptually, a number of layouts of the major equipment in FGR heating systems, and to qualitatively consider their application.

In viewing these conceptual layouts and considering their applicability, a number of general factors should be kept in mind:

- Space heating and sanitary water heating are considered to be the primary goal and space cooling is only considered to the extent that it is noted when a certain system also allows space cooling.
- In FGR systems the more common applications is for the geothermal fluid to be returned to the geothermal resource site for injection, and therefore only dual pipe supply and return systems are considered.
- The geothermal fluid, in certain instances, may not be able to be used directly in certain equipment. In situations where this occurs a heat exchanger will be used to isolate the geothermal fluid from that part of the system. It is becoming quite common to isolate the geothermal fluid to the wells and well head equipment in this manner.
- The power output of an FGR well system is directly proportional to the temperature drop (ΔT_G) of the geothermal fluid that is accomplished by the surface system (Well flow rate being constant). Consequently, a larger ΔT_G means a decreased energy cost at the well head.

- The temperature drop of the heating medium (geothermal fluid, water loop, or space air) that is transmitted to do the heating must be sufficiently large to permit economic transmission lines. In general, for the ranges of distances considered here the greater the transmission distance, the greater this ΔT should be.

The conceptual layouts are separated here into the two main categories of (i) direct heating and (ii) heat pump assisted systems.

(34) Direct heating system layouts

When the geothermal resource has delivery temperatures sufficiently high, heating can be accomplished in a direct manner by systems such as illustrated in Figures B-1 and B-2.

Figure B-1 illustrates the use of the geothermal fluid itself as the heating medium. Although the exact nature of the way in which the geothermal energy would be used depends on the temperature of the geothermal fluid, here the geothermal fluid is split into separate supply paths going to both the sanitary water heating and the space heating. Preheating of the sanitary water is accomplished with the fluids that have been partially cooled in the space heating and in the high temperature sanitary water heater. Such a system would require geothermal supply temperatures of about 60°C or greater to allow the final heating of the sanitary water. For lower temperature source fluids, the sanitary water could have a booster heater to get the required delivery temperature. The system of Figure B-1 is only a good choice when the geothermal fluid is very clean in regard to corrosion and scaling.

Figure B-1. Direct heating using the geothermal fluid as the heating medium in the buildings.

Figure B-2. Direct heating from geothermal energy wherein a secondary loop fluid is heated by the geothermal fluid near the wellhead.

Figure B-2, very similar to Figure B-1, shows how the heating system would be isolated from the geothermal fluid with the use of a secondary loop fluid and a heat exchanger at the well head. Plate type heat exchangers are being readily used for these applications.

The systems of Figures B-1 and B-2 can feasibly operate down to quite low temperatures, in fact the building space heating systems themselves can be designed to economically operate on supply temperatures as low as about 35 to 40°C (See sections (37) and (42) for more discussion of the temperature that can be used). Of course, the sanitary hot water could only be preheated at these temperatures. However, because of the well and transmission system costs, the necessary temperature drop of the geothermal fluid in Figure B-1, and of both the geothermal fluid and secondary loop fluid in Figure B-2 requires the geothermal resource temperature to be somewhat greater than this.

Note that the systems of Figures B-1 and B-2 both have the characteristic that during times of high heating requirements the geothermal part of the system may actually supply less total heating than it does at some other periods. This occurs because in order to get adequate heating from the terminal units, the peaking unit increases the supply temperature which consequently also increases the temperature leaving the terminal unit and for a fixed geothermal temperature means a decrease in energy output from the geothermal resource.

The systems of Figures B-1 and B-2 can also provide space cooling by off-the-shelf absorption systems when the supply temperature to the unit is about 80°C. At this supply temperature however, the temperature drop would only be about 10°C, so to obtain the necessary ΔT_G , a resource temperature

somewhat above this 80°C would be required. It must be noted also, though, that new units developed for solar absorption cooling can operate satisfactorily at inlet temperatures of about 60°C providing the condenser and absorber cooling water temperatures are relatively low, being about 20 to 25°C (Reistad, et al., 1979).

(35) Heat pump assisted systems

Heat pump assisted systems appear to have applicability in FGR under two main circumstances:

- When the resource temperature is too low to allow a reasonable temperature drop of the geothermal fluid in a direct heating system, a heat pump can be used to increase the temperature drop.
- When the temperature of the geothermal fluid is reasonably above that required for the applications, but the flow rate of geothermal fluid is inadequate to accomplish the required heating with the temperature drop attainable by a direct system, a heat pump can be used to increase the temperature drop of the geothermal fluid thereby increasing the energy output of the geothermal system.

This work will concentrate on the first of these circumstances; Niess, 1979 discusses the second. Reistad, et al., 1978 present a basic study which considers the thermodynamic performance of heat pump assisted systems versus direct heating geothermal systems. That study indicated that the heat pump system has potential for resource temperatures in the range of several tens of °F below the desired heating temperature to several tens of °F above the heating temperature. This work considers the performance and economics of specific systems for this range of operation.

There are many ways in which the heat pump assisted systems can be configured. Figures B-3 through B-10 illustrate the main concepts. There are two major types of heat pump assisted systems, the centralized and the distributed systems. Calm, 1979 discusses these types of systems in the context of using waste heat recovery rather than geothermal energy.

Centralized systems: The centralized systems use large industrial or commercial building type heat pumps located either near the wellhead or at centralized points within the city (see Figure B-3). In these systems, the heat pump increases the supply temperature of the secondary water loop and heating in the buildings is carried out by the use of heat transfer equipment similar to that used in the direct systems.

Figures B-4 through B-8 show several configurations that might be used for centralized systems. Figure B-4 shows a configuration where the geothermal fluid is first cooled in a heat exchanger and then further cooled in the evaporator of the heat pump. The separate heat exchanger is desirable when the geothermal fluid temperature is somewhat greater than the secondary loop return fluid temperature. Its use will provide some heating of the secondary loop without a power input to the heat pump.

The direct use of the geothermal fluid in the evaporator of a heat pump is not practiced at this time because of scaling and potential corrosion and consequent maintenance problems.* For this reason a more likely system configuration is that shown in Figure B-5. Here the heat exchanger is used for

*For fluids that have a tendency to scale, the plate type heat exchanger is very nice because of the ease with which it can be cleaned. Such units have not been used as heat pump evaporators probably because of high pressure losses and/or refrigerant leakage. In addition, the prospect of a failure with a brine getting into the compressor of the heat pump system discourages direct use of the geothermal fluid in the evaporator.

Figure B-3. Centralized heat pump assisted systems.

Figure B-4. Centralized heat pump assisted system with geothermal fluid going through the heat pump evaporator.

Figure B-5. Centralized heat pump assisted system with separate loop fluid being cooled in the heat pump evaporator and heated by the geothermal fluid.

Figure B-6. Centralized heat pump system being used in Creil, France (BRGM, 1978).

Figure B-7. Centralized heat pump system which directly uses the geothermal fluid as heating medium (Dvorov, 1975).

Figure B-8. Engine driven heat pump assisted system which includes heat recovery.

Figure B-9. Distributed heat pump system where each residence has a separate water-to-air heat pump that can recover energy from a secondary loop heated by the geothermal resource. The T_L/T_H indicates the possibility of either cooling or heating from the loop fluid, depending on its temperature.

a.)

b.)

Figure B-10. Illustration of distributed heat pump system at the residence.

all geothermal temperatures, and the heat pump allows a larger temperature drop of the geothermal fluid than direct systems by decreasing the secondary loop water temperature returning to the wellhead heat exchanger.

