Special Report No. 5

A Symposium on Geothermal Energy and its Direct Uses in the Eastern United States

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Work performed under

U.S. Department of Energy

Grant No. ET-78-G-03-2118

April 1979

**Geothermal Resources Council
P. O. Box 98
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GEOHERMAL RESOURCES: AN INTRODUCTION WITH EMPHASIS ON LOW TEMPERATURE RESERVOIRS

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ABSTRACT

Utilization of the enormous potential of terrestrial heat with today's technology is economically feasible if a subsurface reservoir exists from which a fluid with elevated temperature can be produced. For district heating the minimum temperature is 55-60°C (130-140°F) and the production rate around 70 m³/h (300 gpm); thus the reservoir must have high natural porosity and permeability. In impermeable rocks artificial heat extraction loops can be created.

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

1. Definition, Classification

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

Geothermal resources can be divided into two broad classes (Muffler, 1976): 1) resources related to young igneous intrusions in the upper crust, and 2) resources not related to young igneous intrusions. The first class can be further subdivided

into three types of resources: a) magma, b) hot dry rock, and c) convecting hydrothermal systems. The second class can be subdivided into four resources types: a) resources in a low permeability conductive environment (=warm or hot dry rock, depending on depth), resources in a low permeability environment modified by circulation of meteoric water (e.g. thermal springs), c) resources in a high porosity/permeability environment (confined or unconfined deep aquifers), and d) resources in a high-porosity environment at pressures greatly in excess of hydrostatic (=geopressurized).

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

TEMPERATURE OF RESERVOIR FLUID (°C)													
0	20	40	60	80	100	120	140	160	180	200	220	240	260
FISH FARMING		AGRICULTURE, HORTICULTURE			GREEN-HOUSES		ELECTRICAL POWER PRODUCTION, USING BINARY CYCLE			ELECTRIC POWER PRODUCTION			
HEALTH SPAS					SPACE HEATING		INDUSTRIAL PROCESSING						

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

2. Geothermal Background

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

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

$$T(z) = T_0 + q \sum_1^z (\Delta z_i / K_i) \quad (1)$$

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

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

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

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

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

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

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

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

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

3. Thermal Springs

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

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

In many cases a deeper-lying reservoir with high temperatures exist from which the thermal waters emerge to the surface; significant cooling can occur during ascent due to the mixture of cold ground

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

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

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

4. Deep Aquifers

In sedimentary basins deep water-bearing formations can be present without displaying any surface activity. The heat content of these aquifers can be of economic interest: developments in the Paris basin (see Rybach, this volume) and in Hungary clearly indicate that for district heating and agricultural applications a formation temperature range of 55°C (130°F) - 80°C (176°F) at flow rates of about 100 m³/h (440 gpm) per producing well (=5-8 MW thermal output¹ above ambient temperature) can be of economic interest.

Whereas the formation temperature depends on the geothermal situation in a given area the flow rate and performance of a deep aquifer depend on many

parameters: the volume of water (which in turn depends on porosity), the pressure conditions, the permeability of the formation, the physical restrictions of the production well and casing (e.g. diameter) and the type of completion equipment utilized (e.g. pump). Production rates of the above-mentioned order can only be maintained for water-bearing horizons of high permeability. The permeability of sedimentary rocks depends on the interconnected pore space fraction as well as on the degree of fracturing (=secondary permeability). The permeability (given in millidarcies (md), 1 md = 10⁻¹⁵m²) usually decreases with depth (Fig 4). To obtain the above-mentioned extraction rate the transmissivity (aquifer thickness x permeability) must be in the order of several hundreds of md m.

PERMEABILITY OF ROCKS IN DIFFERENT LOCATIONS

a) MOLASSEBECKEN IN BAVARIA

b) NORTH-AND NORTHWEST-GERMANY

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

¹Thermal output, $\dot{Q}$ (MW) = $1.17 \cdot 10^{-3} \dot{m} \Delta T$; where $\dot{m}$ is the rate of production (m³/h) and ΔT the useful temperature drop (deg).

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

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

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

A standard technique of exploitation of deep aquifers is the "doublet" method: a pair (or pairs) of production and reinjection wells. The reinjection (after heat extraction by heat exchangers) maintains constant reservoir pressure and also

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

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

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

5. Hot Dry Rock (HDR)

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

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

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

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

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

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

where c_w is the volumetric heat capacity of water and K is a constant (includes material properties of rock and water). The thermal drawdown is gov-

erned by the parameter $R^2/\dot{m}$; with medium production rates quasi-stationary state can be established (e.g. 20 L/s (310 gpm) for 10 MW (th)).

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

6. Environmental Considerations

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

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

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

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GENERAL GEOLOGY OF THE EAST COAST WITH EMPHASIS ON POTENTIAL
GEOTHERMAL ENERGY REGIONS: A DETAILED SUMMARY

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Introduction and Background

The relative stability of the East with respect to earthquakes and volcanic activity does not immediately suggest the vast reserve of low to moderate temperature (40° - 125°C ?, or 104° - 260°F ?) geothermal energy that probably exists here. It is understandably difficult to seriously consider geothermal prospects in the East as long as the word "geothermal" brings forth an image of Old Faithful erupting at Yellowstone! Nevertheless, for the low temperatures needed to economically heat large housing (3000 units) and industrial complexes, for example, some of the eastern hydrothermal reservoirs may be both large and favorably located with respect to potential utilization. The importance of developing this resource is easily understood from the observation that currently about 40% of our fuel consumption is devoted to space heating.

Below the effects of the diurnal and annual temperature variation at the surface, (several hundred feet), the temperature in the earth tends to show a regular rise with increasing depth. In the future, it may become economic in this country to develop geothermal sources in deep aquifers from regions of essentially "normal" geothermal gradient, as is currently being done with a gradient of $33^{\circ}\text{C}/\text{Km}$ or $1.8^{\circ}\text{F}/100\text{ ft}$ in the Paris Basin (Rybach, this program). Secondly, mining heat by circulating water through man-made hydraulic fractures in hot crystalline rocks of the basement below insulating sedimentary basins is an existing technology developed at Los Alamos that may have a future in the East. If so, the temperatures available by this method may even be sufficient to generate electric power. Thirdly, natural fracture zones and fold structures that allow convection of heat by the rise of deeply circulating ground water in regions of essentially normal heat flow, e.g. Hot Springs, Virginia, seem to have immediate but more modest(?) application because of apparent limitations in temperature, volume of water, and location.

Of primary interest at present, however, are elements of eastern geologic frameworks which are conducive to generating abnormal (greater than $30^{\circ}\text{C}/\text{Km}$, or $1.6^{\circ}\text{F}/100\text{ ft}$.) thermal gradients. These elements include: 1) sedimentary basin fillings of very low thermal conductivity (i.e. heat damming) sediments, e.g. water saturated clay-rich deposits, and 2) radiogenic heat sources in the crystalline continental crust, especially the younger granites

of Late Paleozoic (300 - 260 m.y.) and younger ages. Optimal geologic frameworks occur where: 1) granites of high heat generating capacity (radiogenic heat supplied by spontaneous fission of naturally occurring U, Th, and ^{40}K in the granite), are 2) overlain by large confined or semiconfined aquifers, which 3) are in turn blanketed by thick (water saturated and clay-rich) strata of low thermal conductivity. Such frameworks appear to be most abundant east of the Fall Line, under the Atlantic Coastal Plain. Environmentally clean heat could be extracted by circulating water from an aquifer up one well, through a heat exchanger, and then reinjecting the water down a second well. The optimal geologic framework described above is often referred to as "the buried pluton concept" and is the principal targeting procedure being used by VPI&SU to explore the Atlantic Coastal Plain geologic province. It could be applied as well to many other suitable regions in the U.S. and elsewhere.

From the foregoing it is clear that the aspects of east coast geology of highest priority in a search for geothermal resources include: 1) the thickness, structure, stratigraphy, hydrology, and thermal conductivity of sediments beneath the Atlantic Coastal Plain, and 2) the structure, composition, age and intensity of metamorphism and of granite emplacement, and the heat production of rocks in the basement under the Atlantic Coastal Plain. Because the character of the Atlantic Coastal Plain sediments is discussed by other speakers on this program, the following is concerned with the evolution of 2) above, the heat sources in the basement.

Regional metamorphism and deformation play a key role in the evolution and location of basement radiogenic heat sources. Uranium and thorium in particular are mobilized in fluids and granitic melts during regional metamorphism. Moving under the influence of gravity, thermal gradients, and deformation, much of the uranium and thorium is permanently lost from or homogenized in a metamorphic terrain. A notable exception is the relative concentration of these elements (U, Th, and K) in granitic melts that may crystallize and remain within the zone of metamorphism. Thus the "plums" are radiogenic granites scattered through a "pudding" of metamorphic gneisses and schists that may be somewhat depleted in these heat producing elements. By "concentrated" we mean about 10 parts

per million (ppm) of U in the granite vs. 1 - 2 ppm in the gneisses and schists of the metamorphic terrain. Hardly ore grade or very radioactive in the usual sense!

In the case of the Appalachian Piedmont and its extension, the basement under the Atlantic Coastal Plain, patterns of metamorphism and igneous activity have wandered through space and time in a complex manner. Thus the U and Th concentrated in granites of one generation may be strongly depleted or homogenized during the metamorphism of another. Only granites that consolidate after the thermal peak of the last metamorphism in an area are likely to have relatively high radiogenic heat production. It is important, therefore, to try to understand these patterns of metamorphism and igneous activity in order to target productive granites beneath the Atlantic Coastal Plain. Targeting of such granites under the Coastal Plain can be assisted by using magnetic, gravity, and seismic surveys, but these are indirect methods that must be controlled by selective core drilling into the crystalline basement. Some cores should come from metamorphic basement rocks (the "pudding") so that we can determine composition, structure, density, seismic velocity, magnetic properties, heat production and the type and age of metamorphism. Other cores must come from young syn- to post-metamorphic granites (the "plums") so that besides their other properties, we can also measure their heat generation directly in order to verify the exploration model and to serve as a double check on certain heat flow related measurements made in the shallower wells of the Atlantic Coastal Plain.

The nature and timing of igneous and metamorphic activity in the crystalline Appalachians (i.e. Blue Ridge, Piedmont, and basement under the Atlantic Coastal Plain) are topics central to plate tectonic hypotheses for the origin of the Appalachians. Because of previous research stimulated by this interest we have a moderate amount of background data to build upon. That is, the data base is sufficient to generate interesting ideas about the nature of possible radiogenic heat sources, but insufficient to verify them. Plate tectonic models provide us with rational hypotheses that explain some of the data and may give us some predictive capability about the nature of certain basement regions. Further discussion of such models, however, is beyond the scope of this paper.

Some Aspects of the Geologic History of the Piedmont as a Guide to the Nature of Heat Sources in the Atlantic Coastal Plain Basement

(The following account greatly oversimplifies a complex geologic terrain. The trends discussed here are not well documented and much work remains to be done.)

Widespread volcanism and plutonism (emplacement of granitic and gabbroic rocks) during the Eocambrian and Cambrian Periods, about 800 to 500 m.y. ago, extended over much of the Piedmont and Blue Ridge. The scanty data suggest that these plutons range from large to small in size, from shallow

to deep levels of emplacement, and were associated with periods of extensive volcanism. All known rocks of this age in the Central and Southern Appalachians have been metamorphosed at least once and appear to be generally characterized by low heat production.

A more distinct pattern appears to have emerged in the igneous and metamorphic history beginning in Ordovician time, about 480 - 425 m.y. ago. In the eastern foothills of the Carolina Blue Ridge and in the western Piedmont of the Carolinas and Virginia, granitic and gabbroic plutons were emplaced during a regional metamorphism that probably ended abruptly as a result of cooling by deformation, uplift, and erosion during the Taconic Orogeny. If the eastern Piedmont was affected by this metamorphism, large regions (the Carolina Slate Belts) were never raised above low (greenschist grade) temperatures and pressures. Additionally, there are probably no Taconic age plutons in the eastern Piedmont south of about Fredericksburg, Virginia.

By latest Ordovician and Silurian time, approximately 400 m.y. ago, a few gabbroic and granitic plutons were injected along the central axis of the Piedmont in the Carolinas. Ductile deformation affected some of these plutons, which suggests that regional metamorphism may have continued from the Taconic event or may have migrated eastward with the plutonic activity. The intensity of igneous and metamorphic activity thus far recognized seems diminished by comparison with the Taconic evidence for relative crustal stability at this time recorded in Silurian rocks of the Valley and Ridge.

Late Devonian to Pennsylvanian time saw the central axis of metamorphism and plutonic intrusion migrate into, or at least reach an intensity maximum, in the eastern Piedmont. Dating of this metamorphism suggests a thermal maximum at about 350 m.y. ago (Acadian Orogeny). The metamorphism diminishes westward into the Blue Ridge where it partially overprints the earlier Taconic metamorphism. It was accompanied, mostly during its waning stage, by widespread plutonism over a span of about 330 to 260 m.y. ago. This produced a very large (ca. 60) group of syn- to post-metamorphic granitic plutons. These Late Paleozoic granites are most abundant along the Fall Line south of Richmond, Virginia, and in Georgia they trend westward into the region south of Atlanta. This westward trend in Georgia appears to be somewhat concordant with Late Paleozoic regional structural features that may link the Appalachians with the Ouachitas.

Because the 350 m.y. Acadian regional metamorphism was the last major metamorphic event to affect the eastern Piedmont, granites of this age or younger have generally retained much of their U and Th. Thus they are the best known sizable group of heat generating plutons south of New England. They commonly produce two or three times as much heat as their older metamorphosed counterparts and the enclosing country rocks.

From the above, the basic pattern in Middle

and Late Paleozoic time was eastward migration of the axis of igneous and metamorphic activity. Thus it is natural to ask whether the trend continues in the basement below the Atlantic Coastal Plain. The answer is - possibly - yes. Within the past year several researchers have discovered ductile deformation overprinting young plutons in the easternmost parts of the Piedmont. If this foreshadows discovery of another still younger generation of plutonic and metamorphic activity under the Coastal Plain, we must determine this and also whether these rocks will have a comparable range of heat generation.

A second pattern is emerging from Piedmont studies that may help in exploring the Coastal Plain basement for heat sources. The Late Paleozoic metamorphic-plutonic age province in the eastern Piedmont is subdivided into several NE-trending belts that have been recognized for many years. Some of these belts are: Charlotte, Carolina Slate, Raleigh, Kiokee, Eastern Slate, etc. The basic rationale for recognizing such belts has involved considerations of the relative intensities of metamorphism, plutonism, and deformation. It now appears that low-metamorphic-grade belts are generally synformal (downwarped) and are only marginally injected by plutons in the age range of latest metamorphism. Much of the downwarping occurred during the protracted period of metamorphism-plutonism, and the low grade terrains, being more rigid than adjacent high grade (and higher temperature) terrains, resisted injection by granite. Those granites that did manage to inject the margins of these low grade (Carolina Slate) belts tend to be circular in surface outcrop and to have inverted teardrop or spike-like shapes. Thus their gravity and magnetic signatures also tend to be somewhat distinct.

Belts of high metamorphic grade, and therefore of greater ductility at the time of metamorphism, have antiformal (upwarped) shapes and contain large concentrations of granite generated during the time of metamorphism and upwarping. Structural studies strongly suggest wholesale migration of ductile country rock (the "pudding") and granitic magma (the "plums") into the crests of high grade belts and away from the bottoms of downwarping lowgrade belts. If this hypothesis proves true, high grade belts (unless very deeply eroded) should have higher heat generation than low grade belts because of the greater concentration of granitic magma emplaced during the last metamorphic-plutonic event. Additionally, granites coeval with the last metamorphism in these higher grade belts tend to be larger and more nearly concordant than plutons that penetrated more rigid crust. Thus these large bodies of magma, such as the Rolesville and Petersburg, may be 50 - 60 miles long and 20 - 30 miles wide, and locally surrounded by haloes of mixed rocks (migmatites) of granite and country rock. Such bodies tend to produce large elliptical regional gravity lows and may also be outlined by magnetic surveys.

Extrapolation from these Piedmont trends suggest that we might expect to find: 1) a continuation of this pattern of alternating high- and low-grade belts in the basement under the Atlantic

Coastal Plain; 2) a concentration of the granites having highest heat production in and marginal to the high grade belts; 3) a possibility of even younger metamorphism and plutonism with heat production ranges different from those measured in the Piedmont. By combining indirect (magnetic, gravity, seismic) and direct (heat flow measurements from shallow and deep Coastal Plain wells, geologic and geophysical studies of selected basement cores) methods we can develop a knowledge of the basement that will eventually allow more routine selection of geothermal sites over buried granites of high heat production. Although a beginning has been made by the U.S.G.S. (high and low grade belts do exist under the Coastal Plain in North Carolina), VPI&SU, Princeton, and several state surveys, much work remains to be done, particularly in obtaining basement core samples to control geophysical-geological extrapolations on a regional basis.

Before leaving this discussion of the Paleozoic development of the Atlantic Coastal Plain basement, the anomalous crust beneath southern South Carolina, and much of Georgia and Florida merits some attention. In this region the familiar schistosity of the northern basement and Piedmont is missing. Poorly dated, very low grade volcanics near the Georgia coast are probably Early Paleozoic or Eocambrian in age, and near the Georgia-Florida border, unmetamorphosed, nearly horizontal Early and Middle Paleozoic sedimentary rocks are found in the basement. Much of this is overlain by Early Mesozoic nonmarine sediments and basaltic lavas. Seemingly these differences are best explained by suturing another continental fragment onto the North American Plate during the late Paleozoic. Whatever the cause, the obviously different geologic history of this segment of the present continent suggests the possibility of different heat production-heat flow characteristics.

Finally Mesozoic and younger lineaments transverse (W to NW trending) to the regional Appalachian trend might in some areas exert a strong influence on heat flow and heat production. Probably there are diffuse but deep fracture zones that extend to the lower crust or mantle. In New England, they are characterized by offshore subsea volcanoes, anomalous seismicity, and Late Paleozoic-Mesozoic emplacement of alkalic granite and gabbro(?) plutons. The Conway Granite, belonging to this trend, has the highest heat flow recorded from a granite of comparable size in the Appalachians. In Virginia, numerous westerly aligned features suggest a similar lineament. Examples are the WNW trending offshore Norfolk scarp, the west trending central Virginia seismic zone, and the Mesozoic to Early Tertiary alkalic shallow intrusives in the Valley and Ridge of Highland County, central western Virginia. In South Carolina a similar feature passing NW through Charleston has been described by Columbia University and U.S.G.S. researchers.

GEOHERMAL EXPLORATION METHODS AND RESULTS ATLANTIC COASTAL PLAIN

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Optimum sites for the development of geothermal energy resources in the eastern United States will probably be associated with the sediments of the Atlantic Coastal Plain. These sediments have a relatively low thermal conductivity resulting in, even for a normal heat flow, relatively high geothermal gradients. If such sediments blanket a radiogenic, heat-producing granite in the basement crystalline rocks, isotherms will be warped upward and higher temperatures will occur at shallower depths. Approximately 50 shallow (300 m; 1000 ft) holes were drilled on the Atlantic Coastal Plain by the Department of Energy during 1978-79 to investigate the distribution of heat flow and the geothermal gradient. To date, the area with the most promising potential appears to be a region between Crisfield, Maryland, and Oak Hall, Virginia. Gradients here are in excess of 40 °C/Km and the thickness of the sedimentary insulator is greater than about 1.2 Km.

Introduction

The first systematic effort to estimate the geothermal resources of the entire United States was made by the U.S. Geological Survey in 1975 and published as USGS Circular 726 (White and Williams, 1975). This study has been updated by a second assessment and published as USGS Circular 790 (Muffler, 1979). Muffler and Cataldi (1979) proposed the use of a consistent terminology for geothermal resource assessment. The "geothermal resource base" is defined as all of the thermal energy in the earth's crust under a given area, measured from the mean annual temperature. The "accessible resource base" is that part of the resource base which is shallow enough to be tapped by production drilling, and is divided into "useful" and "residual" components. The "useful" component is defined as thermal energy that could be extracted at costs competitive with other forms of energy at some specified future time. This useful component is defined as the "geothermal resource". Much exploration remains to be done before the nature and extent of the geothermal resource in the eastern United States can be adequately defined.

Exploration for geothermal resources in the eastern United States takes place in a geologic environment quite unlike that of the west where generation of electric power from geothermal energy is well documented. Use of geothermal energy in the east will probably first be oriented toward non-electric applications using relatively low-temperature fluids as a source of energy for space heating and industrial processes and systems.

This paper briefly discusses the geophysical techniques we have used to investigate the geologic framework of potential geothermal resources of parts of the eastern United States. Geothermal resources in the Appalachian Mountain system and the Atlantic Coastal Plain can be grouped into four types:

- I) Radiogenic heat-producing granite buried beneath a thick blanket of sediments of low thermal conductivity,
- II) Normal geothermal gradient resources,
- III) Warm water emanating from fault zones,
- IV) Hot-dry-rock in regions of abnormal geothermal gradient,

Resource I is the principal subject of this paper. Resource II is widely available throughout much of the United States and is discussed by Sammel (1979). Resource III has been recognized in the eastern United States since before 1884 (Rogers, 1884). Resource IV is described by Pettitt (this Symposium).

Optimum sites for the development of geothermal energy in the eastern United States will probably be associated with the flat-lying, relatively unconsolidated sediments that underlie the Atlantic Coastal Plain (Figure 1). In many locations, these sediments are known to yield large quantities of water. The water in these sediments at any given depth is hotter in some locations than in others and depends on the local value of the geothermal gradient. The gradient depends on the heat flow through the rocks and on the thermal conductivity of the rocks. In a series of extremely important papers, Birch et al. (1968), Lachenbruch (1968), and Roy et al. (1968) showed that the local heat flow has a well-defined relationship to the concentration of uranium (U) and thorium (Th) in fresh, unweathered samples of granite collected

from the surface of the earth. The immediate implication of their observation is that the distribution of U and Th in the upper 10 to 20 km (33,000 to 66,000 ft) of the earth's crust is primarily responsible for the observed lateral variations in surface heat flow in the eastern United States.

One of the principal objectives of the geothermal program at Virginia Polytechnic Institute and State University is to locate relatively young (330 million years old and younger) U- and Th-bearing granite in the basement rocks beneath the sediments of the Atlantic Coastal Plain. The targeting procedure integrates the disciplines of geology, geochemistry, and geophysics. Geologic and geochemical techniques are being applied to the rocks in the Piedmont in an effort to understand the ages, chemistry, and areal distribution of exposed granite plutons (see paper by Glover, this Symposium). Geophysical techniques include the interpretation of gravity and magnetic potential field data, as well as seismic data, and are being applied to both the Piedmont and the Coastal Plain.

Warm water emanating from fracture zones (Resource III) is not the principal focus of this Symposium. Nevertheless, it is appropriate to mention this known resource. The origin of the hot springs in the eastern United States has been discussed by several authors (Rogers, 1884; Reeves, 1932; Hewett and Crickmay, 1937; Stose and Stose, 1947; Dennison and Johnson, 1971; Lowell, 1975; Costain et al., 1976; Geiser, 1976; Hobba et al., 1977; Hobba et al., 1978). Perry et al. (1979) proposed a model for the hot springs in Virginia that we believe applies to most of the hot springs in the eastern United States. Before discussing the geologic framework for the hot springs in Virginia, it will be useful to review selected geophysical methods we have used to date in the eastern United States for the exploration of geothermal resources.

Geophysical Exploration of Geothermal Resources in the Eastern United States

It is beyond the scope of this paper to discuss in detail the various geophysical, geochemical, and geological techniques that are commonly used to evaluate geothermal resources. The exploration methods used are dependent upon the nature of the geothermal resource. Many of the conventional geophysical methods of exploration are discussed by Dobrin (1977) and are, of course, not restricted to geothermal applications. We have used several kinds of geophysical data during the course of our geothermal program. They are discussed briefly below before summarizing the results of our studies on the Atlantic Coastal Plain.

Heat flow. The most important geophysical data for the exploration of geothermal resources in the east consist of values of regional and local heat flow flowing towards the surface of the earth. Heat flow, q , is described by the conduction equation

$$q = KG$$

where the units of q are calories per square cm

per sec, K is thermal conductivity (millicalories per cm-sec-°C), and G is the geothermal gradient in °C/Km ($1^{\circ}\text{F}/100\text{ ft} = 18.23^{\circ}\text{C}/\text{Km}$). This equation applies only to the transport of heat by conduction. Heat transport by fluid convection (hot water) is much more efficient. Any successful geothermal system must incorporate both conduction and convection. A hole drilled to a depth of, say, 300 m (1000 ft) will usually encounter different rock types, each with a different thermal conductivity, K . Because q is constant at any depth in the hole, then as K decreases the geothermal gradient, G , will increase to keep the product KG constant. Simply stated, this means that for any given heat flow, the highest temperature gradients occur in rocks with the lowest thermal conductivities. Shales in the Valley and Ridge province of the Appalachian Mountain System will have temperature gradients that are much higher than those found in holes drilled into dolomite, $\text{CaMg}(\text{CO}_3)_2$. For the same value of the heat flow, q , higher temperatures will be reached at shallower depths if holes are drilled into thick sequences of shale rather than into dolomite. Shale is a better insulator. The unconsolidated sediments of the Atlantic Coastal Plain have an even lower thermal conductivity.

A major unresolved problem in geology and geophysics is why regional and local variations in surface heat flow occur. For the development of a geothermal resource, it is apparent that the combination of high heat flow and low thermal conductivity will result in the highest subsurface temperatures at the shallowest depths. It is beyond the scope of this paper to speculate on the many hypotheses advanced to explain lateral variations in surface heat flow. One undisputed explanation, however, is that variations in lateral and vertical concentrations of U and Th in basement rocks will result in substantial variations in heat flow (Birch et al., 1968).

The generation of heat by the process of radioactive decay is one of conversion of mass to energy according to Einstein's equation, $E=mc^2$. Only three elements have isotopes with long enough half-lives to be important for radioactive heat generation in rocks. These are isotopes of U, Th, and potassium (K). Radioactive isotopes of these elements have half-lives of the order of 1 billion years or more. The heat contribution, H , in calories/gram per year from the radioactive decay of these isotopes is given by the equation

$$H = 0.72U + 0.20\text{Th} + 0.27K$$

where U is in parts per million (ppm) uranium, Th is in ppm thorium, and K is in per cent potassium (Birch, 1954). The constants in this equation have been revised slightly by Rybach (1976).

Thorium is usually more abundant than uranium in granite, the Th/U ratio falling between 3 and 4. Most of the heat produced comes from U and Th; only about 10 - 15% comes from K. The U, Th, and K concentrations of the Cuffytown Creek pluton in South Carolina are about 10 ppm U, 33 ppm Th, and 3.7% K. Thus this granite generates about 15 calories per gram per year. The density of the

granite is about 2.67 grams per cubic centimeter. The granite therefore generates about 12×10^{-13} calories per cubic cm per sec, or about 20,000 watts per cubic mile. In fact, most of the heat flowing towards the surface in the Cuffytown Creek granite comes from the heat generated by the radioactive decay of isotopes of U, Th, and K.

Granitic rocks relatively enriched in U and Th (concentrations as high or higher (?) than the Cuffytown Creek) occur locally in the basement rocks beneath the sediments of the Atlantic Coastal Plain. The concentrations of U and Th in the granites are low, a few parts per million, but these concentrations are higher than those in adjacent rocks in the basement. In spite of these low concentrations, large volumes of granite with U and Th will increase substantially the subsurface temperature. Thus, higher temperatures will be found at shallower depths within the overlying sediments. Radiogenic heat is in addition to the normal heat flow around and beneath the granite plutons and can be greater by more than a factor of 2 than the background heat flow that constitutes the normal heat leaving the earth. In some parts of New England, for example, radiogenic heat from granite constitutes two-thirds of the total heat flow leaving the earth in that area (Birch et al., 1968). An understanding of the distribution of granites and of U and Th in the basement rocks is therefore important to define locations where the highest temperatures will occur at the shallowest depths.

Granite plutons are exposed in the Piedmont Province northwest of the Atlantic Coastal Plain (Figure 1). These exposed basement rocks are concealed to the southeast by a seaward-thickening wedge of sediments beneath the Atlantic Coastal Plain. Few holes have been drilled through the sediments to basement, but the sediment thickness is known to be about 3 km (9900 ft) at Cape Hatteras, NC.

Figure 3 illustrates the effect on subsurface temperature where basement rocks are covered with a thick sequence of sediments of relatively low thermal conductivity. Moderate amounts of heat-producing elements occur in the basement rocks, concentrated primarily in granite. The concentrations assumed are not unreasonable. Heat generations of 15 HGU ($1 \text{ HGU} = 10^{-13} \text{ cal/cm}^3 \text{ per sec}$) have been determined by us in granite plutons exposed in the Piedmont. In New England, exposed granite plutons locally have heat productions of 24 HGU (Birch et al., 1968). The leftmost curve in Figure 2 is the temperature-depth profile in basement crystalline rocks that contain no heat-producing elements, and are not overlain by sediments. As U and Th are added to produce first 10 HGU and then 20 HGU, the subsurface temperature (and therefore the geothermal gradient) increases. Finally, if U- and Th-bearing granite is blanketed by sediments that have a relatively low thermal conductivity, the subsurface temperature is increased further. The relatively unconsolidated sediments of the Atlantic Coastal Plain that overlie granite plutons in the basement is the geologic

environment of high geothermal resource potential in the east. Heat flow and the geothermal gradient should be higher over these granites if the granites contain modest concentrations of U and Th. Locations of shallow (300 m) holes drilled by the Department of Energy on the Atlantic Coastal Plain during 1978-79 to determine the geothermal gradient and heat flow were based primarily on the interpretation of gravity and magnetic potential field data.

Gravity data. The magnitude of the gravitational field at any location on the surface of the earth depends locally on the different rock types at depth. Different rock types have different densities. Some rocks weigh more than others. Granite is the least dense of the igneous intrusive rocks that occur in large volumes. Since granite is less dense than the country rocks into which it has been emplaced, a negative gravity anomaly results (Figure 2). If, however, granite was emplaced in country rock that was also granitic in chemical composition, then the gravity field will not be well-defined over the granite and additional geophysical and/or geological techniques must be used.

An important consideration in the targeting of concealed radiogenic granites beneath the sediments of the Atlantic Coastal Plain is an understanding of the regional geologic framework (see paper by Glover, this volume). In the absence of a gravity or magnetic anomaly, an understanding of the regional geology and the possible nature of concealed basement trends is important. Relatively few holes have sampled the basement to date.

Magnetic data. The normal (approximately symmetrical) magnetic dipole field of the earth is distorted by the presence of magnetic minerals in rocks, the most important of which is magnetite. Granite plutons usually contain a small percentage of magnetite. The first step in the interpretation of aeromagnetic data is to subtract the earth's dipole field and examine the "magnetic anomalies" that remain (see Costain, 1979 for a general summary of the description and interpretation of magnetic anomalies). An excellent magnetic anomaly associated with a granite exposed in the Piedmont is shown in Figure 4. Similar granite bodies concealed beneath the sediments of the Atlantic Coastal Plain might be detected by their magnetic signatures if the depth of burial is not too great and if metamorphism has not destroyed the magnetic properties of the mineral assemblages. Examination of existing magnetic data obtained over the Coastal Plain suggests that granitic plutons occur in the basement.

Seismic data. Standard techniques of reflection seismology are essential to define the subsurface geometry of a potential geothermal resource in the eastern United States. In general, reflection seismology offers the highest resolution of any geophysical method used to investigate subsurface geology. In particular, reflection seismology is appropriate to

- 1) determine depth to crystalline basement,
- 2) define faults in the basement and/or overlying sediments,
- 3) examine lateral and vertical changes in velocity in the sedimentary section which can then be correlated with lateral changes in thermal conductivity or changes in thickness of potential deep aquifers.

Figure 5 shows a reflection seismic section recently obtained (February, 1979) near Salisbury, MD. The reflection that originates from the basement is well-defined as are several other reflections from within the overlying sedimentary section.

Excellent reflection seismic data can be obtained on the Atlantic Coastal Plain. Proper recording procedures are essential in order to assure that the desired reflections are not obscured by multiple reflections (Dobrin, 1976, p. 89).

Origin of the Hot Springs in Virginia

In the northwestern part of Virginia and adjacent parts of West Virginia, there are approximately 100 springs that have temperatures ranging from slightly above the mean annual air temperature (9-12 °C; 48-54 °F) to about 41 °C (106 °F). In Virginia, nearly all of the warm springs appear to issue from limestone formations of Middle Ordovician age where these formations are brought to the surface by anticlinal folding. The geographic distribution of the springs has been described by Reeves (1932) and summarized by Sammel (1979).

The hottest springs are located in the Warm Springs anticline in Bath and Alleghany Counties in Virginia where four groups of springs known as the Warm Springs, Hot Springs, Healing Springs, and Falling Springs occur. Each group of springs consists of at least three separate springs in close proximity. The group at Warm Springs is made up of three springs within about 30 m (100 ft) of each other and a fourth about 250 m (820 ft) to the southwest. At Hot Springs, eight warm springs occur over an area of about 4000 square m (6 square miles). Healing Springs consists of three separate springs less than 3 m apart. Falling Springs are made up of a number of flows and seepages at a generally lower temperature (25 °C; 77 °F max) than the other warm springs in the Warm Springs anticline, and with a much greater discharge (250 L/sec = 3960 gpm = 5,700,000 gpd) than any other warm springs in the region. The flow rate of Hot Springs is 63 L/sec (=998 gpm = 1,438,000 gpd) at a maximum temperature of 41 °C (106 °F). At Bolar Spring, the flow rate is 130 L/sec (=2060 gpm = 2,900,000 gpd) at a maximum temperature of 22 °C (72 °F). Flow rates are taken from Sammel (1979).

Rogers (1884) and Reeves (1932) both concluded that the warm and moderately warm springs issue from rocks of Cambrian and Ordovician age where

these formations rise from considerable depth as the result of anticlinal folding of sedimentary rocks. Rogers proposed that surface water entering the rocks at their outcrop in high ridges sinks to considerable depths along joints and fissures until it reaches a permeable bed, and then rises along the dip of this bed to its outcrop in an adjacent valley. According to Reeves (1932, p. 26), however, some of the anticlines are broken by thrust faults, but he states that there is no positive evidence that any of the warm springs are along faults. Reeves further concluded that most of the springs of the region undoubtedly are not so located, and that few of the springs are probably fed by water rising along fault planes or through fissures bordering fault planes. Reeves (1932, p. 28) concluded that the springs are produced by meteoric (rain) water entering a permeable bed along its outcrop at a relatively high altitude on the crest or limb of one anticline and rising to the surface where the same bed crops out at a lower altitude in another anticline, the temperature of the waters being an expression of the normal earth temperature in the deep synclinal basins through which the water circulates. Reeves' hypothesis is similar to Rogers' in that it attributes the temperature of the springs to normal earth temperatures. It differs from Rogers' hypothesis in that it predicts movement through permeable beds from one anticline to another rather than movement through joints and fissures from an anticlinal ridge to adjacent valleys.

Rogers (1884), Watson (1924), Reeves (1932) and Hobba et al. (1977) all concluded that the spring waters are of meteoric origin. The occurrence of igneous sills and dikes in Highland County, Virginia suggested to Dennison and Johnson (1971) an alternative heat source other than deep circulation of meteoric water. Igneous intrusions are exposed just 30 km (20 miles) north of Hot Springs, Virginia. They suggested that a deep still-cooling pluton provides heat to the thermal springs centered in Bath County, and that the pluton is either the source of the dikes in Highland County, or possibly represents a later thermal pulse related to the 38th parallel fracture zone, which has been an east-west zone of sporadic igneous activity from late Precambrian to Eocene time.

A hole approximately 305 m (1000 ft) in depth was drilled into the Beekmantown dolomite in the Warm Springs anticline about 8 km southwest of the Hot Springs, Virginia specifically for the purpose of obtaining a reliable heat flow determination (Costain et al., 1976). The geothermal gradient in the hole was 9.3 °C/Km (0.5 °F/100 ft). The thermal conductivity of the Beekmantown dolomite was 12.4 mcal/cm-sec-°C. The heat flow is therefore about 1.2 HFU (1 HFU = 10⁻⁶ cal/cm²-sec). This is a representative heat flow value for the region and does not support the hypothesis of a still-cooling pluton at depth.