Figure B-6 shows a diagram for the centralized type heat pump system being used in Creil France. Here, the heat pumps (3 in series) cool the return fluid from 2000 apartments heated with floor panels before the fluid enters the heat exchangers where it obtains energy from the geothermal fluid. The output from the heat pumps is used to heat the return fluid from 2000 apartments that use wall convectors and which require a somewhat higher supply temperature than those using the floor panels. Auxilliary energy increases the supply temperature to both apartment complexes at the higher loads.

Figure B-7 shows a complex system that directly uses the geothermal fluid, which was reported by Dvorov, 1975. Here the fluid would have to be very clean.

Figure B-8 illustrates a system that thermodynamically is substantially superior to the systems illustrated above. Here, an engine driven heat pump is used in a manner similar to that described above where electric driven heat pumps were used. But, with the engine driven heat pumps, heat recovery from the exhaust and water jacket can be accomplished to provide a better efficiency and higher (economically achievable) temperatures. These systems are currently being studied by Burmeister and Wain (Petersen, 1978). They do have the potential disadvantage of requiring oil or natural gas as the fuel, whereas the source energy for the electric driven systems can just as well be coal or nuclear energy.

Distributed systems: In the distributed systems, each space or group of spaces is considered to have a separate water-to-air heat pump unit that extracts energy from the geothermal or (more usual) the secondary fluid and heats air from the space temperature to a given supply temperature. The distribution is schematically illustrated in Figure B-9. Figure B-10 shows a more detailed illustration of two possible air and fluid loop flows. The configuration shown in Figure B-10a is felt to be the one that is most appropriate in the application of distributed systems. However, in some circumstances, the system illustrated in Figure B-10b which contains an additional heat exchanger separate from the heat pump (similar to the previously discussed centralized systems) may be desirable. The system of Figure B-10a is considered to be more appropriate for residential applications because it is less complex than that of Figure B-10b and at the temperatures for which the heat-pump-assisted systems are applicable the benefit of the extra heat exchanger is probably quite small. The system of Figure B-10a is the one for which the performance and economic evaluations are made in this work (See section 41).

(XII) TERMINAL UNIT SYSTEMS

(36) Types of terminal units

The term "terminal unit" as used in this report refers to the equipment located at the user site for accomplishing the heating. Table B-1 lists the main types of terminal unit systems that would be used in FGR space heating systems. They are divided into the two main classifications of (i) air systems and (ii) water systems.

Such terminal units, with the exception of variable temperature water source heat pumps, are widely used in conventional heating systems. Forced air systems, both furnace and heat pump (air-to-air) based, are by far the most common residential systems in the U.S. at this time. Baseboard convective type systems are the next most common. The radiant panel systems in common use in the U.S. generally fall into two categories: (i) Radiant floor systems which have pipes embedded in the floor and have hot water circulating through them. These systems are felt to be very good heating systems but are quite expensive and do not allow for air conditioning. They have, consequently, found their greatest application in relatively expensive residences in regions where air conditioning is not required; and (ii) Radiant ceiling systems using electric heating cables embedded in the ceiling. These are fairly common in regions where electricity prices have been low.

The larger wall convectors and floor radiant panel systems are quite common in Europe.

(37) Applicability in FGR systems

Because the general types of units indicated in Table B-1 have been in

Table B-1. Types of Terminal Systems

AIR SYSTEMS

- a. Fan-coil with heat transfer from the geothermal or loop fluid
- b. Individual heat pumps which use the geothermal or loop fluid as a low temperature energy source

WATER SYSTEMS

- a. Baseboard convectors
- b. Wall convectors as used in Europe and Iceland
- c. Radiant wall, floor or ceiling panels
- d. Combinations of c. and a. or b.

common use for some time, it is commonly felt that they may be directly used with geothermal energy. There are, however, two main differences between the application of these units in conventional systems and in geothermal systems:

- The supply fluid temperature in the conventional system may be selected at any value within a relatively broad range without a major change in the overall energy efficiency of the system, while in geothermal applications the supply temperature is restricted by the available resource.
- The temperature drop of the heating fluid may be quite small (less than 10°C is not uncommon) in conventional systems whereas in a geothermal system, the temperature drop is directly proportional to the power output from the well and must be substantially larger, usually several tens of °C.

The use of fan-coils, baseboard convectors, radiant floor panels and water source heat pumps for residential space heating in the U.S. from geothermal resources have been considered previously (Culver, 1976; Engen, 1978). The work by Culver considers a single residence and examines the various systems for heating only. His conclusions were:

- Forced air heating - Will continue to be one of the most popular geothermal heating systems. Can be applicable down to a temperature of about 52°C.
- Baseboard convector systems - Can be more economic than forced air systems but are restricted to delivery water temperatures of about 65°C. Use of these systems at lower temperatures imposes substantial restrictions on interior decorating.

- Radiant floor panel systems - Can usually be used with supply temperatures of 45°C and with restricted use of floor coverings could use fluids down to as low as 38°C.
- Heat pump systems - They are the only method of using the fluid at temperatures less than about 38°C but have quite high costs, in comparison to the other systems that require higher temperatures, when heating only is considered. For cooling also, however, it is probably the most economical system. In addition, there is substantial activity in water source heat pump technology that will improve the position of such systems in the heating only situation.

Engen built on Culver's work, carrying out additional techno-economic evaluations, again for a single suburban residence and for the terminal units that Culver considered. Tables B-2, B-3, and B-4 taken from his work present energy requirements, conventional energy requirements, and annual heating costs for both the geothermal heating systems at several temperatures and the conventional alternative systems. The studies were carried out for off-the-shelf components and a climate like that of Salt Lake City, Utah, or Boise, Idaho. These tables lead to conclusions regarding the economics of various terminal units in geothermal space heating that are for the most part, the same as those presented above from Culver. Engen further iterated the additional conclusions:

- Forced air units - Are probably the most desirable type of residential heating systems because of the general acceptance of these units, and the ease of adapting filtrations, humidity con-

Table B-2. Annual Energy Cost (\$) for Selected Space Heating Systems for a Suburban Residence (Engen, 1978)

Electricity @ 2¢/kWhr, 100% efficiency, (\$5.86/million Btu)

Natural gas @ 30¢/therm, 75% efficiency, (\$4.00/million Btu net)

Oil @ 40¢/gal, 70% efficiency, (\$3.94/million Btu net)

Geothermal, \$1.75-\$6.00/million Btu, 100% efficiency over operating Δt , cost range based on Boise Warm Springs Water District rate and new system estimated rate

Annual Heat Load, 1.152×10^8 Btu

HEATING SYSTEM	FORCED AIR	CONVECTION	RADIANT HOT WATER FLOOR PANEL
Electric	687	676	680
Natural Gas	474	465	470
Oil	436		
Geothermal ^[a] (geothermal energy only)	202-690	202-690	202-690
Additional energy (electricity) required for system operation (pump or fan) ^[b]			
Water-to-air heat pump ($\Delta t=10^\circ\text{F}$)	300		
Operating energy, 120°F water	32		
Operating energy, 140°F water	25	8	21
Operating energy, 160°F water	20	4	8
Operating energy, 180°F water	12	2	5

[a] Heat pump requires 6.52×10^7 Btu geothermal energy @ \$144-\$390 annually, COP = 2.3, where COP = Btuh output/kW input x 3413 Btuh/kW.

[b] Conventional heating system cost includes electrical operating costs about equal to the 180°F geothermal systems.