The gradient within the core of the Warm Springs anticline is about 10 °C/Km in the Beekmantown Dolomite. If this low gradient is main-

tained to greater depths, water would have to circulate to a depth of only approximately 3 km (10,000 ft) to be heated to the temperatures observed at the surface. Since the thickness of sediments in the area is greater than 4 km (13,000 ft), deep circulation of meteoric water completely within the sedimentary section is possible. It then remains to identify the ground water recharge area for the springs and the factors that control locations where the springs discharge. Perry et al. (1979) proposed the following model.

All of the warm springs in the valley are grouped near topographic gaps associated with vertical transverse fracture zones (linears). The limited data available suggest that faults and/or joints play an important role in the location of the springs, since gaps have developed only along these zones. The Warm Springs anticline is a doubly-plunging anticline with a near-vertical to overturned northwestern limb. The resistant Silurian quartzites are responsible for the high relief in the area. It is postulated that meteoric water enters the Silurian quartzites and possibly adjacent carbonate units along steep to vertical bedding planes on the northwest limb of the anticline, extends to depths sufficient to heat the water, and then rises rapidly along the essentially east-west transverse fracture zones which intersect the bedding-plane permeability at depth. A cross section of this model oriented approximately at right angles to the transverse fracture zones is shown in Figure 6. In this model, ground-water flow lines are shown with an essentially vertical orientation beneath the recharge areas. They diverge at depth and intersect the transverse fracture zones. The temperature of the water issuing from springs located along the transverse fracture zones depends to a large extent on the degree of mixing that has taken place as the meteoric water rises rapidly to the surface along the relatively permeable fracture zone.

In support of this model, there appears to be a correlation between the coincidence of water gaps, the occurrence of warm springs, and the presence of nearby steeply-dipping to vertical quartzite units in areas other than the Warm Springs anticline. The warm spring (22 °C; 72 °F) at Bolar occurs in the same geologic setting.

Geothermal Exploration of the Atlantic Coastal Plain

During 1978-79, 49 holes were drilled to a depth of approximately 300 m (1000 ft) on the Atlantic Coastal Plain. The geographic distribution of the holes is shown in Figure 1. The locations of the drill sites were chosen on the basis of:

- 1) gravity data,
- 2) magnetic data,
- 3) known thickness of Coastal Plain sediments,
- 4) apparent thermal anomalies based on geothermal gradients determined in existing holes,

- 5) much of the available basement core data,
- 6) suitable sites for the evaluation of the radiogenic pluton model,
- 7) proximity to energy markets.

The sediments of the Atlantic Coastal Plain include a number of semi-confined "leaky" aquifers. These aquifers are separated by relatively impermeable sediments. The water present in the pore space of each semi-confined aquifer may have a different "energy per unit weight", otherwise defined as "hydraulic head", h . Three quantities determine the value of h at any point in an aquifer: the elevation of the point above an arbitrary reference level (basement), the pressure energy (the higher the fluid pressure the greater the pressure energy), and the kinetic energy (speed at which water moves through the pore space of the aquifer). If there were no confining beds, the value of the hydraulic head, h , would be approximately the same anywhere in the sediments above basement (except for small differences associated with variations in ground-water velocity).

The fundamental equation of ground-water flow is governed by Darcy's Law,

$$V = P(dh/dl)$$

where V is the "Darcy velocity" of ground-water flow. The actual velocity of water through the pore space is given by V/n where n is the porosity of the aquifer. P is the permeability of the aquifer; the "hydraulic gradient" is dh/dl . The equation simply states that water flows from a higher energy state (hydraulic head, h) to a lower energy state, always. The difference in energy states is accounted for by energy lost due to friction as the water moves through the pore space of the aquifer. The presence of confining beds causes different values of h to occur in different aquifers. A hole drilled into the sediments of the Coastal Plain will encounter different values of h , which would result in upward (or downward) flow in the hole and prevent the determination of an accurate geothermal gradient. For this reason, each hole was cased to its total depth and cemented to prevent circulation between aquifers. Convection in or near a hole can result in an unreliable geothermal gradient determined in a shallow (300 m) hole.

Temperatures were measured at intervals of 2.5 m (8 ft) in each hole. Average gradients, G , were determined in each hole by the least-squares fit of a straight line over the entire interval of the hole below a depth of about 50 m (160 ft). An attempt was made to recover two sediment core samples, each 8 m (25 ft) in length from each hole. Core recovery was variable because of the unconsolidated nature of the sediments. Thermal conductivity, K , was determined in the laboratory using needle probe techniques.

Temperature profiles, geothermal gradients, and thermal conductivities are reported in a series of progress reports (Costain et. al., 1977, 1978, 1979).

Because the difference in concentrations of U and Th in basement rocks affects the geothermal gradient in the overlying sediments, it was important to site several holes both on and off potential field anomalies. The Portsmouth gravity anomaly (Figure 2) is an excellent example of a negative gravity anomaly over a presumed buried granite pluton. A magnetic anomaly is also present. The sediments here are about 600 m (1900 ft) in thickness. A hole was drilled that encountered granite at a depth of about 600 m, and 90 m (300 ft) of continuous granite core (BQ) are now being recovered. Determinations of heat generation, age, and chemistry will be made on the core. A heat flow value will also be determined over the 90-m interval in the granite to confirm the value of heat flow determined in the overlying sediments. The geothermal gradient in the hole over the gravity anomaly is about 42 °C/Km; the gradient in a hole drilled nearby (12 km) but off the anomaly in the same lithologic sequence of sediments is 27 °C/Km. We regard this as excellent confirmation of the radiogenic pluton model.

Lambiase et al. (1979) discuss in detail the distribution and values of the geothermal gradients obtained in the holes drilled on the Atlantic Coastal Plain. The most promising area to date appears to be between Crisfield, Maryland, and Oak Hall, Virginia, in southern Maryland and northern Virginia on the Eastern Shore (Figure 1). Higher gradients (48 °C/Km) were found elsewhere, for example, within the large negative gravity anomaly in the vicinity of Chesapeake Bay, but the depth to basement there is less.

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Acknowledgments

This work was sponsored by the Department of Energy under Contract Numbers 5103 and 5648 to principal investigators J. K. Costain, L. Glover III, and A. K. Sinha.

Figure 1. Locations of shallow (300 m) heat flow holes drilled on Atlantic Coastal Plain are shown as small dots.

Figure 2. Gravity map of parts of Delaware, Maryland, and North Carolina. Contour interval is 5 milligals. Gravity stations indicated by small dots.

Figure 3. Effect on subsurface temperatures of insulating blanket of sediments of low thermal conductivity.

Figure 4. Circular magnetic anomaly associated with the Liberty Hill-Kershaw granite pluton. Northwest-trending linear anomalies are Triassic dikes.

Figure 5. Reflection seismic section (24-fold) obtained near Salisbury, Maryland.

Figure 6. Hypothetical vertical cross section at Hot Springs, Virginia. Section is oriented at approximately right angles to transverse fracture zones.

GEOTHERMAL EXPLORATION METHODS AND RESULTS - INLAND STATES

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ABSTRACT

The Los Alamos Scientific Laboratory (LASL) geothermal exploration sequence includes: (a) review of AAPG/USGS gradient maps, (b) literature search, (c) consideration of potential markets, (d) groundwater silica geothermometry, (e) analysis of bottom-hole temperatures, (f) heat flow measurement of available wells, and (g) drilling of new test holes. This procedure has located anomalies near Syracuse, NY (36°C/km, 56°C silica max.), near Buffalo, NY (36°C/km, 65°C silica max.), southeast Ohio, western and southwestern Nebraska, and three new warm springs in Arkansas. Other investigations have found high heat generation (14-25 HGU) in the White Mountain batholith NH (170°C calculated at 6 km depth), uparching of the Adirondac Dome, NY, and potentially economic electricity from hot brines in southwest Arkansas.

INTRODUCTION

To encourage the use of geothermal energy in the eastern United States, the Department of Energy, through LASL, is evaluating the geothermal potential of several states between the Rocky Mountains and the Atlantic Coastal Plain. LASL has developed a general pattern for geothermal exploration in these states, and is pursuing this pattern in several states as funds permit. We are also pursuing some departures from the general pattern where special geologic or economic conditions have been found.

METHODS

The LASL approach to eastern states geothermal exploration is based initially on the AAPG geothermal gradient maps (1974, 1976) and on published geologic literature. States which have no local concentrations of gradients higher than 35°C/km and no surface expression of local geothermal phenomena are given relatively low priority for study. Literature about states with above average gradients is searched to find available heat flow measurements and possible geologic causes of high gradients or high heat flow. Concurrently, plans are made to conduct geochemical sampling of spring and well water. LASL experience to date has been that the silica concentrations give more reliable or consistent estimates of temperatures at depth than do the sodium-potassium-calcium ratios. Results of the literature and well data survey, with some consi-

deration of proximity to potential users, have been used to determine which prospects will receive geothermometry and heat flow studies. Present plans are to complete these studies over several areas before selecting a few sites for geophysical studies and test drilling. Most of the above work is being done under contracts supervised by the LASL Geological Applications Group.

RESULTS

Under the general plan outlined above, work is in progress in New York, Ohio, Nebraska, and Arkansas. In New York, a group headed by Dennis Hodge at State University of New York, Buffalo, and assisted by Chan Swanberg and Paul Morgan of New Mexico State University, has completed literature and data surveys. Two anomalous areas, the Cayuga anomaly 50 km southwest of Syracuse and the East Aurora anomaly southeast of Buffalo, have temperature gradients exceeding 36°C/km. Silica geothermometry of ground waters from these areas indicates a maximum temperature of 56°C at the Cayuga anomaly and 60°C at the East Aurora anomaly. Both anomalies are associated with gravity lows which may be caused by granitic plutons in the underlying basement. Radioactivity in the plutons could cause the geothermal anomalies. Bottom hole temperatures available from several thousand oil wells are being re-evaluated to improve the state gradient map. Temperature logging of selected wells in the anomalous areas is in progress.

In Ohio, a group headed by Yoram Eckstein, from Kent State University, is working on literature and data searches. They have located at least 15 wells suitable for heat flow measurements. Thermal conductivity measurements have been completed on 44 core samples from four of these wells. Samples from these and other well cores are to be analyzed at Los Alamos Scientific Laboratory to determine their uranium, thorium, and potassium-40 content, to enable calculation of heat generation and heat flow. No well-defined anomalies have yet been identified although gradients in southeastern Ohio are generally higher than elsewhere in the state.

The work in Nebraska is being done jointly by William Gosnold of the University of Nebraska-Omaha and personnel of the Hydrology Section of the Nebraska Conservation and Survey Division. Fifteen or twenty holes less than 100 m deep are to be temperature logged to determine gradients. In a large area in western Nebraska, deep aquifers on the east

flank of the Denver-Julesburg basin contain anomalously warm water, and in southeastern Nebraska, where the Nemaha ridge brings Precambrian basement rock to within 200 m of the surface, gradients exceed 25°C/km. Too little information is available yet for even an evaluation of Nebraska's geothermal potential.

One of the largest surface expressions of geothermal heat in the eastern states was first visited by white men in the early 1500's, at what is now Hot Springs, Arkansas. Although the surface geology of the area has been mapped, nothing is known of the deeper structures because of the concern that drilling would disrupt the spring flow. One other small area of warm springs at Caddo Gap, approximately 55 km southwest of Hot Springs, is currently undeveloped although it has been known for many years. Recently, by analysis of available geologic maps, the author has located three small previously unreported warm springs near Hot Springs, on folded structures similar to the one at Hot Springs. Interpretation of the complex folded structures which control geothermal spring flow in the Ouachitas must await future drilling. Ground water sampling of a few springs and wells throughout the Ouachita Mountains, for silica geothermometry, is to be done this year. Re-evaluation of bottom hole temperatures from oil wells in southern Arkansas and new gas wells being drilled in northern Arkansas hopefully will be done when funds become available.

OTHER STUDIES

One of four local studies done independently of the general exploration plan was completed in New Hampshire where the Conway granite is known to contain very high percentages of uranium and thorium. A hole was drilled 915 m deep near Conway, with core recovered from most of the hole. Sections from these cores have been analyzed to determine the distribution of the radioelements. Although the granite produces 14 to 25 heat generation units, its temperature is low because it is not covered by any insulating blanket of low conductivity rock. A gravity survey completed for LASL by P. H. Osberg and associates of the University of Maine indicates that the batholith is a horizontal tabular body 3 to 5 km thick and 30 to 40 km in diameter.

A circular topographic anomaly near Blue Mountain Lake in east central New York was studied by Yngvar Isaachsen of the State University of New York-Albany. Detailed photo interpretation and reconnaissance field mapping showed no evidence of volcanism or other geothermal activity, although the site remains a possible target for natural gas exploration because of possible doming of the Paleozoic sedimentary rocks.

Isaachsen also completed a leveling traverse across the southern Adirondack dome which showed that the dome is currently rising, with the maximum rate of uplift near the center of the dome. He speculates that the uplift may be caused by a local mantle increase in temperature or a tectonic upwarp of the mantle, bringing higher temperature rock closer to the surface.

Investigation of another unusual geothermal energy source is being pursued in southwestern Arkansas by the Arkansas Power and Light Company (AP&L). In that area, several chemical companies pump brine at 62°C from a very permeable limestone at depths of 2400 to 3000 m. After bromine is extracted, the brines at approximately 63°C are wasted to disposal wells. AP&L has received support from DOE to build a binary phase heat exchanger, turbine, and generator to produce electricity from these moderate temperature brines. The economic viability of the project depends upon the success of the experimental heat exchanger and the price asked by the chemical companies for use of the waste brines.

CONCLUSIONS

Thus, it is apparent that sources of low- to moderate-temperature geothermal energy occur widely throughout the eastern United States. Exploration for and evaluation of these sources has not yet progressed as far as for the higher temperature sources of the west. Modest funding and manpower devoted to this work is beginning to provide the data necessary to evaluate some of these eastern prospects. As the technology to utilize low temperature sources become available, these sources will make an increasing contribution to America's energy base.

ACKNOWLEDGEMENTS

The author thanks Gerry Brophy of DOE, and A. William Laughlin of LASL, who have provided continuing encouragement and direction for this work, the several contractors who have provided the results reported above, and the many private landowners and state officials who have assisted with this program.

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GEOTHERMAL EXPLORATION AND DEVELOPMENT DRILLING PROGRAMS
FOR 50 HEAT FLOW HOLES AND A DEEP TEST WELL

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ABSTRACT

This paper describes the management and drilling techniques used to drill 50 heat flow measurement holes on the Atlantic Coastal Plain between July 1, 1978 through January 28, 1979. The organization and logistic support required for this effort are shown to be more important than drilling techniques for these shallow holes.

The plans for a geothermal test well near Crisfield, MD are described in some detail in the second part of this paper.

SHALLOW 1000 FEET HEAT FLOW HOLES

The drilling of heat flow measurement holes on the Atlantic Coastal Plain was begun in late June, 1978 on behalf of the Department of Energy's Division of Geothermal Energy. Dr. Jerry Brophy is the program manager for DOE. Dr. Costain of Virginia Polytechnic Institute and State University had selected 62 original sites as shown by the circles on figure 1 for exploratory drilling, and the Division of Geothermal Energy desired to have all sites drilled within six months after effective date of the contract between DOE and Gruy Federal, Inc. At the end of January, 1979, Gruy Federal and its drilling contractor, Energy Service Company, had completed 50 heat flow test holes, most of which were 1000 feet deep, but with several as deep as 2000 feet. The triangles on figure 1 indicate second pass holes which were drilled to detail the interesting areas found in the first pass drilling.

During the operations in Maryland, Virginia, and North Carolina in October through January, the drilling team was able to complete three holes per week provided that the holes were not more than 50 miles apart. No moves were permitted at night nor on weekends in any of the states. The moving schedule had to be carefully planned in advance so that moves could be made on Monday morning, Wednesday and Friday afternoon. This permitted a round the

clock operation.

Since the Atlantic Coastal Plain is considered a frontier operation by most of the oil well service companies, including Halliburton and Christiansen, it was necessary to have dedicated Halliburton cementing and Christiansen coring crews accompany the drilling rig on a daily basis, thus providing service as needed with no transportation delays.

The time required to drill a typical heat flow hole is shown in figure 2. It is apparent that actual drilling and coring time is about equal to moving and rig up and rig down time, and the operation turned out to be a logistics problem, rather than a drilling problem. In

FIGURE 1

FIGURE 2

order to complete a hole every three days, the organization of this team had to provide for advance leasing, permitting, and site preparation as shown in figure 3. All of the people shown were in the field full time with the exception of the officer in charge. Col. McCain was obtaining leases one state ahead, Mr. Paul O'Connor was obtaining drilling and transportation permits daily for the rig and truck movements, Mr. Glascock was either preparing future sites, cleaning up past sites, or helping pull rig and heavy equipment out of the mud. Mr. Radford and Mr. Peace established engineering headquarters convenient to the rig operations as possible. The advance parties and on site management provided an efficient operation which resulted in reduced rig time, lower cementing and coring costs and yielded a hole cost well below that which would have been obtained on a single well serviced from West Virginia or Pennsylvania.

FIGURE 3

Figure 4 is a photograph of the rig in operation at Ocean City, MD and a schematic of a completed heat flow hole is shown in figure 5. The simple well head is used to insert Dr. Costain's temperature measuring device through the two-inch full opening valve after temperature gradient and static temperature stabilized. Dr. Costain intends to continue measurements in these holes for one to two years.

Two 25 foot cores were attempted during the drilling of each well. Figure 6 shows how the core was sent to the laboratories. Cores were taken in a PVC liner of 30 feet length and sawed in the field into five-foot lengths. Core recovery was variable due to the predominance of unconsolidated sands in the Atlantic Coastal Plain. However, it was a rare occurrence when no core was recovered from a hole.

FIGURE 4

SCHEMATIC OF BASIC WELL DESIGN FOR 1000-FOOT
HEAT FLOW MEASUREMENT WELLS.

FIGURE 5

FIGURE 6

Table I summarizes the test hole drilling program to date.

GRUY FEDERAL, INC.