Table B-3. Estimated Annual Space Heating Costs (4) for Suburban Residence (Engen, 1978)
(Annual Heat Load 1.152×10^8 Btu)

<u>HEATING SYSTEM</u>	<u>FORCED AIR</u>	<u>CONVECTION</u>	<u>RADIANT HOT WATER FLOOR PANEL</u>
Electric (total annual cost)	965	917	1244
Natural gas (total annual cost)	736	743	1069
Oil (total annual cost)	800		
Geothermal energy (cost in addition to capital and operating costs shown below)	202-690	202-690	202-690
Water-to-air heat pump ($\Delta t = 10^\circ\text{F}$) [a]	837 (943) [b]		
120°F water	362 (493)		
140°F water	325 (456)	272 (404)	617 (747)
160°F water	311 (416)	240 (346)	520 (626)
180°F water	310 (415)	204 (310)	518 (624)

[a] Heat pump requires 6.52×10^7 Btu geothermal energy @ \$114-\$390 annually, COP = 2.3.

[b] Cost with heat exchanger indicated as ().

Table B-4. Annual Energy Required for Selected Space Heating Systems
for Suburban Residence (Engen, 1978)

Annual heat load = 1.152×10^8 Btu

Annual Operating time = 2060 hrs

<u>CONVENTIONAL HEATING SYSTEMS</u>		<u>FORCED AIR</u>	<u>CONVECTION (3 ZONE)</u>	<u>H.W. PANEL (3 ZONE)</u>
Heating energy source ^[a] & thermal efficiency				
Electricity	kWhr @ 100%	33,750	33,750	33,750
Oil	gal @ 70%	1,059	1,059	1,059
Natural Gas	therm @ 75%	1,536	1,536	1,536
Operating energy - electricity, kWhr				
Fan	1500 cfm	626		
Circulation pump (80% efficiency)			78	192

<u>GEOHERMAL HEATING SYSTEMS</u>	<u>FORCED AIR</u>					<u>CONVECTION (3 ZONE)</u>			<u>RADIANT PANEL (3 ZONE)</u>		
Water temp., °F	70	120	140	160	180	140	160	180	140	160	180
Temp. drop, °F	10	10	12	25	35	12	20	28	12	20	28
Flow rate, gpm	6	11.2	9.3	4.5	3.2	9.3	5.6	4	9.3	5.6	4
Air flow, cfm	1500	1600	1500	1500	1300						

Heating Energy
Source

Geothermal,
Btu x 10^5 652 1152 1152 1152 1152 1152 1152 1152 1152 1152 1152 1152

Electrical kWhr
(heat pump COP=
2.3) 14675

Operating energy,
electricity,
kWhr

Fan 652 1584 978 978 939

Circulation
pump, (80%
efficiency)

393 168 114 1068 402 270

^[a] Heating energy conversion constants

Electricity 3413 Btu/kWhr
Oil 1.45×10^5 Btu/gal
Natural gas 10^5 Btu/therm

trol, or cooling. These systems can use fluid at supply temperatures as low as 50°C.

- Baseboard convector systems - These appear to be the most economical type of system, but require supply temperatures of 60°C or higher.
- Radiant floor panel systems - Can use water at supply temperatures as low as 38°C, but are quite expensive.
- Heat pump systems - The water source heat pump systems can use fluids at much lower temperatures than the other systems, but if used only for heating are among the most expensive of the systems considered.

Figure B-11 from EG&G, 1978 summarizes the relative economic position of these terminal units as evaluated in Engen's work.

This figure indicates that the geothermal systems to be selected at various fluid supply temperatures are:

10 to 33°C	-	Heat Pump
50 to 60°C	-	Forced Air
60°C and up	-	Forced Air or Convective Baseboard Units (both are quite close)

Notice that this leaves a gap in the terminal unit selection for fluid supply temperatures between 33 and 50°C. Heat pumps with modification in design can operate in this region. In addition, Rosseen, 1978 indicates that they have in operation an office building designed for a water supply temperature of only 30°C in a solar-powered forced air heating system. Here special hollow floor beams are used for the air distribution. Also, the radiant floor systems as

UNIT COST OF POPULAR RESIDENTIAL HEATING SYSTEMS (1978)

ANNUAL TOTALIZED COST FOR RESIDENTIAL SPACE HEATING (1978)

Figure B-11. Relative applicability of terminal unit systems in geothermal applications (EG&G, 1978).

used in Europe typically have supply temperatures of about 38°C (but they probably do not have the extensive floor covering that the U.S. residence requires).

In the evaluations by Engen, reported above, as was noted the equipment units were off-the-shelf items. Particularly for the heat pump units, this has shown them in a poor light. For example, the heating COP used to represent the performance at 70°F water source temperature was 2.3, the annual COP for an air-to-air unit is probably 2 to 2.25 so the improvement in going to the geothermal fluid as a source is slight. The reason for this is that the off-the-shelf unit was primarily designed for air conditioning and cannot adequately take advantage of the increased source temperature.

The terminal units that are considered in detail in this work are the forced air and water source heat pump systems. The heat pump systems will be considered for source temperatures up to about 45°C and the forced air systems will be considered for source temperatures down to about 38°C.

(XIII) PEAKING

District heating systems have substantial load variations and the overall system design must include provisions for properly meeting them. Because the cost of geothermal systems is due mainly to "front-end" capital expenditures rather than to operating costs, it is usually cost effective to incorporate into the system some type of peaking system rather than having a main geothermal system that will be oversize for all except the maximum demand periods. Such peaking systems must have lower first cost per unit of capacity than the main overall system, but may have much higher operating costs.

Here we first consider the nature of the load variations and then discuss several ways in which system capacity increases can be effected to meet them.

(38) Load variations

The load variations can be characterized as arising from three main causes: (i) annual cycles of temperature, (ii) daily cycles of temperature, and (iii) personal habits such as the lowering of thermostats at night, different working hours, shower times, etc.

When outside temperature for the heating season is plotted versus hours at or below that temperature, a curve like Figure B-12 for the Portland climate, results. The ASHRAE 97 1/2° temperature is normally selected as the design point and is illustrated as point A on the figure. Since the heating power requirement is proportional to the difference between the inside temperature and the outside temperature, the power versus hours of duration has the same shape as that for the temperature versus hours curve. Consequently, Figure B-12 also has a power scale plotted on it.

Since energy required is power multiplied by hours of operation, it must

Figure B-12. The temperature (and power) versus accumulated time at or below the given temperature for Portland, OR, 1977.

be the area under the curve in Figure B-12. The shaded area represents the energy that could be supplied by a system capable of delivering 60% of the design requirement power of the residence. This is much more than 60% of the yearly energy requirement for the year. Figures B-13 and B-14 show the percentage of energy requirements that would be met as a function of the capacity (power level) of a heating system for several climates and for the cases of sanitary water heating either being included or not being included. These curves illustrate that about 90% of the energy requirements of residential space heating in these climates can be met with systems that have a power capability of about 55 to 70% of the 97 1/2° ASHRAE design point power. These comparisons can also be put in terms of load factor (energy provided by a system/output Power of System x 8760 hrs). For the Pendleton, OR, climate, a system designed for 100% of the power requirement of the residential system would have a load factor of about 0.3 while for a system designed at 60% of the residential design requirement would have a load factor of about 0.45.

Figures B-12, B-13, and B-14 concern mainly the annual variation in temperature. Consider now the diurnal temperature variation. The daily variation of temperature, of course, varies widely throughout the year. The period at which it is expected to impact the design of a heating system is, however, mainly for those conditions where the outside temperature approaches the design point. Examination of weather records near the design point for the Portland climate indicated that although there may be quite large ($> 20^{\circ}\text{F}$) diurnal temperature variations, there may also be periods of extended duration where the variation is quite small ($< 5^{\circ}\text{F}$). Thus, although the diurnal variation may influence the design and operation of the system it cannot be counted on to decrease the overall system power demand significantly.

Figure B-13. Percent of peak design power versus the percent of total yearly energy requirements that would be met by a system of that power capacity. Sanitary hot water heating is not included.

Figure B-14. Percent of peak power versus the percent of total yearly energy requirements that would be met by a system of that power capacity. Sanitary hot water heating is included.

Variations in the demand power due to personal habits can for the most part be considered to be on a daily cycle.* These variations can be incorporated into the system design on a statistical basis for large enough populations. The major peaks in demand that result are usually reduced substantially by storage because the peaks are typically of quite short duration (especially true for sanitary water heating).

(39) Peaking methods

There are a variety of methods to achieve a capacity increase for a certain period of time in order to limit the size of the main geothermal system:

- Variable Pumping of the Geothermal Reservoir
- Storage
- Fossil Fueled Peaking Station
- Terminal Unit Modification Peaking
- Heat Pump Peaking

Variable pumping of the geothermal reservoir: Variable pumping of the geothermal reservoir can be a good way of meeting the peaking demands of a system. This is presently done in Iceland and has been considered for FGR systems by Bodvarsson and Hansen, 1977.

Storage: The main use of storage to this date in geothermal systems has been to meet short-term load increases that occur on a daily basis primarily due to personal habits. It can be envisioned however, where storage may play a larger role in regard to meeting both diurnal and yearly load variations. The general aspect of storage in aquifers for meeting annual load variations is discussed in Section (24).

*Although certainly there is also a weekly cycle, it is not usually a major factor in the system design.

The possibility of increased application of storage for meeting daily load variations as fossil fuel prices increase is mainly due to two circumstances:

- **Limited Production Rate:** When the geothermal production rate is limited below the peak requirement for a period, but above the average requirement for the same period, storage can be used by producing the reservoir continuously at the limit and meeting the peak by a combination of direct production and reduction of storage.
- **Limited Transmission Line Capacity:** When the geothermal resource is located a substantial distance from the load, storage near the load center can be beneficial in allowing smaller pipelines and decreasing problems arising from the inertia of such a system.

This storage has generally been accomplished in geothermal systems by storage of the hot fluid. Other methods, such as adding capacity to the buildings themselves can also be used and may have substantial benefits in other areas, for example, reducing air-conditioning needs.

Fossil fired peaking station: The use of a fossil fueled unit to increase the temperature of the supply fluid to the district heating system as the outside temperature decreases (and the load gets larger) is a common application. It is used in open systems in Iceland and closed loop systems in France as well as other places. This type of system will certainly continue as the main type of peaking system for some time to come.

Terminal unit modification peaking: The fossil fueled peaking station increases the capacity of the terminal unit by increasing the supply temperature. Unfortunately this also increases the leaving temperature which for both closed and

open heating systems, decreases the proportion of heating from the geothermal system. It appears that a system which would increase capacity by decreasing leaving temperatures would improve the overall system. This could be accomplished by increasing surface area, the heat transfer coefficient, or the lowering of the air temperature in the terminal unit. In a forced air terminal unit system, increasing the fan speed at higher loads will provide both a better heat transfer coefficient and lower (leaving) air temperature, while requiring additional electricity consumption. It appears that with modest oversizing of the terminal unit coil and the use of the multiple speed fan, this type of peaking could be justified. (However, the fossil unit has an inherent advantage in also playing the role as a standby system.)

Heat pump peaking: The capacity of a geothermal production system can be increased by use of a heat pump which extracts additional energy from the geothermal fluid and provides either an increased flow at the same temperature, or an increased temperature for the same flow in the heating fluid circuit. This type of system is in operation in France. It must be noted, however, that since heat pumps, like geothermal energy systems, are capital intensive, such an operation is not the usual peaking. Such a system is only reasonable if the heat pump operates at a reasonable load factor for the year. For this to be the case, then the geothermal system by itself (without the heat pump operating) must only be capable of providing 10 to 30% (approximate range only) of the power demand for the application. The maximum power that occurs for only a few hours a year will probably be met by another form of peaking (fossil fueled units are used in France).

(XIV) EVALUATION OF THE WORTH OF GEOTHERMAL FLUIDS

In this section, the objective is to evaluate and examine the economic break-even price that could be paid for geothermal fluids, relative to conventional fuels, in a district heating operation. The break-even price is dependent on a large number of factors, the major ones of which are presented in Table B-5. Those marked with an asterisk in Table B-5 are considered either as a variable or as a multi-valued parameter. Of these, the main emphasis is on the terminal unit and the geothermal fluid temperature.

(40) Study definition

To delineate the extent and bounds of the study conducted here, the treatment of each of the major factors listed in Table B-5 will now be considered.

Temperature of geothermal fluid: The system which uses a secondary loop fluid is felt to be the more common type of installation, and was the type of system assumed here. No analysis of the wellhead heat exchanger was accomplished, but the approach temperature in the plate type heat exchangers quite often used for this application are typically economic at less than 5°C. Secondary loop fluid temperatures ranging from 15°C(60°F) to 60°C (140°F) were considered, and consequently with the 5°C approach temperature, the geothermal fluid supply temperatures may be considered to vary quite closely over this same range.

Table B-5. Major factors influencing the economic break-even price of geothermal fluids for district heating.

- * TEMPERATURE OF GEOTHERMAL FLUID
- * TYPE OF TERMINAL UNIT
- * CLIMATE
 - Peak Heating
 - Degree Days
 - Cooling Requirement
- * TYPE OF RESIDENTIAL UNIT
 - DENSITY OF UNITS
- * TOTAL NUMBER OF UNITS
- * ALTERNATIVE ENERGY COSTS
- * FINANCING FOR RESIDENCE EQUIPMENT AND DISTRIBUTION SYSTEM

Type of terminal unit: Section XII of this report considers the various types of terminal units. Here, the two types of terminal units considered are the forced air direct heating system and the distributed heat pump assisted system.

Climate: Two climatic areas were considered, Portland, OR and Pendleton, OR. The ASHRAE recommended 97-1/2° design temperature and the heating degree day values are -5°C (23°F); 2575 °C·Days (4635 °F·Days) and -15 °C(+5°F); 2848 °C·Days (5127 °F·Days) respectively. It was also desired to consider an Eastern United States site; Trenton, New Jersey was selected. It turned out that the Trenton climatic conditions are quite comparable to those of Portland and really lie between those of Portland and Pendleton. Since the evaluations were made first for the Portland and Pendleton climates, they were not repeated for the Trenton site.

Residence type and density: Table B-6 lists the specifications of the residences considered, in terms of their type, size, energy loss characteristics, number of people, water consumption and density. Three levels of building construction corresponding to different degrees of energy conservation are presented in a context patterned after Kirschbaum and Veyo, 1977. Level 2, which corresponds to residences constructed according to standards in common use during the most recent five-year period, is the one selected for major consideration here. Furthermore, for the most part, only low rise apartments and suburban applications are considered. Table B-7 presents the space heating power and annual energy requirements for single units and for a group of units with 1,000 population for each building type and each of the two

Table B-6. CHARACTERISTICS OF RESIDENCES CONSIDERED^{1/}

Type ^{2/}	ENERGY LOSS COEFF. W/°Cm ² (Btu/hr°F ft ²)		Average Floor Area Per Unit m ² (ft ²)	Average No. of People Per Unit	Average ^{3/} Hot Water Demand (Gal/Day)	Density ^{4/} Units/km ² (Units/Acre)	Population ^{4/} Density /km ² (/acre)	No. of Stories
Suburban			139 (1500)	3.5	(70)	1000 (4)	3500 (14)	1
Level 1	3.5	0.58						
Level 2	2.35	0.39						
Level 3	1.5	0.26						
Low Rise Apt.			102 (1100)	3	(60)	(30)		3
Level 1	2.3 ^{5/}	0.38						
Level 2	1.7 ^{5/}	0.29						
Level 3	1.0	0.16						
High-Rise Apt.			74 (800)	2	(40)	16,000 (65)	32,000 (130)	10
Level 1	2.1	0.35						
Level 2	1.5	0.26						
Level 3	0.9	0.15						

_____ - Primary level considered in this work.

^{1/} Most of the data in this table are compiled as average representations from references McDonald (1977), Reistad (1977), Kirschbaum (1977), and Reistad et al. (1974).