SUMMARY OF HEAT FLOW HOLES

STATE	NO. OF WELLS	CORE		DEPTHS	
		AVG. FOOTAGE/ WELL	ZREC	FROM	TO
NEW JERSEY	5	55'/WELL	45	998	1047
MARYLAND	13	60'/WELL	55	1000	1666
DELAWARE	5	69'/WELL	45	980	1048
VIRGINIA	16	40'/WELL	50	1000	1800
NORTH CAROLINA	11	50'/WELL	60	731	1066
TOTAL	50				

TABLE 1

DEEP TEST WELL

From the heat flow data obtained from the wells shown in Table 1, a DOE Division of Geothermal Energy Selection Committee selected a site at Crisfield, MD for a deep test well to basement. The well will be approximately 5000 feet deep, the hoped for temperature near basement is predicted to be 80°C, and it is planned to test at least three aquifers within the salt water region of the well for chemical composition and flow.

Figure 7 shows the site for the deep test near Crisfield, MD. The test well, Crisfield Airport No. 1, will be located on property adjacent to the runways at the Crisfield Municipal Airport in Somerset County, Maryland. This property is jointly owned by the City of Crisfield and the County of Somerset. The drill site will cover approximately 3/4 acre at the production test well site and slightly less at the disposal well site.

Figure 8 shows the well schematic. A 17½ inch casing will be run and cemented to the surface. A 17½ inch hole will be drilled to approximately 1800 feet and 13-3/8 inch casing run and cemented to the surface. A 12-1/4 inch hole will be drilled to the top of the basement estimated at 5000 feet and 9-5/8 inch casing set and cemented to at least 200 feet inside 13-3/8 inch casing. While drilling the 12-1/4 inch hole before the 13-3/8 inch casing is set, a total of six cores will be taken at the discretion of the VPI&SU geologist. After the 9-5/8 inch casing has been set, the well will be drilled and cored approximately 700 feet into the basement. Upon reaching total depth (approximately 5700 feet), the basement will be hydraulically fractured to obtain at least two injection rates, utilizing a

FIGURE 7

GRUY FEDERAL, INC.

WELL SCHEMATIC

FIGURE 8

packer set in the 9-5/8 inch casing on 2-7/8 inch tubing. After fracturing, the open hole will be plugged and any prospective producing zones will be selectively perforated and tested.

Figure 9 shows the well logs which will be run in the open hole and subsequently in the cased hole. These logs were selected to yield all available useful information about the hole and the formation characteristics.

OPEN HOLE LOGS:

- SPONTANEOUS POTENTIAL
- SPHERICALLY FOCUSED INDUCTION
- SONIC
- CALIPER
- FORMATION DENSITY
- TEMPERATURE

CASED HOLE LOGS:

- CEMENT BOND
- GAMMA RAY
- CASING COLLAR LOCATOR
- CONTINUOUS NEUTRON

FIGURE 9

COMPLETION

The well will be completed as follows (see figure 7):

A permanent type packer will be set in the shoe joint of the 9-5/8 inch casing and the open hole squeezed with 100 sacks Class H cement, then 50 sacks Class H cement will be dumped on top of the packer. The zone or zones of interest will be perforated utilizing shaped charges at a density of four holes per foot. Only 20 feet of the zone will be perforated on each trip into the well. Several zones will be perforated and tested selectively by the use of additional drillable packers. Final completion will depend on preliminary test results.

TESTING

In each zone of interest the following analytical techniques will be used to estimate the aquifer properties:

1. Classical pressure drawdown and buildup analysis to determine skin effect (well bore damage) and permeability.

2. Non-linear regression analysis to determine skin effect, permeability, and porosity.

3. Core analysis to estimate the mean permeability and porosity.

4. Log analysis to estimate porosity and net porous thickness.

5. Single-phase, single-well numerical reservoir simulator to history match the pressures and determine permeability, porosity and skin effect.

Given permeability and porosity, the hydrologist will be able to compute the transmissibility and the storage coefficient.

SURFACE FACILITIES

The surface facilities will consist of a data header, a liquid meter, several settling tanks, two centrifugal injection pumps and two disposable cartridge filters. A schematic of these facilities is shown in figure 10. The data header will be manifolded to measure selectively the following properties of the flowing fluid:

- o temperature
- o pH
- o conductivity
- o scale deposition
- o sand detection

In addition, a port is provided to permit ease of sampling the flowing fluid. To analyze the composition of the fluid, a mobile chemical laboratory will remain on site.

The results from this test well should be available from the Division of Geothermal Energy in July or August, 1979.

FIGURE 10

CENOZOIC AND MESOZOIC AQUIFER SYSTEMS OF THE ATLANTIC COASTAL PLAIN*

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INTRODUCTION

An aquifer system is defined as "a heterogeneous body of intercalated permeable and less permeable material that acts as a water-yielding unit of regional extent" (American Geological Institute, 1974, p. 34). In a broad sense, the entire sediment mass of Cenozoic and Mesozoic age, that lies along the Atlantic Coastal margin and which consists of lens-like layers of chiefly unconsolidated sediment, may be considered one aquifer system. In a more restricted sense and for practical descriptive and operative purposes, component chronostratigraphic units (lenses) of the sediment mass, offset and stacked one above the other, may be considered to represent individual aquifer systems that, to a greater or lesser extent, are hydraulically interconnected. They are so considered in this summary, because they are material units, characterized by lithologic heterogeneity and variable permeability, that act as water-yielding units of regional extent. Moreover, they have practical utility - boundaries of chronostratigraphic units can be determined, and the external and internal geometry of the units can be mapped in the subsurface by conventional geologic methods (Brown and others, 1972).

Geothermal energy may be generated in the crust, either radiogenically or by mechanical-thermal energy conversion, as when igneous intrusions are present at shallow depths in the crust (Grose, 1971) and/or as when mechanisms such as stress, shear-strain, and friction are operative in the crust (Roy and others, 1972). Component parts of the vertical succession of aquifer systems, that comprise a sediment mass overlying the crust, may have potential either as geothermal reservoirs or reservoir seals. To a considerable degree, the geothermal potential of an aquifer system depends not only upon its proximity to a crustal heat source, but also upon its position within the sediment mass and its position relative to other aquifer systems that may be present, and the nature of, thicknesses, volumes, relative permeabilities, and thermal conductivities of its component materials.

* Approved for publication by the Director,
U.S. Geological Survey

In areas such as the Atlantic Coastal Plain, where suspected crustal heat sources have not yet been fully documented, the geothermal potential of aquifer systems may, in the absence of a known heat source, and in part, be quantified, on the basis of geologic information, for comparative, region-wide, screening purposes. The basic geologic information required is (1) that which defines the regional structural-stratigraphic framework and the manner in which it controls the position and composition of aquifer systems present in the sediment mass, and (2) that which delineates aquifer systems and their component parts.

STRUCTURAL-STRATIGRAPHIC FRAMEWORK

Anything more than a cursory introduction to the geothermal potential of the Atlantic Coastal Plain's aquifer systems demands some degree of familiarity and specific knowledge of the area's overall structural-stratigraphic framework and the manner in which that framework controls the ground-water storage and distribution system. Two basic structural-stratigraphic concepts are currently applied to the Atlantic Coastal Plain; one old and one new. They have little in common.

Benson (1976) describes the old concept as follows:

"The historical concept of the subsurface geology of the Atlantic Coastal Plain Province suggests a wedge of sediments of Mesozoic and Cenozoic age that dips uniformly toward the southeast. The sediments were thought to comprise a series of units, unbroken by faults, with uniform or gradually increasing thickness, as they extend seaward beneath the continental shelf to the continental slope where they crop out beneath the sea. The basement surface upon which the sediments were deposited likewise was considered a uniformly seaward-sloping erosional surface developed on crystalline rocks of Precambrian and Paleozoic age that crop out in the Piedmont Province of the eastern United States."

This is a concept in which the depositional dip of layers of the sediment mass is considered essentially uniform, unidirectional, and concordant with the present-day dip of the underlying basement surface.

In accordance with this simple model of a structural-stratigraphic, monoclinical system for the Atlantic Coastal Plain, permeable stratigraphic units (formations), delineated in outcrop and projected into and through the subsurface as gently-dipping, compositionally-constant layers, have been defined, by numerous investigators, as aquifers. Many or most of these have been considered to have regional extent (Sinnott and Cushing, 1978). Although oversimplified, the resultant hydrologic model is one in which ground water in the sediment mass is considered to travel significant distances from an outcrop area and in the direction of the continental shelf (from the northwest toward the southeast). It is presumed to travel through gently-dipping (15-20 ft/mi) permeable layers (aquifers) interspersed with other less-permeable layers (confining beds) having the capacity to leak water, at various rates, into the more permeable layers. At varying distances, either inland or seaward of the shoreline, both the permeable and less-permeable layers are considered to contain saline water.

A new concept of the structural-stratigraphic framework of the Atlantic Coastal Plain was developed (Brown and others, 1972) as part of a detailed subsurface study of the geometry of the sediment mass, and the manner in which it controls permeability distribution in the area extending from Long Island, N.Y. through North Carolina. The new concept is that the basement underlying the coastal plain consists of a mosaic of fault-bounded blocks and that differential horizontal and vertical movement of the blocks relative to each other, controlled both the depositional and subsequent erosional patterns recognized in Mesozoic and Cenozoic sediments on the Atlantic Coastal Plain. The areal distribution, thickness, and composition of chronostratigraphic units comprising the sediment mass represent a response to structural configurations generated by relative movement of fault-bounded blocks during and/or after their deposition. The basic structural configuration produced at any one time by the relative movement of blocks is that of graben, half-graben, horst systems. Based upon changes in the alignments and geometry of successive chronostratigraphic units, two such systems, characterized by different alignments and that alternate in their occurrence, are judged to have controlled both the deposition and subsequent erosion of Mesozoic and Cenozoic sediments. Depositional troughs, aligned differently in each of the two systems (NE-SW and N-S, respectively), are angularly discordant with respect to each other. In terms of both their external geometry (location, shape and thickness) and internal geometry (composition, depositional strike and dip, facies gradient, energy levels of deposition, etc.), chronostratigraphic units, deposited when one system was operative, exhibit angular discordance with respect to those deposited when the other system was operative. Thus, permeable, tabular or lenticular bodies of sand (aquifers), associated with one group of chronostratigraphic units,

have a different orientation and properties than those associated with the other group of chronostratigraphic units. The differences include patterns of intrinsic permeability distribution (zonation) characteristic of each group of units and which is chiefly dependent upon the composition and distribution of their component facies. Intrinsic permeability distribution patterns recognized in one group of chronostratigraphic units have different alignment and distribution from those recognized in the other group.

For purposes of comparing some basic elements of the new and historical concepts of the Atlantic Coastal Plain's structural-stratigraphic framework, the new concept is one in which the depositional dip of layers or lenses within the sediment mass is considered nonuniform, instead of uniform, multidirectional, instead of unidirectional, and, in large part, discordant, instead of concordant, with the present-day dip of the underlying basement surface. Unlike the historical concept that attempts to explain the evolution of the sediment mass by means of a forced-fit of its component stratigraphic parts so as to establish agreement with a preconceived structural model, the new concept uses the intrinsic geometry of the sediment mass to derive a mutually-satisfying, structural-stratigraphic model of coastal plain evolution.

Except locally in the Atlantic Coastal Plain, the concept of permeable stratigraphic units (formations), designated as aquifers in the outcrop area and projected significant distances into and through the subsurface as unidirectional, gently-dipping, compositionally-constant layers, is not supported by geologic fact.

AQUIFER SYSTEMS

Given the "new" concept for purposes of evaluating the geothermal potential of aquifer systems in the Atlantic Coastal Plain, additional geologic information is required that permits delineation of aquifer systems and determination of the areal extents, compositions, volumes, and relative permeabilities of their component parts.

Both on the basis of the types and amounts of necessary information available, the region can be divided into two segments: a northern one, extending from Long Island, N.Y. through North Carolina, and a southern one, that includes South Carolina and Georgia. Pertinent geologic information is relatively abundant in the northern segment and sparse in the southern segment. In the northern one, the maximum depth to the top of the basement surface is about 10,000 feet below mean sea level, in the vicinity of Cape Hatteras, N.C. (Brown and others, 1972, pl. 5). In the southern one, the maximum depth to the top of the pre-Cretaceous surface is about 7,000 feet below mean sea level in Seminole County, Ga. (Brown and others, 1978, pl. 3A).

For descriptive and operative purposes, the regional sediment mass can be divided into those parts that contain Mesozoic and Cenozoic sedimentary rocks, respectively. In the northern segment, the volume of Mesozoic sedimentary rocks is about 17,900 mi³ and that of Cenozoic about 5,800 mi³. The maximum thickness of Mesozoic sedimentary rocks is about 7,100 feet (Dare County, N.C.) and that of Cenozoic about 2,900 feet (Dare County, N.C.) (Brown and others, 1972). In the southern segment, the volume of Mesozoic sedimentary rocks is about 20,000 mi³ and that of Cenozoic about 11,300 mi³. The maximum thickness of Mesozoic sedimentary rocks is about 5,200 feet (Seminole County, Ga.) and that of Cenozoic about 3,000 feet (Camden County, Ga.) (Brown and others, 1978).

Northern Segment - Atlantic Coastal Plain

In the northern segment, the sediment mass, extending from the basement surface to the land surface, has been mapped in some detail (Brown and others, 1972). Seventeen regional chronostratigraphic sequences, comprising nine of Mesozoic age and eight of Cenozoic age, were delineated in the subsurface by means of a series of structure maps and a series of isopach-lithofacies-permeability-distribution maps. For each sequence, the series of maps shows the configuration of its surface, its thickness, its facies composition, and the distribution (zonation) of its intrinsic permeability. By definition, each sequence or chronostratigraphic unit also is an aquifer system, because it represents a material unit, characterized by lithologic heterogeneity and variable permeability, that acts as a water-yielding unit of regional extent. Therefore, the maps drawn to show the external and internal geometry of chronostratigraphic units that comprise the sediment mass also show the external and internal geometry of aquifer systems that comprise the sediment mass. For purposes of evaluating their geothermal potential, the areal extent and volume for each lithofacies and each intrinsic permeability zone have been calculated for each aquifer system mapped. The maps previously constructed for each system (Brown and others, 1972), together with the calculated values derived from these maps for each system, provide a quantitative basis for evaluating reservoir and reservoir-seal potential (geothermal potential) of individual aquifer systems and for comparing that of different systems. Quantitative evaluation and comparison can be made in terms of the spatial distribution of aquifer systems relative to each other and to the underlying basement surface. Comparison can also be made in terms of the compositions, areal extents, volumes, and relative permeabilities of their component parts. The calculated, map-derived values, for the areal extent and volume of each lithofacies and each relative intrinsic permeability zone in each aquifer system, are combined and summarized (Tables 1 and 2) for 14 of the 17 aquifer systems present in the sediment mass. These systems were

selected for their areal extent and thickness and/or depth of burial. They are judged to be of possible interest in a reconnaissance program of geothermal exploration. The aquifer systems listed in the tables are identified and arranged according to the identification and arrangement of their time-equivalent counterparts in the geologic sequence (see Brown and others, 1972, pl. 2). The oldest aquifer system is shown in the column to the left and the youngest in the column to the right.

Southern segment - Atlantic Coastal Plain

In the southern segment the types and amounts of data needed to evaluate the geothermal potential of aquifer systems, either qualitatively or quantitatively, are sparse. A wide assortment of publications describe local geohydrologic conditions and documents the fact that large quantities of ground water are stored in and transmitted through different segments of the sediment mass, chiefly in its upper part. However, point-source data in local areas have not generally been collated for purposes of drawing regional subsurface maps that illustrate both the spatial distribution and facies composition of chronostratigraphic units and their counterpart aquifer systems. Therefore, and except perhaps in local areas, it is not possible to determine the areal extent, thickness, volume, and permeability of bodies of sand or shale that would need to be considered in evaluating the geothermal reservoir or reservoir-seal potential of aquifer systems.

The spatial distribution of chronostratigraphic units, and their counterpart aquifer systems, in a part of the Mesozoic segment of the sediment mass, were mapped for purposes of evaluating waste-storage potential in the deep subsurface and of delineating, areally and volumetrically, the component parts of each aquifer system that contained either usable or non-usable ground water (Brown and others, 1978). In that report, usable ground water was defined as that which contained less than 10,000 mg/L dissolved solids. Basic data from that report are combined and summarized in table 3. When used in conjunction with the maps of aquifer systems in that report, these data may be useful for purposes of evaluating the geothermal potential of aquifers in the deep subsurface.

Table 1. Cenozoic Aquifer Systems, Atlantic Coastal Plain, North Carolina to Long Island, New York

	Midway aquifer system	Sabine aquifer system	Claiborne aquifer system	Jackson aquifer system	Oligocene aquifer system	Middle Miocene aquifer system
Total volume ¹	971	217	1,062	263	261	1,661
Total area ²	34,500	16,730	28,860	8,445	6,800	30,205
Lithologic facies						
Sand: 75-100%						
Volume	82.1	50.8	22.7	9.6	5.1	8.1
Area	4,775	3,140	2,175	310	345	1,580
Sand: 50-75%						
Shale: 25-50%						
Volume	260	20.8	98.8	135	7.6	197
Area	11,900	1,295	5,200	2,775	280	4,200
Shale: 50-75%						
Sand: 25-50%						
Volume	211	16.9	103	56	-	966
Area	7,125	1,720	4,575	1,400	-	15,125
Shale: 75-100%						
Volume	188	72.2	78.8	61.2	-	425
Area	5,450	7,300	4,150	3,550	-	8,275
Limestone: 25-50%						
Clastics: 50-75%						
Volume	118	25.3	7.2	0.1	12.5	55
Area	2,800	1,645	435	31	375	840
Limestone: 50-75%						
Clastics: 25-50%						
Volume	44.4	24.1	70.5	0.9	37.8	9.8
Area	1,100	1,225	1,225	290	1,100	175
Limestone: 75-100%						
Volume	67.5	6.9	681	0.2	198	0.1
Area	1,350	405	11,100	89	4,700	10
Relative intrinsic permeabilities						
Very high						
Volume	-	-	-	-	198	-
Area	-	-	-	-	4,700	-
High						
Volume	0.6	-	681	-	-	9.4
Area	95	-	11,100	-	-	115
Moderately high						
Volume	13.7	0.9	7.9	7.5	42.4	58.8
Area	1,150	230	655	195	1,400	1,100
Moderate						
Volume	74.7	51.3	18.9	3.3	12.9	4.8
Area	4,300	3,025	1,650	500	405	1,390
Moderately low						
Volume	390	43.5	173	135	7.7	197
Area	15,800	2,625	6,755	2,800	295	4,200
Low						
Volume	238	42.2	103	56	-	966
Area	6,555	3,150	4,550	1,400	-	15,125
Very low						
Volume	254	79.1	78.2	61.2	-	425
Area	6,600	7,700	4,150	3,550	-	8,275

¹Volume - mi³²Area - mi²

Table 2. Mesozoic Aquifer Systems, Atlantic Coastal Plain,
North Carolina to Long Island, New York

	Aquifer system H	Aquifer system G	Aquifer system F	Aquifer system E	Aquifer system D	Aquifer system C	Aquifer system B	Aquifer system A
Total volume ¹	4,662	3,124	5,321	888	900	1,215	1,099	711
Total area ²	29,220	28,495	55,455	22,835	24,885	35,685	31,650	28,555
Lithologic facies								
Sand: 75-100%								
Volume	20.4	9.4	81	18.3	38.5	104	35	69
Area	795	475	1,125	820	1,325	3,375	980	2,700
Sand: 50-75%								
Shale: 25-50%								
Volume	643	71.7	974	70.8	176	338	101	181
Area	7,730	2,125	10,975	2,125	6,320	10,250	3,650	6,400
Shale: 50-75%								
Sand: 25-50%								
Volume	3,785	2,552	3,855	126	548	618	293	324
Area	19,610	22,100	29,200	5,125	13,600	15,400	10,500	11,850
Shale: 75-100%								
Volume	40	444	408	539	124	155	656	124
Area	460	3,550	4,050	12,240	3,450	6,660	16,075	6,635
Limestone: 25-50%								
Clastics: 50-75%								
Volume	96.2	46.9	3	103	13.5	-	14	11.8
Area	360	245	105	2,050	190	-	445	815
Limestone: 50-75%								
Clastics: 25-50%								
Volume	77.4	-	-	30.9	-	-	-	1.2
Area	265	-	-	475	-	-	-	155
Limestone: 75-100%								
Volume	-	-	-	-	-	-	-	-
Area	-	-	-	-	-	-	-	-
Relative intrinsic permeabilities								
Very high								
Volume	-	-	-	-	-	-	-	-
Area	-	-	-	-	-	-	-	-
High								
Volume	14.9	9.4	-	0.9	1.2	21.5	-	-
Area	665	475	-	187	100	465	-	-
Moderately high								
Volume	-	-	84	0.7	36.9	22.5	4.6	1.1
Area	-	-	1,225	48	1,175	1,675	265	190
Moderate								
Volume	644	62.7	716	16.4	189	259	58.4	70.9
Area	7,725	1,805	7,775	590	6,550	8,425	2,380	2,715
Moderately low								
Volume	83.1	2,561	3,854	153	540	181	158	179
Area	395	22,420	39,220	5,500	12,910	5,500	5,080	6,200
Low								
Volume	3,880	46.9	259	178	8.9	576	222	324
Area	19,975	245	3,180	4,255	700	12,970	7,850	11,850
Very low								
Volume	40	444	408	539	124	155	656	136
Area	460	3,550	4,055	12,255	3,450	6,650	16,075	7,600

¹Volume - mi³²Area - mi²

Table 3. Mesozoic Aquifer Systems, Atlantic Coastal Plain, Georgia and South Carolina

	Aquifer system H(?)	Aquifer system G(?)	Aquifer system F	Aquifer system E	Aquifer system D	Aquifer system C	Aquifer system B	Aquifer system A
Total volume ¹	583	872	4,875	852	4,496	2,648	3,146	3,410
Total area ²	4,678	6,257	60,000	30,725	48,090	55,590	50,050	50,450
Percentage of aquifers containing usable ground water								
Volume	0	0	57	48	89	76	87	90
Area	0	0	73	55	85	84	86	88
Aquifers containing usable ground water								
Volume	0	0	2,795	409	4,023	2,009	2,735	3,061
Area	0	0	43,681	17,072	40,850	46,714	42,818	44,626
Aquifers containing non-usable ground water								
Volume	583	872	2,080	443	473	639	411	349
Area	4,678	6,257	16,319	13,653	7,240	8,876	7,232	5,824

¹Volume - mi³²Area - mi²

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RESERVOIR ENGINEERING AND EVALUATION

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INTRODUCTION

An understanding of the physics of fluid flow and heat transport in geothermal systems is important with regard to the classification of and exploration for geothermal resources. This understanding is perhaps even more important in terms of aiding in determining if the resource can be developed economically. Obviously, geothermal systems are very complex with many processes occurring in them. Some of these physical processes include: 1) convective and conductive transport of heat in the fluid and rock matrix, 2) the transport of water and (or) steam in porous and fractured media, 3) solute transport including chemical reactions that affect the flow characteristics of the medium, and 4) consolidation and land subsidence effects associated with fluid withdrawal. For many field problems, some of these processes have negligible effects and may be omitted, leading to a somewhat simpler description. Even with the simplifications, some rational framework is required in order to keep track of the important processes and how these processes interact.

One approach to attempt this "bookkeeping" of the physical behavior of geothermal systems is to use a mathematical model. Such a model consists of a set of equations that describe the transport processes active within the system and the solution to these equations subject to conditions that prevail at a particular site. This set of equations is general and may be used to consider two major subdivisions of geothermal modeling: 1) modeling the geothermal system under natural conditions in an effort to better understand how it forms and persists within the earth's crust, and 2) modeling the geothermal system during exploitation in order to predict its behavior subject to man-made stresses.

The formation of geothermal systems is thought to be associated with recent volcanism or significant tectonic movements. As a result of these activities, magmatic intrusions may occur at shallow depths in the earth's crust. Meteoric water is recharged to depth where it is heated directly or indirectly by the intruded magma. Density differences caused by the heating drive the fluid buoyantly upward where, hopefully, it can be exploited for power production. To be economically significant, a geothermal resource must have high

temperatures and be located at shallow depths within the earth's crust.

Since current technology does not permit economical extraction of heat directly from dry rock, geothermal resources must also contain a fluid (either steam or water) to transfer heat from the geothermal reservoir to the surface. In addition, the reservoir must have sufficient volume, porosity, and permeability to yield adequate flow rates to wells.

One simulates a geothermal system to understand its behavior as well as to estimate the quantity of recoverable energy and the rate at which mass and energy may be extracted. To achieve these objectives, known geological information obtained from both surface techniques and drilling is utilized to determine equation parameters and boundary and initial conditions. During the earlier stages of field development, this information is limited, and the simulation model will undoubtedly be crude. Through the simulation of a variety of producing schemes, however, the energy available and its rate of extraction may be roughly estimated. Reservoir characteristics can be varied to determine what parameters are most critical to reservoir production, and what additional data is required to improve the simulation. If the decision is made to develop the field further, the reservoir model may be used to help answer such engineering questions as optimal well location and spacing, or whether or not to reinject condensate. As more geological information becomes available through continued drilling, the simulation model may be updated to give a more accurate analysis of the geothermal reservoir.

In this discussion, we restrict our attention to hydrothermal systems, that is, geothermal systems containing water. In particular, hydrothermal-convection systems are considered where most of the heat is transferred by circulating fluids rather than by heat conduction. These systems can be further subdivided as either liquid dominated or vapor dominated (White, Muffler, and Truesdell, 1971). In the liquid-dominated type, water is the continuous phase throughout the system that provides the pressure control. Continuity of the liquid phase is evident from reservoir pressures that are near hydrostatic and presence of soluble salts that are not found in significant quantities

in low-pressure steam. In the vapor-dominated type, steam is the continuous, pressure-controlling phase, although water is also present.

Hydrothermal Systems

As stated, hydrothermal systems are geothermal systems that contain fluid. Although geothermal fluids contain impurities, many reservoirs are often approximated as pure-water systems. Consider figure 1, a pressure-temperature diagram of the liquid-vapor region for pure water (Whiting and Ramey, 1969). The points A, B, and C represent possible conditions for a hydrothermal system:

Fig. 1 Generalized pressure-temperature diagram for pure water showing points A, B, and C located in the compressed-liquid, saturated liquid-steam, and superheated steam regions, respectively (after Whiting and Ramey, 1969).

compressed-liquid, saturated liquid-steam, and superheated steam, respectively. These points are shown in figure 2, which is a pressure-enthalpy diagram for pure water (Whiting and Ramey, 1969). The compressed-liquid region is the condition existing in liquid-dominated hydrothermal systems. The vapor-dominated system described by White *et al.* (1971) is believed to exist mainly in the saturated liquid-steam region. In vapor-dominated systems, it is also probable, especially when influenced by exploitation, that parts of the system contain superheated steam.

At point A (see figure 1) in the compressed-liquid region, the system has one component, water, and one phase, liquid. According to Gibb's phase rule, two independent intensive properties (for example, temperature and pressure) must be specified to determine the thermodynamic state of the system. Once these properties are specified, point A can be located on any other thermodynamic diagram (for example, the pressure-enthalpy diagram). Liquid-dominated reservoirs with these initial conditions yield water to wells.

Fig. 2 Generalized pressure-enthalpy diagram for pure water showing points A, B, and C located in the compressed-liquid, saturated liquid-steam, and superheated steam regions, respectively (after Whiting and Ramey, 1969). Bold lines are isotherms and the dashed lines are lines of equal steam quality.

A decrease in pressure in the wellbore, however, causes steam to form, providing a mixture of steam and water at the wellhead. Field data (Grindley, 1965) indicate that production of a geothermal reservoir initially at point A will tend to cause an isothermal depletion, with reservoir pressures decreasing until the vapor-pressure is reached.

At the vapor-pressure curve, point B (figure 1), one intensive property determines the thermodynamic state. Although the thermodynamic condition is specified as liquid and vapor in equilibrium, the relative amounts can not be determined unless two independent properties such as pressure and mixture enthalpy are known. Note from figure 2 that temperature and pressure do not determine the relative amounts since temperature and pressure are not independent in the two-phase region.

Once vapor forms in the reservoir, temperatures drop slightly as a result of the heat of vaporization used to form steam. Because the water saturation is high, the relative permeability for the liquid phase dominates, and water continues to be produced from the reservoir. Pressure decreases only slightly in the two-phase region because pressure is maintained by the formation of steam. As production continues, however, water saturations decrease, temperatures decrease, and consequently, pressures also decrease, with more steam being produced from the reservoir.

Point C lies entirely in the vapor (superheated steam) region. This condition probably rarely occurs naturally in a reservoir. As in the compressed-liquid region, two independent intensive properties are required to define the thermodynamic

state. In this case, the reservoir would also tend to deplete isothermally.

This description of reservoir behavior has been based on the assumption that the reservoir fluid is pure water and (or) steam. Geothermal fluids, however, contain dissolved solids and noncondensable gases. For example, the total dissolved solids for the Wairakei, New Zealand field is less than 3% by weight, whereas some geothermal fluids in Imperial Valley, California contain as much as 30% dissolved solids by weight. Therefore, the vapor pressure of the fluid in a geothermal reservoir may not necessarily be that represented in the steam tables. For a fixed pressure, the boiling temperature of water will be elevated by the presence of impurities. General field behavior, however, should be qualitatively similar to that outlined for pure water.

THEORETICAL DEVELOPMENT

The physical properties of the fluid and reservoir vary spatially and temporally, and effects of gravity segregation of steam and water require vertical as well as horizontal treatment. Consequently, a general model must be a distributed parameter model with the capability of three-dimensional simulation. To answer important engineering questions, a general model must not only accommodate the transient flow of compressed liquid, steam-water mixture, and superheated steam, but also must allow for phase changes. In this discussion, we neglect solute transport and chemical reactions that may occur in the geothermal system. Furthermore, we assume that the reservoir can be treated as a porous medium.

The general governing equations consist of mass, momentum, and thermal energy balances for each phase present in a geothermal system. Using a set of constitutive relationships, these balance equations may be reduced to two or three nonlinear partial differential equations.

Mass Balance

The mass balances for steam, s , and water, w , may be written as:

$$-\frac{\partial}{\partial x_i} (\bar{v}_s \rho_s) + q_s + d_v = \frac{\partial(\phi S_s \rho_s)}{\partial t} \quad (1)$$

and

$$-\frac{\partial}{\partial x_i} (\bar{v}_w \rho_w) + q_w - d_w = \frac{\partial(\phi S_w \rho_w)}{\partial t} \quad (2)$$

where

- $\bar{v}$ = phase average velocity [Lt^{-1}]
- ρ = average density, [ML^{-3}]
- q = source term, [$ML^{-3}t^{-1}$]
- d_v = rate of vaporization, [$ML^{-3}t^{-1}$]
- ϕ = porosity, dimensionless
- S = saturation, dimensionless, where $S_w + S_s = 1$

Momentum Balance

For velocity, we assume that Darcy's equation for multiphase flow may be used

$$\bar{v}_s = -\frac{\bar{k} k_{rs}}{\mu_s} \left(\frac{\partial p_s}{\partial x_j} - \rho_s \bar{g} \right) \quad (3)$$

and

$$\bar{v}_w = -\frac{\bar{k} k_{rw}}{\mu_w} \left(\frac{\partial p_w}{\partial x_j} - \rho_w \bar{g} \right) \quad (4)$$

where

- k = local intrinsic permeability tensor [L^2]
- k_r = relative permeability, dimensionless
- μ = dynamic viscosity, [$ML^{-1}t^{-1}$]
- p = pressure, [$ML^{-1}t^{-2}$]
- $\bar{g}$ = gravitational acceleration, [Lt^{-2}]

Energy Balance

The thermal energy equations, neglecting viscous dissipation, for steam, water, and rock (r) are:

$$\begin{aligned} \frac{\partial(\phi S_s \rho_s U_s)}{\partial t} + \frac{\partial}{\partial x_i} (\rho_s U_s \bar{v}_s) + \frac{\partial \bar{\lambda}_s}{\partial x_i} + p_s \frac{\partial \bar{v}_s}{\partial x_i} \\ + q_s h_s + Q_{ws} + Q_{rs} = 0, \end{aligned} \quad (5)$$

$$\begin{aligned} \frac{\partial(\phi S_w \rho_w U_w)}{\partial t} + \frac{\partial}{\partial x_i} (\rho_w U_w \bar{v}_w) + \frac{\partial \bar{\lambda}_w}{\partial x_i} + p_w \frac{\partial \bar{v}_w}{\partial x_i} \\ + q_w h_w + Q_{sw} + Q_{rw} = 0, \end{aligned} \quad (6)$$

$$\frac{\partial[(1-\phi)\rho_r U_r]}{\partial t} + \frac{\partial \bar{\lambda}_r}{\partial x_i} + Q_{sr} + Q_{wr} = 0, \quad (7)$$

in which

- U = internal energy per unit mass [$L^2 t^{-2}$]
- h = enthalpy per unit mass [$L^2 t^{-2}$]
- Q = interphase heat transfer term [$ML^{-1} t^{-3}$]
- $\bar{\lambda}$ = combined conduction - dispersion vector [MLt^{-3}]

The first subscript of the Q term refers to the phase from which the energy is obtained, whereas the second subscript refers to the phase receiving the energy.

Constitutive Relationships and Simplifying Assumptions

The equations presented in the previous sections have 23 dependent variables, e.g. densities, relative permeabilities and viscosities. Many of these can be related to particular thermodynamic variables and thus, additional equations are needed expressing them as functions of these variables. To obtain equations (1) - (7), it was necessary to make the following simplifying assumptions:

1) solute transport, chemical reactions, kinetic energy, viscous dissipation, and potential energy can be neglected; and 2) the geothermal reservoir behaves as a porous medium. In order to simplify the equations further and reduce the number of dependent variables, constitutive relationships, (i.e. expressions relating dependent variables), are used. In general, constitutive relationships are determined in the field and used to obtain the most simplified subset of the general equations that describe a particular geothermal reservoir application. For example, if a reservoir is liquid-dominated, with no chance for steam formation, it would be unnecessary to include the steam balance equations. For some applications, such as well-test analysis, isothermal conditions often exist over the period of analysis so that energy balance equations can be neglected.

For general two-phase reservoir applications, the constitutive relationships concern thermodynamics, capillary pressure, relative permeability, viscosity, reservoir consolidation, thermal exchange between phases, and thermal dispersion-conduction.

The thermodynamics of single-component water provide relationships between $S_g, S_w, \rho_g, \rho_w, U_g, U_w, h_g, h_w, p_g, p_w, \rho$ (mixture density of steam and water), h (mixture enthalpy of steam and water), and T (temperature). The final governing equations are usually reduced to two or three that are posed in terms of two or three thermodynamic variables. Models based on pressure-mixture enthalpy, pressure-mixture internal energy, mixture density-mixture internal energy, and pressure-temperature-saturation have been suggested by various authors.

Capillary pressure is the difference between steam pressure and water pressure, defined as

$$P_c = P_g - P_w \quad (8)$$

It is a property of the porous medium, but, in general, is also dependent upon the volume saturation of liquid and the temperature. Capillary pressure has the effect of apparently lowering the vapor pressure of water. Ramey *et al.* (1973) point out that the reason for this lowering is that vapor pressure data found in steam tables (Meyer, *et al.*, 1968; Keenan, *et al.*, 1969) are based on flat steam-water interfaces, whereas the interface in porous media is curved. The amount the vapor-pressure curve is lowered in a geothermal reservoir is not completely understood. The work of Calhoun, *et al.* (1949) on consolidated rock does show a lowering with decreased fluid saturation. Cady (1969) and Bilhartz (1971), however, indicate no

significant vapor pressure lowering in experiments using unconsolidated sands. An important difference in these results is that the experiments of Calhoun and others were made at a temperature of 36°C, while those of Cady and Bilhartz were done over a temperature range from 121°C to 240°C. Further work on the importance of capillary pressure in geothermal reservoirs is required. For many applications capillary pressure is assumed to be negligible.

Relative permeability is a property of the porous medium, and is also dependent on the volume saturation of liquid. It can be thought of as the ratio of a phase permeability to the total permeability and ranges in values from 0.0 to 1.0. Relative permeability is commonly treated as a function of saturation alone and relationships similar to those in Brooks and Corey (1964) are used. Ramey, *et al.* (1974), point out that relative permeability can also be a function of temperature. Using unconsolidated sand and working with oil and water, Poston, *et al.* (1970), observed that for increased temperatures, the relative permeability curves shift to the left on the saturation axis.