^{2/} Three levels of construction are presented (after Kirschbaum (1977): Level 1 - typical of residential building practices employed during the period of 5 to 15 years ago; Level 2 - residences constructed according to standards in common use during the recent 5 year period; Level 3 - projected values for residences built with very strict energy conservation guidelines. Level 2 is used as the normal type of construction to be considered in this work.

^{3/} Estimated hot water use at a supply temperature of 140°F, from Reistad (1977). Estimates of energy requirements must also include losses from the storage tank. Jackson (1972) reports about an 18% loss for a 50 gallon storage tank.

^{4/} McDonald (1977).

^{5/} Coulbois and Herault (1975) report that in the Parisian Basin in France, the accepted levels of energy loss from apartments are about 0.8 to 1.1 W/°Cm³. For a typical 2.44 m (8 ft) ceiling height, these result in loss coefficients of 1.0 to 2.7 W/°Cm². There, the apartments are typically 3 to 5 stories.

Table B-7.

SPACE HEATING POWER AND ENERGY REQUIREMENTS OF SOME COMMUNITIES^{1/}

Building Type	People Per Unit	PORTLAND (-5°C DESIGN)				PENDLETON (-15°C DESIGN)			
		PER UNIT		FOR 1000 POPULATION		PER UNIT		FOR 1000 POPULATION	
		Peak Design (kW)	Yearly Energy Use (kW-hr)	Peak Design (MW)	Base Design (MW) ^{2/}	Peak Design (kW)	Yearly Energy Use (kW-hr)	Peak Design (MW)	Base Design (MW)
Suburban	3.5								
Level 1		12.72 [13.58]	38,117 [43,461]	3.63 [3.88]	2.18 [2.33]	17.59 [18.45]		5.01 [5.25]	3.01 [3.16]
2		8.54 [9.40]	25,592 [30,936]	2.44 [2.69]	1.46 [1.61]	11.81 [12.67]	30,338 [35,682]	3.37 [3.62]	2.02 [2.17]
3		5.45 [6.31]		1.56 [1.81]	0.94 [1.09]	7.54 [8.40]		2.15 [2.40]	1.29 [1.44]
Low Rise	3								
Level 1		6.12 [6.85]	18,354 [22,909]	2.04 [2.28]	1.22 [1.37]	8.47 [9.20]		2.82 [3.06]	1.69 [1.84]
2		4.53 [5.26]	13,618 [18,173]	1.51 [1.75]	0.91 [1.06]	6.26 [6.99]	16,143 [20,698]	2.08 [2.32]	1.25 [1.40]
3		2.66 [3.39]		0.89 [1.13]	0.53 [0.62]	3.67 [4.40]		1.22 [1.46]	0.73 [0.88]
High Rise	2								
Level 1		4.05 [4.54]		2.03	1.22	5.61 [6.10]		2.80 [3.04]	1.68 [1.83]
2		2.89 [3.38]	8,687 [11,753]	1.45	0.88	4.00 [4.49]	10,298 [13,364]	2.00 [2.25]	1.20 [1.35]
3		1.73 [2.22]		0.87	0.52	2.39 [2.88]		1.20 [1.45]	0.72 [0.87]

^{1/} All values in [] include sanitary water heating requirements. The design rate is estimated at rate equivalent to the daily consumption occurring during 17 hours of demand.

^{2/} Here, base design means 60% of peak design. This represents a capacity capable of supplying 85 to 95% of the yearly energy requirements for the locations considered.

_____ Cases considered here.

climates. Both a peak design and a base design (60% of peak) are presented for the 1,000 population grouping; illustrating the significant reduction in well power that is possible when peaking is provided.

Number of units: The basic performance and in-building costing calculations are carried out for a single unit of the type selected. When including the cost of the distribution system, however, developments of populations of 5,000 people are considered.

Alternative energy costs: The analysis is done here relative to two basic conventional type systems, electric resistance heating and air-to-air heat pumps. It is realized that these systems are not necessarily the most economic in all regions of the U.S. However, in light of the dramatically changing situation in regard to both price and availability of oil and gas the electric based systems appear to be a good choice.* The range of electricity costs considered for the comparison systems are 2 to 5¢/kW·hr. For comparison, Table A-6, presented earlier, illustrates the costs of energy in Trenton and Portland during January 1979.

Financing of residential equipment and distribution system: The distribution system on the other hand was considered to be financed either by a private utility or by a municipality, and here, the costs of McDonald, 1978 and Bloomster, et al., 1977 have been used which show a 50% increase in distribution

*We also have not considered the influence of controls in other types of electrical heating systems. For instance electric ceiling or baseboard heat can economically have individual room control and at high electricity costs can be much cheaper than forced air electric resistance.

costs with private utility financing compared to municipal financing. The residential equipment was considered to be financed by the individual residence owner at an interest rate of 9%.

Inside comfort condition: The interior condition was specified at 70 °F and there was no provision made for humidification in either climate.

Peaking and storage: In this section, the only treatment concerning either peaking or storage is that base designs representing 60% of the peak design are illustrated in regard to required geothermal fluid flow rates.

(41) Heat pump assisted system

Description: The heat pump assisted system (HPS) that is considered here is illustrated schematically in Figure B-15. The unit supplies space heating only and the air temperature into the condenser is constant at 21°C.*

Figure B-15 presents a system typical of commercially available water source heat pumps. However, at the residential size the commercially marketed water source heat pumps have not been directed at a primarily heating market, but rather they have, for the most part, been designed to have a very good performance for cooling and merely a reasonable performance for heating. In this work we are considering a heat pump unit designed primarily for heating and at each different geothermal loop fluid temperature and temperature drop

*The sanitary hot water (SHW) heating could also be supplied to a large extent from the heat pump, but doing so would make the analysis more complex and was deferred at this point. It should be noted, however, that the inclusion of the SHW would in general improve the position of using geothermal energy.

Figure B-15. Basic heat pump assisted system located at residential user, with geothermal or loop water as energy source in the evaporator.

it is assumed that the unit is redesigned for proper performance.

The next section on performance details the specifications and performance of the units considered here.

Performance: As mentioned above, the commercially available water source heat pumps that are of residential size have been designed primarily for cooling rather than heating. When these are used with geothermal fluid for heating, they do not make good use of the higher temperature of the geothermal fluid because they have not been designed for it. Briggs and Shaffer, 1977 show there is relatively little improvement in COP as the water temperature increases above about 15 to 20°C. Figure B-16 shows a plot of the heating coefficient of performance (COPH) for a number of these commercial units as a function of the fluid supply temperature. Superimposed on this data is a plot of the COPH of a hypothetical heat pump with a constant condenser temperature of 49°C (120°F) and with a performance of 0.5 that of an ideal Carnot cycle unit. Actual units can in general be expected to have a performance of about 0.5 that of a Carnot unit. Notice here, however, that the performance of the commercial units closely approach the performance of the hypothetical unit only at the 60°F temperature. As the loop fluid temperature is increased the commercial unit performance drops off relative to the hypothetical cycle.