Viscosity is dependent on both the pressure and temperature, but the pressure dependence is small and generally neglected.

Coupled equations for consolidation, fluid flow, and heat transport in geothermal reservoirs may be derived and solved, but consolidation is not the process of concern in many studies. A simple approximation of consolidation that incorporates its main effect on fluid flow may be used. This approximation relates the porosity to pressure by,

$$\phi = \phi_1 + \beta (p - p_1) \quad (9)$$

where ϕ_1 and p_1 are the initial porosity and pressure, respectively, and β is the intergranular, vertical compressibility coefficient.

The movement of steam and water through porous media is sufficiently slow, and surface areas of all phases are sufficiently large, that it is reasonable to assume that local thermal equilibrium among phases is achieved instantaneously. This common assumption permits the energy equations for rock, steam, and water to be combined and the medium conduction-dispersion term to be expressed as a function of a single temperature. In most developments the lumped conduction-dispersion term is defined by a Fourier-type equation,

$$\bar{\lambda}_s + \bar{\lambda}_w + \bar{\lambda}_r = \bar{k}_m \nabla T \quad (10)$$

where T is temperature and, in general, the medium conduction-dispersion $\bar{k}_m$ is a tensor quantity. Regarding the thermal dispersion tensor it should be noted that Mercer (1973) separates the medium thermal dispersion tensor into three parts: conduction in the solid phase, diffusion in the liquid phase, and a velocity-dependent dispersion in the liquid phase. This last part is an attempt to take into account the heat transport related to

the mixing of different temperature waters as they flow through the pore spaces. Furthermore, Somerton, et al. (1974), point out that the thermal conductivity of the medium is a function of temperature, porosity, and water saturation.

Initial and Boundary Conditions

In order to obtain a solution to the governing equations for geothermal reservoirs, hydrodynamic and thermal boundary and initial conditions must be specified. These conditions can be deduced from a thorough examination of hydrologic and geologic data. There are generally three types of hydrodynamic boundary conditions in geothermal reservoirs: 1) constant pressure boundary conditions, 2) no-flow boundary conditions along impermeable surfaces, and 3) specified flux. The corresponding thermal boundary conditions are 1) constant temperature, 2) no heat flow-insulated boundary, and 3) specified heat flux. When production or injection wells exist in the reservoir, additional boundary conditions specifying either the pressures or the mass flow rates for the sources or sinks are required. Initial conditions, specifying thermodynamic variables throughout the reservoir at the beginning of the simulation, determine whether the reservoir is liquid- or vapor-dominated. In addition, the boundary conditions determine the flow conditions. Depending on the hydrodynamic and thermal boundary conditions, both free (or natural) and forced convection may occur in geothermal systems. Free convection generally dominates flow conditions in geothermal reservoirs before exploitation, while forced convection dominates during exploitation when externally imposed pressure gradients are generated due to production and/or reinjection of fluids.

Equation Parameters

In addition to boundary and initial conditions, many of the equation parameters, which are also field parameters (for example, permeability), need to be determined. Some of these are determined by performing laboratory tests on core samples. Thermal conductivities and porosities may be obtained in this fashion. Permeabilities, however, are generally determined in the field using *in situ* techniques, such as well testing. This involves analyzing pressure data using simplified subsets of the general governing equations. This is often referred to as an inverse problem, since permeabilities are "backed out" from pressure build-up or drawdown data.

Such analyses have been performed on several liquid-dominated reservoirs (Narasimhan, 1977) with limited success. These tests have established that well-testing, based on techniques developed in the fields of petroleum engineering and hydrogeology, is a valuable tool in estimating *in situ* parameters and in deciphering the geometry of geothermal reservoirs.

The application of transient pressure analysis methods to vapor-dominated reservoirs has generally been done using methods developed for noncondensable

gas reservoirs. Moench and Atkinson (1977) examine this problem and conclude that the presence of a vaporizing liquid will not complicate evaluation of the reservoir permeability-thickness product from drawdown data when the usual methods of gas reservoir engineering are applied. Simulated pressure buildup data, on the other hand, show characteristics that are markedly different from that expected for noncondensable gas.

CONCLUDING REMARKS

Numerous models based on the concepts presented in this paper have been applied to geothermal systems under both natural conditions and exploitation. A complete review of free convection models applied to natural systems is included in Witherspoon, et al. (1975). A review of reservoir models used to examine exploitation effects is presented by Faust and Mercer (1979). From these reports, it seems obvious that our mathematical tools, both analytical and numerical, are sufficiently powerful to solve the most difficult problems. Unfortunately, the conceptual basis of these mathematical models appears to need reinforcement. The geologic materials in which heat transport processes occur are not easily idealized. Constitutive relationships for thermal dispersion and relative permeability, and the description of flow and transport in fractured rock are areas that need further study. Finally, additional field verification of the complicated mathematical models are needed.

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HOT DRY ROCK PROGRAM IN THE EASTERN U. S.

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ABSTRACT

The Los Alamos Scientific Laboratory (LASL) Hot Dry Rock Geothermal Energy Project is the first U. S. field test of this huge geothermal resource base. In the concept developed by LASL, a man-made geothermal reservoir is formed by drilling a deep hole into relatively impermeable hot rock, creating a large surface area for heat transfer by fracturing the rock with hydraulic pressure, then drilling a second hole to intersect the fracture to complete the circulation loop. Such a demonstration system has been completed at Fenton Hill in north-central New Mexico, at a depth of 3050 m (10 000 ft) and a bottomhole temperature of 205°C (402°F). The system has been successfully circulated for approximately 2800 h to determine temperature drawdown, permeation water loss and flow characteristics of the pressurized reservoir, to examine chemistry changes in the circulating fluid, and to monitor for induced seismic effects. As a result of these successful experiments, a national program for development of the hot dry rock potential is now being conducted by LASL. Additional sites are being evaluated in the U. S. for prospective demonstration plants. Two of the most promising eastern locations at this time appear to be northcentral New York State and the eastern shore of Maryland and Virginia. Hot dry rock sites in the east will probably closely follow the technology developed in New Mexico--at least for the first several projects. Several areas in the east have geothermal gradients that are high enough to be considered for electrical power generation, as well as nonelectrical uses.

INTRODUCTION

At sufficient depths, rock hot enough to be a potentially useful energy source exists everywhere. Formerly, it was thought that only the western third of the United States possessed a significant potential for the near-term utilization of manmade hot dry rock (HDR) geothermal reservoirs. Regional heat flow data indicate that about 95 000 square miles in the west is underlain by hot dry rock at temperatures above 290°C (554°F) at a depth of 5 km (16 400 ft). Recently, several regions of the eastern U. S. have also been identified for possible development of HDR reservoirs of moderate depth. Although probably of somewhat lower temperatures than the western sites, these eastern HDR reservoirs can also be used to produce electricity or for direct heat utilization.

The total amount of potentially useful energy stored in the hot dry rock beneath the continental "lower" United States--at depths less than 10 km (32 000 ft) and temperatures greater than 150°C (302°F)--is estimated to be 13 million quads assuming an average gradient of 22°C/km. By contrast, the current energy usage by the United States is about 75 quads per year from all sources. Of these 75 quads, approximately 28 quads are used for low temperature (less than 300°C), nonelectrical uses; the remainder being used for high-grade electrical generation, primary metals reduction, and the transportation sector. Figure 1 depicts the energy use spectra of the low temperature nonelectrical portion of our total energy consumption. It is with this portion of U. S. consumption that HDR energy systems will have the biggest impact.

Fig. 1 The shaded area under the curve depicts the integrated energy use spectra of the total U.S. energy consumption below 300°C, amounting to approximately 28 quads (1 quad = 10^{15} BTU).

LOS ALAMOS HDR PROJECT

The LASL HDR Geothermal Project at Fenton Hill, New Mexico, is the first attempt to demonstrate the technical and economic feasibility of extracting heat from hot dry rock. In the Los Alamos concept, a manmade geothermal reservoir is formed by drilling a borehole into hot impermeable rock, creating a large vertical fracture at the bottom, then intersecting the fractured area with a second borehole. The fracture is formed by large-scale hydraulic-fracturing techniques developed by the oil and gas industry, and provides a very large surface area for heat transfer. The heat contained in the rock is brought to the surface by circulation of water through the system. Buoyant circulation of the fluid within the vertical fracture assists in pumping the fluid through the loop. The water in the loop is pressurized to avoid boiling, thereby increasing the rate of heat transport up the withdrawal holes compared to that possible with steam.

Preliminary experiments and analyses indicate that thermal stresses created by cooling of the hot dry rock in such a manmade reservoir may gradually enlarge the fracture system so that its useful life-time may be extended to 30 to 40 years--far beyond the potential of the original reservoir. If these thermal stress cracks grow preferentially downward and outward into hotter, uncooled rock, as seems probable, the quality of the geothermal source may actually improve as energy is withdrawn from it (Fig. 2).

Fig. 2 Thermal stress cracking may occur in the hot dry rock system as the fractured zone is cooled by circulating water. This phenomena would permit water to remove the heat from a larger volume of rock, thereby greatly extending the life and size of the geothermal reservoir.

FENTON HILL SITE

To test the concept, a location in northern New Mexico at Fenton Hill (now identified as HDR Site No. 1) was selected as being geologically appropriate for the development of the first HDR experiment. The area is located about 20 air miles west of Los Alamos. A million years ago, the Valles Caldera was formed when a huge volcano erupted and then subsided into its own empty magma chamber. As a result of this relatively recent volcanism, a large amount of heat is still retained in the underlying rock within a few kilometers of the surface.

The first deep exploratory hole (GT-2) was begun at Fenton Hill in February 1974. It was completed at a depth of 2929 m (9610 ft), with a diameter of 24.4 cm (9-5/8 in) and a bottomhole temperature of 197°C (387°F). A near-vertical, 122 m radius (400 ft) fracture was thought to have been created near the bottom of the hole. Although the Precambrian granitic rock seemed to be broken by extensive natural fractures at various depths in the hole, the water leakoff was slight.

The second hole (EE-1) was located 72 m (252 ft) northeast of the first. Drilling began in May 1975 and was completed at a depth of 3064 m (10 053 ft), with a bottomhole temperature of 205°C (402°F). Directional drilling techniques were used to angle EE-1 toward the fracture at the bottom of GT-2. The hole was drilled through a 205° spiral, turning counterclockwise from an initial northwest heading to a northeast heading, in the attempt to intersect the fracture. On October 14, 1975, flow between the two boreholes was established, creating for the first time a manmade connection in hot, nearly impermeable basement rock.

However, because of inaccuracies in locating the fracture when the intersection was attempted, EE-1 missed the fracture by about 8 m (27 ft). At that time, instruments did not exist which could locate the boreholes with respect to each other at the extreme conditions of temperature and pressure in the bottom of the holes. In April 1977, GT-2 was directionally redrilled to intercept a fracture system produced from EE-1, and a connection with a relatively low impedance was achieved (Fig. 3).

The predominant Precambrian rock in both holes is banded granitic gneiss. A relatively extensive and homogeneous biotite-granodiorite body was encountered at depth. Fractures were usually well healed or sealed, as determined by coring and geophysical logging. Nearly all drilling in the crystalline basement was done with full-face tricone rock bits, except for coring. For standard drilling, penetration rates ranged from 0.9 m/h (2.8 ft/h) to a maximum of 11.6 m/h (38 ft/h). The maximum standard drilling interval for a single bit was 205 m (672 ft) in 75 h. These holes now constitute the bulk of existing U. S. drilling experience in hot granitic rock using conventional oil-field equipment.

PROJECTED DEVELOPMENT

With a total of more than 2800 h of operation in the energy extraction mode, the HDR circulation tests have experienced no particular problems. Water chemistry has remained quite manageable, and no induced seismicity has been detected by the surrounding seismic network. In April 1979, drilling will begin again at Fenton Hill, to expand the system to depths of 4262 m (14 000 ft), where temperature of 275°C (528°F) are expected. Such a system might be able to produce electricity for 10 000 customers and would provide valuable information for the design and construction of a small scale electrical generating plant that uses this new energy source.

If success continues at Fenton Hill, then the first demonstrations of the use of HDR geothermal energy, both for generating electricity and for nonelectrical purposes, could be in progress by 1985. The first systems will probably be small, each producing about 50-100 MW (thermal) or 10 MW (electrical) but they will conform to the new idea of decentralization of energy production using "neighborhood" power plants.

FEDERAL HDR GEOTHERMAL ENERGY DEVELOPMENT PROGRAM

On a national basis, LASL has been designated by DOE/DGE to be the lead agency in developing the nation's HDR resource. Investigations are presently underway in both eastern and western states, some near large load centers, to identify additional HDR sites with different geologic conditions as the next experimental energy extraction locations. Within the next several months, two 100-square-mile areas in the United States will be chosen as prospective sites for prototype development. Choice of the sites will be made by LASL working with the Federal HDR Program Development Council. Industrial firms, under contract to DOE and LASL, will investigate the sites for technical feasibility, and one or more areas will be pinpointed for a deep drilling test and possibly a subsequent demonstration plant. Drilling at other sites in following years may proceed after additional field studies. The Federal Program will determine the potential of HDR geothermal energy as a significant energy source and provide a basis for its timely commercial development. The manager for the program is Dr. Gregory Nunz of the Los Alamos Scientific Laboratory.

EASTERN HDR PARAMETERS

The first one of several eastern HDR sites will probably closely follow the technology successfully developed at Fenton Hill in New Mexico: two wells will be drilled, and a hydraulic fracture created in low permeability crystalline basement rock. However, a different heat source from Fenton Hill will be sought, in order to broaden our knowledge of the HDR resource base. We would hope to find and explore a more widely distributed type of heat source than the young silicic volcanoes of the west--mantle upwarp, crustal thinning, radiogenic decay, or tectonic areas. Also, a different

Fig. 3 Conceptual diagram of an experimental hot dry rock geothermal system, similar to HDR Site No. 1 at Fenton Hill.

CIRCULATION EXPERIMENTS

On June 3, 1977, during a 20 h pumping experiment, cold water pumped down EE-1 at 6.9 MPa (1000 psi) was returned to the surface in GT-2 at 130°C (266°F). In January 1978, and continuing into April, a prolonged circulation and heat extraction experiment was begun to determine the mechanical, physical, and chemical properties of the reservoir and the heat exchanger system. After 1800 h (75 days) of continuous circulation, the results from this test have been very encouraging. Water losses have been low (average less than 5 gpm), while the reservoir flow impedance decreased from 15 psi/gpm to less than 3 psi/gpm with an increase in the size of and the degree of mixing within the fractured system. Power production was 5 MW (t), with heat being wasted to the atmosphere. The thermal draw-down could be modeled using an 8000 m² (86 000 ft²) fracture surface area. Several aspects of the flow and chemical behavior indicate that thermal contraction and pore fluid pressurization may have enlarged the volume of rock accessible for heat extraction during the circulation test.

Replumbing of the surface circulation equipment to allow greater flow rates occurred during the summer of 1978, and pumping began again in September to further characterize reservoir behavior. After circulating for 950 h, the experiments were terminated due to excessive water losses from failure of the cement behind the casing in EE-1.

type of reservoir rock, other than granitic, would make for a logical, but not too far-out, extension of our present experience.

Either electric or nonelectric sites would be satisfactory. A site with temperatures high enough for electrical power generation (200°C) would be preferred, but a site with a basement temperature more than 100°C would be suitable for space heating, food processing, etc. From the standpoint of strict economics (disregarding the worth of technological advancement), the nonelectric reservoir rock would probably have to be within 3 to 3.5 km (9800 to 11 500 ft) of the surface to offset drilling costs. Rock temperatures suitable for power generation could probably be as deep as 4 to 5 km (13 000 to 16 000 ft) to be economically feasible. In addition, the power generation site could be located almost anywhere and still tie into the local power line grid, for distribution to the regional network. The nonelectric site however, would have to be located within 15 km (9 miles) of potential users to make the heat-transmission pipelines economically feasible.

EASTERN HDR EXPLORATION

Without the surface manifestations of hot springs (and occasionally geysers and fumaroles) that are the western indicators of subterranean heat, exploration methods for HDR heat sources in the east have to be more sophisticated. It's true that even slightly warm springs and chemical geothermometers are good initial starting points for exploration for geothermal potential, but we're learning in the west how to apply the geophysical prospecting methods that have been developed by the mining, petroleum, and hydrothermal industries. These methods are now being applied with promising results in the east.

An outline for HDR exploration in the east follows the same rationale as in the west:

- (1) Collection of available water temperature, geothermal gradient and heat flow data from existing springs and wells.
- (2) Determination of promising reservoir heat sources by examination of chemical geothermometry data from those waters.
- (3) Use of geophysical prospecting surveys to determine geologic structure, rock density anomalies, and indicators of high temperatures:
 - a. Seismic reflection and refraction
 - b. Gravity
 - c. Magnetic
 - d. Electrical
 - e. Magnetotelluric
- (4) Drill shallow holes to determine heat flows in areas of interest.
- (5) Conduct detailed comprehensive geological and geophysical explorations in a limited 100-square-mile area.

- (6) Drill a deep hole to confirm gradient, heat flow, and existence of suitable basement rock.

In general, the work indicated in steps 1 and 2 is already well along, having been initiated by individual State Geological Surveys or universities, although some states are just getting started. Work through step 4 has been in progress for nearly four years along the Atlantic Coastal Plain and Piedmont by John Costain and his group at Virginia Polytechnic Institute. As a result of the VPI work, a deep hole is scheduled to start this spring at Crisfield, Maryland, as the first test in the Atlantic Coastal Plain. Under the National HDR Program, LASL will provide funding to drill the bottom 700 ft to investigate the hot dry rock reservoir potential.

NEAR-TERM EASTERN POSSIBILITIES

Geothermal gradients in the east normally range from 10°C/km to 40°C/km. By contrast, the gradient at Fenton Hill is 60°C/km and throughout much of the west it averages more than 30°C/km.

In the Buffalo-Syracuse area of New York State, gradients have been estimated at 36°C/km, which would produce a bottomhole temperature of about 125°C at 3 km (10 000 ft). This area is being considered by the HDR Program Development Council as a site for detailed exploration as listed in step 5 above.