In order to consider heat pump assisted systems in the light that we felt would show their potential, we modelled the heat pump and considered its performance to be characterized as 0.5 that of a Carnot unit for the compressor power; and the fan power was assumed constant. The specifications of Table B-8 along with Figure B-15 illustrate the model for an 11.7 kW

Figure B-16. Heating coefficient of performance (COPH) for several commercially available water source heat pumps and hypothetical unit (modified) which has a constant condenser temperature of 49°C (120°F) and a performance 0.5 that of an ideal Carnot cycle unit.

Table B-8. Specifications of Heat Pump Model for 11.7 kW Heating Capacity Unit

$$\dot{Q}_{\text{output}} = 11.7 \text{ kW (40,000 Btu/hr)}$$

$$\dot{W}_{x,\text{fan}} = 0.42 \text{ kW}$$

Air Temperature into Condenser - 21°C (70°F)

Air Temperature Leaving Condenser - 41°C (105°F)

Condenser Temperature - 49°C (120°F)

Approach Temperature, Air Side - 8.3°C (15°F)

Approach Temperature, Water Side - 5.6°C (10°F)

$$\text{COPH} = \frac{\dot{Q}_{\text{output}} + \dot{W}_{x,\text{fan}}}{\frac{\dot{Q}_{\text{output}}}{a(\text{COPH})_{\text{cc}}} + \dot{W}_{x,\text{fan}}}$$

where

$$a = 0.50$$

$$\text{COPH}_{\text{cc}} = \text{Carnot cycle COPH based on condenser and evaporator temperatures} = (T_c / (T_c - T_e))$$

output unit. The temperatures of the air, inlet and outlet, and the condenser temperature are maintained constant at 21°C, 40°C and 49°C respectively. For each different inlet loop fluid temperature and temperature drop, the unit is redesigned to maintain a constant heating output of 11.7 kW. The approach temperatures assumed were 5.6°C for the refrigerant-to-water heat exchanger and 8.3°C for the refrigerant-to-air heat exchanger. The COPH is determined from the equation presented.

Table B-9 presents the COPH and the required water flow rate for this unit as a function of the water inlet temperature and its temperature drop. Figure B-17 presents the COPH in graphical form to compare with the commercially available residential units. Also included in Figure B-17 are points showing the performance of the "templifier" unit which is an industrial type unit being marketed by Westinghouse for use with higher temperature fluids than normal units.

Economic evaluation: As indicated above, the economic evaluation is a determination of the break-even price that can be paid for the geothermal fluid when comparing the cost of the geothermal system to electric resistance heating. Table B-10 presents the economic parameters assumed for the geothermal system and the electric resistance system.

Figures B-18, B-19, and B-20 present the break-even price of the geothermal fluid for the three cases of suburban residences in Portland and Pendleton and low rise apartments in Pendleton relative to electric resistance heating. The values are presented as a function of the geothermal fluid supply temperature with the cost of electricity as a parameter. The individual point on each curve corresponding to a specific geothermal supply

Table B-9. COPH and flow requirements (GPM) for 2-1/2 ton water source heat pump as a function of entering fluid temperature and temperature drop.

Loop Fluid Entering Temperature	Loop Fluid Temperature Drop	10°F (5.6°C)	15	25	35	45	55	65
60°F (15.6°C)		3.32 (5.59)	3.15 (3.64)					
70 (21.1)		3.74 (5.86)	3.52 (3.82)	3.15 (2.19)				
80 (26.7)		4.27 (6.13)	3.99 (4.0)	3.52 (2.29)	3.15 (1.56)			
90 (32.2)		4.97 (6.39)	4.59 (4.17)	3.99 (2.4)	3.52 (1.64)	3.15 (1.21)		
100 (37.8)		5.96 (6.66)	5.42 (4.35)	4.59 (2.5)	3.99 (1.72)	3.52 (1.27)	3.15 (0.99)	
110 (43.3)		7.43 (6.93)	6.62 (4.53)	5.42 (2.51)	4.59 (1.79)	3.99 (1.33)	3.52 (1.04)	3.15 (0.84)

Figure B-17. COPH of modified water source heat pump unit as a function of loop fluid temperature and temperature drop. Also illustrated is the Westinghouse Templifier unit.

Table B-10. Assumptions for economic analysis of heat pump system and electric resistance heating system

GENERAL

Installation cost (\$)	100% of initial cost
Maintenance cost (\$/yr)	10% of initial cost
Interest rate	9%

HEAT PUMP SYSTEM (HPS)

Life expectancy	13 years
Condenser temperature	48.9°C (120°F)
Air entering temperature	21.1°C (70°F)
Water entering temperature	15.6 to 43.3°C (60 to 110°F)

ELECTRIC RESISTANCE FORCED AIR SYSTEM

Life expectancy	14 years
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Figure B-18. The value of thermal water at the consumer level for the heat pump system, relative to electric resistance heating, for suburban residences located in a Portland, OR, climate.

Figure B-19. The value of thermal water at the consumer level for the heat pump system, relative to electric resistance heating, for suburban residences located in a Pendleton, OR, climate.

Figure B-20. The value of thermal water at the consumer level for the heat pump system, relative to electric resistance heating, for low rise apartments located in a Pendleton, OR, climate.

temperature is for the temperature drop across the heat pump that will result in the greatest price that can be paid for the geothermal fluid. In the cases considered here, this results in the largest temperature drop allowable and corresponds to the entry in the furthestmost space to the right for each supply temperature in Table B-9. This ΔT is the supply temperature minus 45°F for the heat pump systems evaluated here.

It is informative to adjust the break-even prices of Figures B-18, B-19, and B-20 to be a price that represents that which could be paid at the entrance to a distribution system rather than merely at the consumer "doorstep". This can be accomplished by taking these figures and superimposing the distribution cost that would be incurred at each supply temperature and its corresponding temperature drop. The approach used to accomplish this is to take the work of MacDonald, 1978 and Bloomster, Fassbender, MacDonald, 1977 and revise it to correspond to the climate, building type, population density and level, design temperature drop, etc. that is desired. Figures B-21, B-22, and B-23 illustrate the previous three figures, but here with the distribution costs superimposed. The worth of the geothermal fluid at the distribution system entrance, is then the difference between the break-even price curve corresponding to the desired electricity rate and the specific distribution cost curve. Figure B-24 presents this difference for the low rise apartments in a 5,000 population for the Pendleton climate.

The per unit cost of fluid presented above may be used to compare with the cost of geothermal fluid from a specific system to determine the feasibility, but it doesn't necessarily indicate the total picture. Another indication is the total expenditure that can be made for the geothermal production system. To determine this, the unit water price that can be paid can be multiplied by the yearly water consumption to obtain an allowable yearly expenditure that the

Figure B-21. Fluid worth at the consumer level and distribution cost for 5,000 population service area of suburban residences in a Portland, OR, climate.

Figure B-22. Fluid worth at the consumer level and distribution cost for 5,000 population service area of suburban residences in a Pendleton, OR climate.

Figure B-23. Fluid worth at the consumer level and distribution cost for 5,000 population service area of low-rise apartments in a Pendleton, OR, climate.

district heating system can pay for the geothermal production system. This allowable yearly expenditure when divided by the overall annual capitalization factor then yields the allowable initial investment in the geothermal production system.

Figure B-25 presents both the allowable yearly expenditure and allowable initial investment in the geothermal production system as a function of the temperature of the geothermal fluid, assuming an overall 20% annual capital recovery factor. The figure is for a 5,000 population development in a Pendleton climate and illustrates the influence of the cost of electricity and municipal vs. private utility financing of the distribution system as well as the variation of geothermal fluid temperature. Also illustrated is the required geothermal fluid flow rate for both the peak design and the base design of 60% of the peak.

This figure illustrates that for a situation wherein 100°F water is available and the distribution system is municipally financed, \$0.55 M, \$1.4 M and \$2.25 M could be invested in the geothermal resource itself to produce a flow of 720 GPM to satisfy the base load up to 60% of the peak and compete with electrical resistance heating at a price of 3, 4, or 5¢/kWh respectively.

Another informative way of viewing these economic data is to consider that the flow of an average well might be estimated at 500 GPM (31.6 kg/s) and the allowable investment per FGR system production unit (either borehole pair for loop systems or borehole for uniform systems) evaluated on this basis. Figure B-26 illustrates in bar-graph form this allowable investment for the 5,000 population apartment grouping in a Pendleton climate. The influence of the major variables, alternative energy cost (electricity cost), financing method and temperature of the geothermal fluid are illustrated.

Figure B-24. Value of fluid at the district heating association level for use in a heat pump system relative to electric resistance heating for a 5,000 population service area of low rise apartments in a Pendleton, OR, climate.

Figure B-25. Allowable yearly expenditure and allowable initial investment (at 20% overall capital recovery factor) in an FGR production system where the fluid is to be used in a heat pump system and the geothermal system is competitive with electric resistance heating. Also illustrated are the flows required at both peak and 60% of peak design power.

Figure B-26. Allowable investment in FGR production system per production unit as a function of temperature, electricity cost and distribution financing for district heating, by the distributed heat pump system, of a 5,000 population low rise apartment complex in a Pendleton, OR, climate. The borehole is assumed to deliver 500 GPM (31.6 kg/s).

(42) Forced Air Systems

Description: Forced air geothermal systems (FAS) for residences and apartments, as envisioned here, would consist of a fan-coil unit instead of the usual forced-air oil, gas, or electric resistance furnace. The fan-coil unit would have a finned tube heat exchanger through which the geothermal fluid would flow. Figure B-27 illustrates the system. The temperature of the air returning from the space is assumed constant at a nominal value of 21°C (70°F).

Performance: In the fan-coil units, the items that characterize the performance are:

- Air delivery temperature (for constant inlet temperature)
- Entering geothermal loop fluid temperature
- Temperature drop of geothermal loop fluid
- Pump power
- Fan power

The air delivery temperature directly influences the amount of air that must be sent to the space since the heating load $\dot{Q}$ is equal to

$$\dot{Q} = \dot{m}_{\text{air}} C_p (T_D - T_S)$$

where $\dot{m}_{\text{air}}$ is the mass flow rate of air, T_D is the delivery temperature, and T_S is the space temperature.

The air delivery temperature thus cannot be too close to the space temperature or the flow rate of the air to and from the space will be too large for reasonable ducting and air distribution within the spaces. Furthermore, the air delivery temperature may not too closely approach the geothermal loop fluid inlet temperature or the surface area of the heat exchanger will be too

Figure B-27. Schematic illustration of direct geothermal forced air system (FAS).

great. Present practices in conventional systems have delivery temperatures in the ranges illustrated in Table B-11. In this work, the air delivery temperature varies in the range 37 to 55°C.

The entering geothermal loop fluid temperature is the major variable being considered and values from 38 to 66°C are considered.

The temperature drop of the geothermal fluid was found to have a very significant influence on the heat pump system economic feasibility. Here, the temperature drop is considered as a variable, although in general the study is directed toward making the temperature drop as large as possible for the specific set of entering geothermal loop fluid temperature and space temperature, while maintaining the friction losses on both the air and water sides at reasonable values. In this regard, two approaches were taken:

- Fan-coil units typical of present use in various residential applications were selected from manufacturer catalogs to give the maximum temperature drop of the geothermal loop fluid.
- Commercial type coils were selected to obtain desired temperature drop of the geothermal fluid.

The residential fan-coil units selected from catalogs were inherently restricted to quite low temperature drops. From the commercial type units, however, quite sizeable temperature drops were realized and these appear to be much more applicable to geothermal system use than those units that have typically been used as fan-coil units in residential applications. The commercial type coils will be considered almost exclusively here, although some comparison with the typical residential system unit will be presented.

Economic evaluation: In a manner analogous to that presented for the heat pump

Table B-11. Typical air delivery temperatures for conventional residential forced air systems

<u>Type of System</u>	<u>Supply Temperature</u>
Oil Furnace	55 - 70°C
Gas Furnace	55 - 70°C
Electric Resistance Furnace	52 - 60°C
Heat Pump	38 - 46°C

system, the break-even price that can be paid for the geothermal fluid when comparing the cost of the geothermal system to that of electric resistance heating is now presented for the forced air system.

Table B-12 presents the economic parameters assumed for the geothermal system, those for the electric resistance heating system were illustrated in Table B-10. Figure B-28 illustrates the costs of the duct system as a function of volume flow rate of the air; these were developed for a suburban residence.

Figure B-29 presents the break-even price of the geothermal fluid for the Portland suburban residence as a function of entering geothermal loop fluid temperature for three cases. The three cases illustrated are (i) the heat pump system, (ii) the forced air system with commercial heat exchanger coils, and (iii) the forced air system with residential fan-coil units. Note that the temperature drop of the geothermal loop fluid (ΔT) is also illustrated for each of the three cases. It is very evident from this figure that it is important to design for a large ΔT across the coil. From this point on, unless indicated otherwise, the forced air system using the commercial coils will be the only forced air system considered. Figure B-30 presents the break-even price for the forced air system in low rise apartments for the Pendleton climate, at the consumer site. Figure B-31 presents the break-even price for the same cases, but at the entrance to the distribution system for a population of 5000.

Figure B-32 presents both the allowable yearly expenditure and allowable initial investment in the geothermal production system as a function of the geothermal fluid. The figure is again for a 5000 population development in the Pendleton climate and illustrates the influence of cost of electricity and method of financing the distribution system as well as the variation of geothermal fluid temperature. Also illustrated is the required geothermal fluid flow rate for both the peak design and the base design that would meet 60% of

Table B-12. Data and assumptions for economic analysis of direct forced air geothermal system (FAS)

Installation cost (\$)	100% of initial cost
Maintenance cost (\$/yr)	10% of initial cost
Interest rate	9%
Life expectancy	15 years
Air entering temperature	21.1°C (70°F)
Water entering temperature	37.8 to 65.6°C (100 to 150°F)

Figure B-28. Cost of duct system as a function of flowrate for a suburban residence, including insulation and installation.

Figure B-29. The value of thermal water at the consumer level as a function of temperature for the HPS and the FAS relative to electric resistance heating. For the FAS, both systems that use commercial unit coils and off-the-shelf residential type coils are illustrated.

Figure B-30. The value of thermal water at the consumer level, as a function of temperature for the forced air system relative to electric resistance heating for low rise apartments in a Pendleton, OR, climate.

Figure B-31. Value of fluid at the district heating association level for use in a forced air system relative to electric resistance heating for a 5000 population service area of low rise apartments in a Pendleton, OR, climate.

Figure B-32. Allowable yearly expenditure and allowable initial investment (at 20% overall capital recovery factor) in an FGR production system where the fluid is used in a forced air system and the geothermal system is competitive with electric resistance heating.

the peak power and about 90% of the energy requirements of the demand system.

Let us again consider that the flow of an average well might be 500 GPM (31.6 kg/s). The allowable investment in the FGR system per production unit can then be estimated. Figure B-33 presents these allowable investment estimates for the forced air system and the 5000 population low-rise apartment development in the Pendleton climate.