At Stumpy Point, NC, and Wallops Island, VA, geothermal gradients of 47°C/km and 35°C/km respectively, have been estimated. This area is also a strong candidate for one of the next HDR geothermal demonstration projects. With continued interest and exploration, new promising areas are being discovered. There may be hundreds of plutons, containing relatively high amounts of radioactive elements, along the Atlantic Coastal Plain, hiding under thick sediments.

The New England Conway granite is the most recent known pluton in the east, and contains heat-generating uranium, thorium, and potassium. In local areas where alluvial blankets have prevented this radiogenic heat from escaping into the atmosphere, gradients may be high enough to warrant HDR consideration.

OTHER HDR SYSTEMS

The picture of HDR energy systems that continues to appear the most feasible at this time is one of at least two deep, large diameter drilled holes through which cool water is introduced into a natural thermal reservoir and hot water is recovered. Variations on this general theme are possible however, in the nature of the natural thermal reservoir, how it is developed and stimulated, and how flow through it is handled in the operating mode. The low matrix permeability of the reservoir rock is considered to be a critical factor, although instances can be envisioned where flow between parallel

fractures, through thin permeable layers, or even thick permeable formations could be successfully controlled even though the matrix permeability was significantly higher. A number of these possibilities have been described in a recent paper by M. C. Smith of LASL.

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CONCLUSIONS

With the successful implementation of the first HDR Energy Demonstration Project (HDR Site No. 1) at Fenton Hill, the Federal Program is now underway, actively investigating new prospective sites. A large number of areas of promising geothermal interest have already been identified across the United States, including several in the east. These sites represent a variety of geologic environments and will permit a slow, but ever increasing extension of our knowledge of extracting energy from the hot dry rocks of the earth. The more we look for promising additional sites, the more we seem to find. The relative engineering simplicity of this type of energy system and the sheer abundance of the potential resource make it inevitable that it will be economically developed in many parts of the world.

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WORLDWIDE DIRECT APPLICATION REVIEW

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ABSTRACT

Direct utilization of geothermal energy has been used by many countries in the past on a small scale for bathing, cooking, and heating. Today, there are still many small-scale individual uses, however, many large-scale projects have been developed for district heating, greenhouse complexes and industrial processing. The number of large-scale projects will continue to grow due to the escalation of fossil fuel costs and the proven technology of using insulated transmission lines and efficient heat exchangers for geothermal fluids. Today, 7,050 MW (thermal) of geothermal energy are used in direct applications, mainly in Iceland, New Zealand, USSR, Japan, and Hungary. In all cases, the cost of geothermal utilization is below that of comparable fossil fuel energy.

INTRODUCTION

Traditionally, direct use of geothermal energy has been on a small scale by individuals. Surface hot springs and shallow wells could be justified with on-the-spot use of short transmission distances in uninsulated pipes or channels. However, at today's prices for development and hardware, the cost savings of these individual uses are often marginal. Large-scale demands require more productions and can thus justify deeper wells, longer transmission distances, more sophisticated utilization, and lower temperatures.

Most of present day direct heat developments involve large-scale projects such as district heating (Iceland), greenhouse complexes (Hungary), or major industrial use (New Zealand). Heat exchangers are also becoming more efficient and better adapted to geothermal use, allowing the use of lower-temperature waters and highly saline fluids. Heat pumps are extending geothermal development into traditionally nongeothermal countries such as France, Austria, and Denmark.

Transmission distances of 50 and 100 km are being considered and proven economical on paper (Akureyri, Iceland), with 20 km presently a reality (Reykjavik). Transmission temperature losses in the below 100°C range are around 0.1°C/km for insulated pipe and 1°C/km for uninsulated pipes. Steam and superheated water cannot be transmitted long distances economically due to the higher temperature differences. Well depths of 2000 to 4000 m are now being used where 500 m was economical

before. Deeper wells also allow use of geothermal gradient to advantage in lower-temperature areas.

At present day prices, the geothermal application will cost 60 to 75 percent of the corresponding fossil fuel cost. Due to the expected escalation of fossil fuel prices, the costs of the geothermal system will reduce to 30 to 40 percent in 20 years. Most geothermal direct-use systems will pay for themselves in 5 to 10 years from savings in conventional fuel.

The economics are greatly enhanced where cascading (multistage use) is considered. The Japanese optimize cascading where geothermal fluids are first used for electrical power production, then space heating, cooking, and bathing (Otake). Here, an attempt is made to "squeeze" the "last drop of energy" from the fluid. Lower-temperature cascading could consider space heating, agriculture, bathing (swimming pools), and snow melting.

Today, over 7000 megawatts thermal (MW_t) are utilized in the world for space heating and cooling, agriculture and aquaculture production, and for industrial processes. Of this figure, over 1200 MW_t are used for space heating and cooling, 5500 MW_t for agriculture, aquaculture, and animal husbandry, and over 200 MW_t for industrial processes

Based on communications with personnel in other countries, personal visits to some countries, and references, the following is an estimate of the current worldwide utilization of geothermal energy for nonelectric or direct thermal applications:

Country	Space Heating/ Cooling (MW _t)	Agriculture/ Aquaculture (MW _t)	Industrial Processes (MW _t)
Iceland	680	40	50
New Zealand	50	10	150
Japan	10	30	5
USSR	120	5100	---
Hungary	300	370	---
Italy	50	5	20
France	10	---	---
Others	10	10	5
USA	75	5	5
TOTAL	1245	5570	235

This gives a grand total of 7050 MWt peak use in the world.

The major geothermal developments and utilizations in various countries are briefly described in the following sections. No attempt was made to give details on each project due to space limitations. The details can be found in the reference listed at the end of this paper.

USA

Direct applications of geothermal energy in the U.S. has been limited when compared to international developments. Therapeutic and bathing uses have received the greatest publicity over the past century, at locations such as Steamboat Springs, Nevada, Hot Spring, Virginia, Lava Hot Springs, Idaho, Steamboat Springs and Glenwood Springs, Colorado, Thermopolis, Wyoming, and Calistoga, California, to name a few. Today, national parks protect many of these geothermal uses and phenomena: Hot Springs, Arkansas National Park (bathing), Lassen Volcanic National Park (sulfur mining), and Yellowstone National Park (tourism).

Space heating, using geothermal energy, also has a recorded use of almost a century in this country, however this use has not received the publicity of the spas. Klamath Falls, Oregon, and Boise, Idaho, have the greatest energy consumption for space heating, with minor amounts used in Reno, Nevada, Lakeview, Oregon, Vale, Oregon, Susanville, California, Calistoga, California, and other locations. In Klamath Falls, over 400 wells are used for space heating, using waters from 40°C to 110°C. The principal heat extraction system is the closed loop downhole heat exchanger utilizing city water in the loop. Larger examples of space heating in Klamath Falls include the Oregon Institute of Technology campus, where three wells up to 600 meters deep, produce up to 1700 l/min of 89°C water, and heat approximately 46,500 m² of floor space. The well water is pumped from the well using deep well centrifugal pumps, and in most cases is used directly in the heating system for each building. The annual operating cost of the campus system is approximately \$30,000, a savings of almost \$250,000 per year, when compared with the cost of heating with conventional fuel. Other notable use in the community includes Presbyterian Intercommunity Hospital, where the present worth of a 20-year savings due to a geothermal retrofitted heating system is over one million dollars, and Maywood Industries, where 45°C water is used for heating a large manufacturing building.

Numerous greenhouse and aquaculture projects have been developed in this country over the past few years. The most interesting fact with these geothermal developments is that many of these projects are located in a colder area where heating by conventional means is not economically feasible. Tree seedlings, tomatoes, cut flowers, and potted plants appear to be the most popular greenhouse product, with catfish, trout, and giant freshwater prawns the most popular aquaculture undertakings. Specific projects are located at Endel, California (greenhouses), Klamath Falls and Lakeview, Oregon (greenhouses and aquaculture), and numerous locations in Idaho (aquaculture).

Two industrial processing uses of geothermal energy are of note in this country, Medo-Bel Creamery in Klamath Falls, where low-temperature fluid is used for pasteurizing milk, and Geothermal Food Processors at Brady Hot Springs, Nevada, where high-temperature fluid is used for dehydration of onions and other vegetables.

Two major direct thermal projects in the USA are in the development stage: the conversion of the Ore-Ida Foods, Inc. plant located in Ontario, Oregon, and a district heating project in Klamath Falls. The Ore-Ida project involves drilling three production wells to a depth of 2000 m feet to obtain a temperature of 150°C. The geothermal energy would replace 55 percent of the energy now supplied by natural gas and fuel oil for potato processing. The total capital investment for this project will be in excess of \$4 million. Using a 10-year life for the depreciation of tangible assets, a 15-year economic study provided a rate of return after taxes of 30 percent compounded continuously. The Klamath Falls project involves piping 105°C water into the commercial area of the downtown area to initially heat 14 government buildings and later the entire commercial district. A 40 cm diameter pipeline will supply the geothermal fluid from the production zone to a centralized plate heat exchanger. A secondary, closed-loop system will supply 93°C water to the buildings. All pipelines will consist of insulated steel placed in a concrete tunnel for maximum life and protection. The primary supply line is sized to handle the projected heating load of the entire commercial district, and the secondary loop to handle a total of eleven blocks of buildings along its route. The capital cost of the initial system will be around \$2 million, with an equivalent annual cost of capital and O & M of \$200,000. The heating cost for the initial eleven blocks of buildings will be \$0.29 per therm. The comparable annual cost of fossil fuel over a 20-year period would be \$0.94 per therm. Construction on both projects should start this coming summer (1979). These, and a number of other projects throughout the country, are being seeded with funds from the Department of Energy.

Iceland

Iceland is located on the crest of the mid-Atlantic ridge and thus is the center of much volcanic and geothermal activity. Both high- and low-temperature systems exist in the country with the former being used for electrical power generation and industrial processing, and the latter used for space heating and greenhouses. At the present time, about half of the country is heated by geothermal energy and by 1980 to 1982, 80 to 85 percent of the country will be heated with geothermal energy. Almost every hot spring and known source of geothermal energy is being utilized to some extent, with areas having no nearby geothermal source to be supplied with hydroelectric power or electrical power from the geothermal plant under construction at Krafla.

The most noted direct thermal applications in the country are: the Reykjavik municipal heating

project serving about 97 percent of the 113,000 people in the area; the Hveragerdi greenhouse community in southwestern Iceland where individual homes, greenhouses, a greenhouse restaurant and a horticulture college are all heated by geothermal hot water and steam--in total over 140,000 m³ of greenhouses are heated by geothermal in Iceland; the Myvatn diatomaceous earth drying plant in northern Iceland using high-temperature steam to remove about 80 percent of the moisture from a diatomaceous slurry dredged from nearby lake Myvatn; and various experimental projects for the drying of wool, fish, seaweed, hay and other grains. Other projects of interest are the Sudurnes Regional Heating project presently under construction on the Reykjanes peninsula, heat exchanging deep saline geothermal fluids with shallow fresh water, the latter which is then piped through a large above-ground distribution system; the Husavik district heating project transporting geothermal hot water 18 km in an economically earth insulated pipeline; and the Akureyri district heating project in northern Iceland, to provide heat for a city of 12,000.

New Zealand

This country is also noted for its variety of direct geothermal applications. All of the sources are located in the Taupo volcanic depression of North Island in the vicinity of the Wirakei and Broadlands electrical power generation fields. At Kawerau, the Tasman Pulp and Paper company uses high-temperature steam for timber drying, black liquor evaporation, pulp and paper drying, and electric power generation. Approximately 345,000 tons of newsprint, 160,000 tons of kraft pulp, and 190,000 m³ of timber are produced annually. Six wells are presently being used to provide 180 tons/hr of steam. One of the largest wells in the world is located here, estimated to produce over 25 MW of thermal energy (170 tons/hr).

At Rotorua, the second-most extensively exploited geothermal resource in the country is located. Steam and hot water from approximately 350 shallow wells has been used on a small scale to heat homes and buildings, domestic hot water supplies, steam cooking boxes, and swimming pools. Geothermal steam and hot water are also used in mineral bathing pools, for hot hours horticulture and soil sterilization, kiln drying of timber, and to drive a large hotel air conditioning refrigeration plant. After use, the geothermal effluent is discharged down shallow soak holes. Rotorua is known for the numerous mineral hot baths and therapeutic baths. The Queen Elizabeth Hospital was built during the war for U.S. servicemen and eventually was developed by the Department of Health as a national hospital for the treatment of rheumatic diseases. The hospital has 200 beds, an outpatient service, and a Cerebral Palsy unit. Both acid and basic heated mud baths are used for the treatment of rheumatic diseases. The Forest Research Institute just outside the city limits, uses geothermal energy of space heating, timber drying, and seed drying and extraction. Future plans are to use the geothermal energy for refrigeration.

In the vicinity of the Broadlands field are several unique applications of geothermal energy.

At the Lands Survey Nursery in Taupo, greenhouses are heated by geothermal steam and soil is sterilized (pasteurized) at 60°C to kill insects, fungus, worms, and some bacteria. At Lake Rotokaua, an estimated 20 million tons of sulfur lie within 60 meters of the surface having a purity of up to 80 percent. Originally, the sulfur was extracted by the Frasch process using geothermal steam injected in 4 bore holes. Presently, they are strip mining the low grade surface deposits and using geothermal steam to extract the sulfur. The sulfur is then combined with cold water in a slurry and shipped by tanker truck for use in fertilizer production. At Broadlands, a cooperative of 12 farms have joined together to construct a geothermal alfalfa (lucerne) dehydration plant. The plant uses 135°C steam in a large forced air heat exchanger for drying. The drier is a simple fixed bed, double pass drier, discharging into a hammermill and pellet press for the final product. The plant produces one ton of compressed pellets per hour from 5 tons of fresh alfalfa. The annual production is from 1,000 to 1,500 tons, with a production of 10,000 tons possible.

Japan

Many diverse uses of geothermal fluids have been attempted in Japan in addition to the well-known power generation and bathing. Most of these uses have been on a small scale, however, their commercial importance is now being recognized.

Greenhouses cover about 15,500 m² in Japan where a variety of vegetables and flowers are grown. Many large greenhouses are operated as tropical gardens for sightseeing purposes. Raising poultry though the use of geothermal energy has been a very successful enterprise. Here, under-the-floor heating is utilized in sheds that raise 40,000 chickens annually. Fish breedings is another successful business where carp and eels are bred and raised. The eels are the most profitable and are raised in 24 cm diameter by 6 m long earthenware pipes. Water in the pipes is held at 23°C by mixing hot spring water with river water. The adult eels weigh from 100 to 150 grams, with a total annual production of 3,800 kg. Alligators and crocodiles are also raised in geothermal water. These reptiles are being bred purely for sightseeing purposes. In combination with greenhouses offering tropical flora, alligator farms are offering increasingly large inducements to the local growth of the tourist industry.

Some space heating is undertaken, but only on a very limited scale. Most hot spring bathing resorts are heated geothermally, as well as communities downstream from the Otake geothermal plant. In this later case, the waste water from the plant (165 tons per hour) is used for space heating, baths and cooking. Plans are being developed for large scale space heating projects in the Sounkyo and Hokkaido areas of Japan.

Japan has also used geothermal hot water for melting snow on highway pavements. The best known location is near the Jozankei Spa, Sapporo City on Hokkaido, where a narrow road with an 8 percent grade has been constructed with pipe laid beneath

the pavement. In this 600 m long section, 88°C hot water is circulated by means of pumps at a rate of about 100 l/min and discharged at 65°C where it is reused for bathing. The system is designed for a 1.7 cm/hr snowfall and cost \$8.67 per square meter to construct, and \$0.13 per square meter to maintain.

Hungary

Geothermal energy in the form of low enthalpy thermal water has been used commercially in Hungary since 1962. At the present time, there are over 130 geothermal wells in Hungary with a peak production of almost 800 MW thermal. Only 30 to 35 percent of this energy is utilized due to variations in seasonal loads. The principal use of the energy is for space heating and greenhouse heating. The main geothermal district heating plant is at Szeged in southern Hungary. Here, university clinics, 1,200 flats, schools, and several municipal buildings are heated along with swimming pools. Several other communities which include factories and hospitals are heated by individual wells.

The greenhouse heating is second only to the USSR, with over 1.2 million m² being heated. Many of these greenhouses are built on rollers, so they can be pulled from their location by tractors, the ground cultivated with large equipment, and then the greenhouse returned to its location. In addition, to minimize cost, much of the building structure pipe supporting system also acts as the supply and radiation system for the geothermal fluid. About 60 wells are used for animal husbandry projects, mainly for heating and cleaning of animal shelters. Priority is given to agricultural use of geothermal energy in Hungary, as this increases the volume and variety of production.

Some experimental work is being performed with grain, hay, tobacco, and paprika drying. In these cases, hot water supplies heat to forced air heat exchangers, and 50° to 60°C air is blown over the product to be dried.

Italy

Historically, boric acid was obtained from the geothermal fluids at Larderello in Tuscany. Originally, the boric acid was obtained by boiling off the geothermal water using firewood as a heat source. From 1827 onwards, geothermal steam was used as the energy source. With increase in production, growth in trade, and refinement of the process, a wide range of boron and ammonium compounds were produced in the early 1900s. This process continued until World War II, where a total of 6,500 tons had been produced. After the war, the plant was put into operation again, only this time the raw product was imported from Turkey, and geothermal steam used as the drying source. Approximately 30 tons of steam per hour are used in the process.

Residual steam for older and low production wells in the Larderello and Castelnuovo area of Tuscany are used for space heating and greenhouse operation. A total of 35,000 m³ of space is

heated, the majority of which is industrial. In addition, a total of 7,000 m² of greenhouses are heated. The savings amounts to \$600,000 per year when compared with fuel oil. Another 20,000 m² of greenhouses are also heated in the Province of Padua. Here, 74 hotels-spas and some private homes are heated with 450 l/sec of 65° to 87°C water. Several other smaller locations exist in Italy where hot springs are utilized in spas and then for domestic heating of the same building.