Figure B-34 represents a superposition of data from Figure B-26 for the heat pump system and Figure B-33 for the forced air system. It presents the allowable investment in the FGR production system per production unit as a function of the temperature of the geothermal fluid for the 5000 population low rise apartment development in the Pendleton climate. Several general conclusions can be drawn from this figure:

- The heat pump system is the economically preferred system at fluid temperatures up to 110°F and possibly up to 120°F.
- Geothermal fluids in the 90 to 110°F range have a value in the heat pump system similar to the value that fluids in the 130 to 150°F range have in the forced air system.
- For regions where the lower-priced electricity prevails, the higher temperature fluids and/or shallow resources are necessary for economic viability. In regions where the electricity prices are in the range of 5¢/kW·hr however, much lower temperature fluids and deeper resources can be economic.

These conclusions must, however, be viewed within the context of the potential variables that have been fixed (i.e., the constraints) for Figure B-34. A number of these constraints have been discussed explicitly as major factors above; other have not. The major constraints that appear to need

Figure B-33. Allowable investment in FGR production system per production unit as a function of temperature, electricity cost, and distribution financing for district heating, by a forced air system, of a 5000 population service area of low rise apartments in a Pendleton, OR, climate. The borehole is assumed to deliver 500 GPM (31.6 kg/s).

Figure B-34. Superposition of results of allowable investment in FGR production systems per production unit for the heat pump system (H) (Fig. b-26) and the forced air system (F) (Fig. B-33).

emphasizing at this point are:

1. Preferential tax treatment. Presently, geothermal or solar installations for private homes are eligible for Federal and in some instances, State tax credits. The applicability of these in a district heating system is not clear at this time. Providing the credits are available, they could substantially increase the relative economic desirability of the geothermal systems.
2. Residential energy requirements. In all of the work presented here, Level 2 type buildings were considered. These units require substantially less energy than the Level 1 units and as a result, the distribution cost as a percent of energy cost is much higher for the Level 2 buildings than it is for the Level 1 buildings. Thus, the improved design of buildings for less energy consumption tends to discourage district heating type systems, although both are probably desirable from the viewpoint of long range planning.
3. Inflation. Because the district heating system and the FGR system main costs are initial investments, and they have long lives, they are advantageous in an inflating economy relative to systems that have most of their costs arising from operating costs. As a result, the proper way of viewing the curves presented here is to consider the electricity cost, not at present values, but at an approximate average value for the life of the system.
4. Alternative energy system. The conventional system that is being compared against is the electric resistance heating system. This is a reasonable choice as discussed above. Another possibility is the air-to-air heat pump. Particularly for the higher electricity

prices and the milder climates, the air-to-air heat pump is recognized as preferable to the electric resistance system. As a result, in these regions it would be expected that comparison with the air-to-air heat pump would decrease the economic desirability of the geothermal systems relative to that illustrated here.

5. Population. The system population considered here is 5000. As the served population is increased, the distribution cost can be decreased substantially. McDonald, 1978 shows a decrease in district heating cost of about 50% for a population increase from 5000 to 30,000 for low-rise apartments.

(C) SUMMARY AND CONCLUSIONS

At this end, we will proceed to summarizing the essential results of the present project and make a few relevant comments. We will, in particular, focus our attention on the question of the technoeconomical feasibility of FGR systems to supply energy for building heating.

It is quite evident that the feasibility of FGR is a function of a number of geological, geophysical, engineering, architectural and financial variables that form a multidimensional parameter space. The general structure of this space is really quite complex and, as has been emphasized above the situation is compounded by the very considerable uncertainty as to the future evolution of costs and prices in the energy market. While it is rather obvious to require FGR systems to have life-times of the order of 20 to 30 years, we are unable to predict the evolution of the energy market for periods of this length. Moreover, we will also have to underline the limited effort and scope of the present project. This situation essentially prevents us from reliable detailed quantification of the measures of long term FGR feasibility, and we will be unable to make direct use of some of the theoretical econometric relations set forth in chapter (IV) above.

We have therefore chosen to outline the bounds of FGR feasibility rather than become involved in a more detailed investigation of the parameter relations. In other words, we will below list a number of quite general conditions that emerge from our study as being the main bounds on the feasibility of FGR in the building heating market. The material that we apply here arises, in particular, from chapter (XIV) of part (B) above.

(43) Mean margins of the feasibility of FGR systems for building heating

Considering the material that has been set forth in this report, we concentrate on the Pacific Northwest and assume that conditions (a) to (d) below can be met.

- (a) The feasibility of FGR is viewed from the vantage point of regions of near normal subsurface temperature and heat flow fields. Fluid conductor structures to recover the heat are assumed to be available at suitable depths. To take examples from the Pacific Northwest, parts of the Willamette Valley in Oregon and the Columbia Basin in Oregon and Washington would be prospective regions of this type (see section (18)).
- (b) Climatic conditions at Pendleton, Oregon, are taken to be representative for large sections of the Pacific Northwest.
- (c) Municipal financing is taken to be possible for the distribution systems. House systems are financed by individual owners. Details of financing as in section (40) above.
- (d) The FGR systems provide only the base heating load amounting to 60% of the peak power but are then able to provide 90% of the annual energy consumption.

As our main criterion we

- (e) evaluate feasibility on the basis of a near term (possibly next five years) price level where the average alternative (fossil fuel, electricity) effective energy costs are taken to be equivalent to 3 cents/kWhr electricity, that is, \$8.40/GJ.

On these premises, we find then that for FGR systems to be feasible

- (f) wells in uniflow and/or loop FGR systems should preferably flow no less than 40 kg/s. Note that this is higher than assumed in section (40).

- (g) The minimum energy market for individual FGR operations supplying either HPS (heat pump assisted) or FAS (forced air) units consists of a community of no less than about 5,000 inhabitants living in low-rise apartments of normal density. The minimum (base) heating load is about 6 MWt.
- (h) The approximate lower bounds for the source temperature are

	Uniflow	Loop
HPS	42	50°C
FAS	52	70°C

Loop exit temperatures are defined in section (40).

(44) Comments

- The margins of feasibility as listed under (a) to (h) above are to be understood as plausible mean or average margins rather than absolute conditions. In other words, an individual condition or margin can be violated provided there is adequate compensation in other areas. For example, a certain reduction of the temperature limits under (h) can be allowed if the wells flow more than 40 kg/s.
- As to the fixed energy cost assumed under (e), we remark that the retail costs of fuel oil in Portland, Oregon, and Trenton, New Jersey, have by early June 1979 already risen to \$5.60/GJ and \$6.31/GJ (effective) respectively. This is more than 30% over the values given in Table A.IV for January 1979. The abrupt rise portrays the difficulties involved in estimating the future price level.
- It is of interest to note that the costs of distributing heat in the systems under consideration above varies from 2.70 to 4.10 \$/GJ for FAS and from 2.80 to 4.80 \$/GJ for HPS.

- Optimal operational conditions (source temperature, depth) will be above the marginal conditions given under (h) above. The optimums depend critically on the parameter f defined in equation (A.28) and (A.29) and will thus be very site specific.
- The marginal temperatures given for loop FGR systems to operate HPS turn out to be higher than the upper LT margin defined in section (2). In general, the temperature region of feasibility of FGR operated HPS is quite narrow.
- We have not made an in-depth comparison of the economics of FGR systems to alternative non-fossil systems such as solar and air-to-air heat pumps. However, referring to the very considerable costs of solar collectors and the resulting high costs of solar energy, we conclude that FGR systems will have an obvious advantage.
- Moreover, as stated at the onset, we have not investigated multiple uses for FGR waters in the HT range (90°C to 150°C) such as combined heating and air conditioning. We are, on the other hand, of the opinion that the feasibility of using HT FGR waters for heating alone is also covered by statement (h) above.

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