France

The geothermal temperature gradient in France is around 36°C per km. Using the geothermal gradient, two heated aquifers can be found in the Paris region, one at 30°C and the other at 70°C. Relatively pure water from the cooler layer has been used in heat pumps to service the Radio Paris building for over 12 years. During the summer, the heat pump is used for air conditioning. A cost comparison at the time of construction indicated that the capital cost of the heat pump (including the well) and a comparable fuel-fired boiler were about the same. The annual operating cost of the heat pump was significantly less, and provided an added bonus in that the water could be reused for domestic purposes in the building instead of purchasing city water service.

More recently, the higher temperature layer of water has been used to heat part of a 3,000-dwelling development of social housing in Melun, near Paris. Here, 2,000 apartments are heated by two wells pumped at a rate of 1400 l/min. The geothermal water passes through a heat exchanger (due to a high salinity) and the secondary side at 55°C is heated by two peak load boilers to 85°C. The geothermal provides just under half of the total heating and domestic water requirements of 11 million Kcal/hr. The two peaking boils are only required during the winter and late fall and early spring. The system has been in operation since 1970 and the only major trouble encountered was the failure of the heat exchanger after six months due to corrosion. These have been replaced with ones of titanium, which have solved the problem. Residents pay an initial hookup fee, and then a flat rate for the quantity of water used.

USSR

The USSR has enormous geothermal reserves with 50 to 60 percent of the country underlain by hot water suitable for commercial use. This resource has temperatures from 40° to 200°C, dissolved solids up to 35 g/l, and exist to a depth of 3500 m. The two main uses of direct geothermal energy is for space heating and agriculture. The majority of the utilization is in the regions of Georgia and Daghestan between the Caspian and Black Seas, and on the Kamchatka peninsula of eastern Siberia. Approximately ten different communities are provided with a portion of their space heating by geothermal, and over 25 million m² of agricultural land is heated by geothermal. The latter figure probably includes about 100,000 m² of greenhouses; with the remainder being heated ground either uncovered or provided with only

minimal protection against the elements. Heat pumps are also apparently being utilized to a great extent. Future uses include thawing frozen ground, salt extraction, and ore processing.

Other Countries

Several other countries are using geothermal energy to a minor amount. Germany, Austria, and Czechoslovakia have used hot springs for bathing and heating of spas for centuries. Present plans are to expand the use of these localized geothermal sources for district heating. India is doing some experimental work with greenhouses in the southern Himalayas, and Turkey is doing experiment work in the Kizildere field with a 1000 m² pilot greenhouse. On Taiwan, experiment work is being undertaken with a lumber-drying kiln to produce 240 m³ of kiln-dried lumber per month, a greenhouse for vegetables and flowers, and a laboratory to test technical procedures of soil sterilization, grain drying, and fish and poultry production with 25° to 60°C fluids. The pilot project will be supplied by one well producing 3.5 tons of dry steam per hour at 130°C. An experimental project at Tiwi on the Philippines is being used for salt production, grain drying, fish canning, and refrigeration. A single well in the Tiwi field, providing almost 8 tons of steam per hour is being used in this research project. Israel is presently doing work with low-temperature fluids for crop growth and development, and for shrimp farming (prawns).

Future Trends

The main emphasis will be in space heating and agricultural production in the future. Large scale and more efficient district heating projects will be undertaken (such as is being proposed in Boise and Klamath Falls). Space heating will become more and more economical with further escalation in conventional fuel prices. Nongeothermal countries such as Denmark are investigating the use of fluids heated by the normal geothermal gradient. Since 43 percent of the energy consumed in the country is for space heating, the use of geothermal is of interest. The project in Melun, France, will serve as a model, using heat pumps or conventional fuel to peak the low-temperature geothermal fluid. Agriculture will have great emphasis placed upon it to increase food production and grow crops in colder climates where none could be grown before on a commercial basis. Soil warming will be used to extend the growing season. Aquaculture will be developed in colder climates, as it has been shown that outdoor ponds can be kept at nearly constant temperature, even in below freezing temperature (Klamath Falls, Oregon). Growth rate and reproduction can be increased with these constant temperatures, an advantage over warm climate locations where solar heating varies. Industrial processing will also increase with existing plants being retrofitted due to shortages of conventional fuel. Refrigeration will be more attractive due to equipment being able to use lower-temperature geothermal resources (down to 75°C).

The main emphasis for direct thermal use and development will be the national interest of various

countries to become less dependent on imported fuels.

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URBAN HEATING FROM GEOTHERMAL AQUIFERS IN THE PARIS BASIN

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Abstract

A total of 10,000 apartments are heated at present by combining the geothermal source with auxiliary boilers and heat pumps in an area of normal geothermal conditions (average geothermal gradient $33^{\circ}\text{C}/\text{km} = 1.8^{\circ}\text{F}/100 \text{ ft.}$). The geothermal contribution which supplies domestic hot water as well amounts to about 70% of the total heat consumed. The resource consists of a deep aquifer (porous Dogger limestone). Due to the high salinity of the formation water (up to 25 g/L) produced, reinjection is necessary. This is performed by the "doublet" system which consists of a twin well (production-reinjection). Typical production rates are $100 \text{ m}^3/\text{h}$ (440 gpm) at $60\text{--}70^{\circ}\text{C}$ ($140\text{--}158^{\circ}\text{F}$). Noticeable temperature drawdown at the production well is not expected before 30 years. Economic analysis shows that the geothermal system is slightly less expensive (at 1977 fuel prices) than conventional fossil-fuel schemes. The French authorities strongly support this development (the risk of the production well is covered by the government) which aims at 800,000 geothermally-heated apartments in the Paris basin by 1990.

1. Introduction

Geothermal installations for space heating and domestic water supply have been in operation in the Paris basin since 1969. The main characteristic of these sites of low-temperature geothermal energy utilization is the relatively high density of dwellings (apartment blocks) which are heated by combining the geothermal source with heat pumps and conventional sources. Geothermal heating for the majority of the dwellings (with a total of 10,000 apartments at present) has been installed quite recently, thus data on the long-term performance are not yet available. The systems are claimed to be economic; it must be pointed out, however, that the main factors affecting the economics are the interest rates that are paid on funds borrowed to carry out the project and the sales price of energy sold which in turn are determined by government decision. In France, the government strongly supports the development of geothermal energy, a domestic energy source.

2. The Resource

The Paris basin is a regularly structured sedimentary sequence which resembles a pile of dishes, the deepest part being located at the center of the basin. Several formations are known from hundreds of oil exploratory drillings to be independent aquifers. At successively greater depths one finds Albien, Middle Cretaceous and Purbeckian sandstones, porous Lusitanien and Dogger limestones and various other porous rocks (Lias, Rhaet, Trias, Devon). The aquifers contain essentially old connate water (water trapped at the time of deposition) with correspondingly high salinity.

The geothermal setting of the Paris basin is quite normal; pronounced anomalies are absent. The mean temperature gradient is around $33^{\circ}\text{C}/\text{km}$ ($1.31^{\circ}\text{F}/100 \text{ ft.}$). Detailed documentation (Housse & Magis, 1976) summarizes the aquifer characteristics: depth, porosity, permeability, transmissivity (=permeability $\times$ thickness), temperature and salinity of formation fluids.

The main target of exploitation is the porous Dogger limestone. Typical reservoir parameters (at the Creil site) are: water temperature 65°C , useful reservoir thickness 90 m (300 ft.), porosity 15%, permeability 300 md, salinity 25 g/L, artesian flow rate $150 \text{ m}^3/\text{h}$ (660 gpm). The total extension of the Dogger reservoir within $>50^{\circ}\text{C}$ ($>122^{\circ}\text{F}$) formation temperature is about 15,000 km^2 (5,800 mi^2).

3. Extraction Technology

The main characteristic of the Paris basin installations is the so-called doublet system which consists of two drillholes: a production and a reinjection hole. Fig. 1 shows the installation scheme. Reinjection of the used fluid is necessary mainly due to environmental concerns since it is unacceptable to dispose the high salinity fluid produced (around 60 tons of dissolved solid per day) into any surface drainage system. The advantages of reinjection are:

- chemical and thermal pollution of the environment is minimized
- the aquifer is kept recharged so that pressure should be maintained throughout the lifetime of the system

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- recycling the water offers the possibility to extract heat from the rock matrix as well.

Disadvantages are:

- precipitation of dissolved solids from the cooler reinjected water may plug the strata

- surrounding the reinjection well
- the electric power required by the reinjection pumps reduces the energetic balance of the installation
- short-circuiting of cool water could result in premature lowering of the output temperature.

Fig. 1 Schematic representation of the "doublet" system

Fig. 2 Temperature drawdown for a doublet system. Model calculation for a doublet spacing of 1300 m, production/reinjection rate of 200 m³/h (880 gpm) aquifer thickness 40 m, porosity 15% (after "La geothermie en France", 1978)

4. Economic Aspects

The economy of a given geothermal installation depends on local factors on the reservoir side as well as on the heat consumer side. A main factor is the amount of fossil fuel which can be saved due to substitution by the geothermal heat. Long-term economy will mainly depend on the development of fossil fuel price. Tables 1 & 2 summarize economic data of a typical geothermal installation in the Paris basin. Economic analysis shows that optimum utilization of the system described above calls for a certain concentration of dwellings next to the doublet: the optimum number of apartments is in the range of 2,500-3,500 ("La geothermie: Chauffage de logements", 1976).

Table 1. Basic data of a typical geothermal installation for urban heating (from "La Geothermie en France", 1978)

Number of apartments	2500
Energy demand p.a. (58 GJ/apartment)	145 TJ
Energy supplied by geothermal source (75% of total energy demand)	109 TJ
Resource yield (doublet, spacing 1800 m)	
flow rate (pumped)	200 m ³ /h (800 gpm)
temperature (gradient 30°C/km) (1.65°F/100 ft)	65°C (150°F)
Installation costs (doublet, heat exchangers, heat pumps, distribution network)	10 Mfrancs ¹ (4 K/francs apt.)

¹corresponds to 2.5 M\$ or 1 K\$/apartment (at February 1979 exchange rates)

Table 2. Cost¹ analysis of a typical geothermal installation for urban heating ("La Geothermie en France) 1978)

Fuel costs	0.135 M\$	0.525 M\$
Electricity for pumping (250 kW on 150 days, 100 kW on 80 days)	0.040 M\$	-
Maintenance (pumps and doublet)	0.025 M\$	-
	0.200 M\$	0.525 M\$
Capital costs (10% for 20 years)	0.293 M\$	-
TOTAL	0.493 M\$	0.525 M\$

SAVING (geothermal vs. conventional) - 6%

¹at February 1979 exchange rates

5. Outlook

The relatively new installations in the Paris basin do not yet provide long-term operational experience. Besides the information needed on performance of heat pumps and efficiency of heat exchangers, unanswered questions are:

- scaling and corrosion in long-term operation (wellbore linings, heat exchangers) as well as changes in solution equilibria in the produced geothermal fluid; possible effects of bacteria
- reservoir performance in time (temperature drawdown, effects of reservoir heterogeneity - directional permeability).

Ongoing research to answer these questions (first results of which are described in Desplain et al., 1977; Goblet et al., 1977) will supply the data necessary to test the models applied to predict the long-term performance of the geothermal heating systems.

The geothermal heating system developed in the Paris basin appears, even with the numerous unknowns at this time, a promising alternative to substitute (at least in part) for fossil fuel. The French authorities strongly support further development (e.g. the risk of drilling of production holes is covered by the government) which aims, according to the "Delegation aux energies nouvelles" (Paris), at 800,000 geothermally-heated apartments in the Paris area by 1990.

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Fluid Heat Management for Direct Geothermal Energy Applications

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ABSTRACT

This paper addresses the problem of utilizing the geothermal fluid as economically as possible in direct applications of geothermal energy. The lower temperature uses are primarily addressed, since these are the only ones likely to make a significant impact in the eastern United States.

I. Capital Investment Utilization of Geothermal Facilities

The two categories of direct heat uses that require different approaches on geothermal fluid management are:

1. Process heat for industries that that operate full-time (or nearly full-time) all year around.
2. Space heating, which is used only part of the year.

There is a major difference between these two categories of applications. The first nearly fully utilizes an expensive capital system. The second poorly utilizes an expensive investment. The conclusion is to concentrate on the process heat applications, and leave the space heating to the low capital cost methods. However, Table I shows that space heating is a far greater energy consumer than industrial process heating below 300°F. Furthermore, Table II breaks down the temperature range for utilization temperature at the end use point. One therefore concludes: If geothermal energy is going to make a significant contribution to the nation's energy needs, then it must be applied to the low utilization markets.

II. Better Utilization of Geothermal/ Investment for Space Heating

Most cities and towns away from the steadying climate effects of the sea coasts have extreme variations in temperature, not just season-to-season but day-to-day. Figure 1 shows the

TABLE I
USA ENERGY USE vs TEMPERATURE

USE	Temperature Of Use (F°)	Amount (Quad, or 10 ¹⁵ Btu)	% of Total
Total Annual Energy Use (1978)	--	75	100%
Space Conditioning and Water Heating	Below 165° [a]	17	23
Industrial Uses-- primarily food processing	165° to 210°	2	3
Industrial Uses	210° to 300°	5	6
Air Conditioning	Electric [b] Today	2	3

[a] Space heating can be accomplished with source temperatures as low as 120°F. Water heating for domestic use with temperatures as low as 140°F. Note: some space heating with steam is at higher temperature.

[b] Air conditioning could be supplied by solar or geothermal heat sources as cool as 180°F.

TABLE II
USA-Temperature of Use vs Amount of Use

Temperature	167°F	200°F	250°F	300°F	400°F
% of Energy Use at or Below This Temperature	20%	23%	27%	32%	42%

temperature frequency histogram for Boise, Idaho, typical of a northern U.S. climate. The degree F-days of heating average about 5700. The trend of the plot is striking, showing that temperatures below 20°F are rare. Yet the design outdoor temperature for Boise heating systems is 3°F (ASHRAE), and it has been common to

design to as low as -10°F .

Fig. 1

Boise, Idaho - Average Annual Temperature Histogram for Heating

As an example of better utilization of the expensive capital investment of the geothermal system, if the maximum geothermal fluid supply to a building in Boise could only maintain indoor comfort at temperatures as low as 28°F , the heating system would have a shortfall for the year of only 6% of the actual total requirements. Yet at 28°F , the geothermal fluid supply can serve twice as many buildings as one designed to serve buildings down to -10°F . Compared to a 3°F design, the geothermal system is utilized 170% more effectively. The result is reducing the costs of the geothermal energy supplied by these factors. For instance, if designed to -10°F , this system in Boise only is used 22% of its full potential. Whereas if designed for 28°F , the utilization factor is 45%.

But what happens to the 6% shortfall? Austerity is one possibility, but is not likely to be acceptable in our affluent society.

The use of a peaking system operated from a storable fuel is an appropriate solution. Even if boiler heat-up raises the effective use of the 6% shortfall to 8% and even if that fuel is expensive, this solution is far better than half of an expensive capital investment sitting idle 94% of the time.

III. Well Sizes and Pumps

Most geothermal wells for direct applications should be pumped even if they are naturally free flowing. Pump costs will generally be only 10 to 25% the cost of the well, yet allow the fluid level to be drawn down to low levels as a result of significantly higher production flow rates.

Again the problem arises of the cost of pumping, even though this is generally a very small fraction of the energy produced. Space heating needs vary hourly. It is wasteful for a pump to be pumping much more fluid than is actually needed. If flow control valves are used, the pump will still be consuming electricity. Variable speed pumps are a partial solution, but the efficiency of the variable speed motors is poor away from the peak performance area of the curve.

Hence it is better to design a system of several wells rather than a single well. This not only gives easier pump staging, but offers effective redundancy to cope with breakdowns. Both from consideration concerning keeping the cost of the initial exploratory well low, and for reservoir performance effects, several wells is a better choice than a single large well.

IV. Heat Exchangers

If the fluid is poor chemically (such as greater than 10,000 ppm. dissolved solids), heat exchange to a pure, non-corrosive, non-scaling fluid for the main heating system is probably a necessity. Tube-in-shell heat exchangers of titanium, brass, or stainless steel will generally be needed.

For the purer fluids, the question of heat exchange should be decided on a case-by-case basis. H_2S is very corrosive to copper tubing, common in hot water air heaters and blowers. Yet, there are some heating systems containing significant H_2S that, fortuitously, have operated for many years with copper-tubed air heaters. These systems had much copper piping upstream, this piping acting as a getter for the H_2S and thereby protecting the expensive heaters. Replacing straight runs of copper pipe periodically is less expensive than building a secondary system.

V. Chemical Problems of Deposition and Corrosion

Practically all geothermal waters have no free oxygen, thus are nominally non-corrosive if oxygen is not allowed to enter. Conversely, from carbonate rocks, the geothermal waters will have a high concentration of bicarbonate ions. These will be lost by depressurization and release of the CO₂ gas. The effect will be precipitation of calcium carbonate. These two reasons make it necessary to maintain pressure on the geothermal fluid from the bottom of the production well to the final point of discharge, thus avoiding the most serious and obvious corrosion and deposition possibilities.

Silica, originally in crystalline state, is not likely to be a problem in geothermal systems in the east. For instance, for 300°F geothermal waters, the amount of crystalline silica will remain in solution in the amorphous phase down to 90°F.

VI. The Incentive for Best Utilization.

As much heat as possible, within economic and technical feasibility, should be extracted from the geothermal water before it is discharged. Consequently, it is preferable to charge the user by the easily measured quantity of water rather than by Btu's utilized. The user thus has the incentive to make the maximum use of the heat content in the water. This approach will allow the user to make the economic decisions concerning how large the air-handling heat exchanger will be, which in turn determines how much heat can be extracted from the geothermal water.

VII. Differences Between Eastern and Western USA in the Fluid Management Decisions.

The above concepts in fluid management system design and operation will apply to geothermal direct heat applications anywhere. However, the resources in the east will generally be at greater depths, requiring much greater fraction of the total investment in the energy supply system. Hence, the incentive, in the East will be greater to "make the most" of the geothermal fluid brought to surface, and to bring as much to the surface as possible by effective use of pumps. The trend in the East, therefore, will be to spend more on surface equipment so as to achieve the better utilization of the available fluid. These trends will result in projects that have larger minimum sizes,

for economical construction and operation. Fortunately, the East has the far higher concentrations of population that can utilize the larger project sizes.

GEOTHERMALLY PASTEURIZED MILK PROCESS

Elmer Belcastro

Medo-Bel Creamery Inc.
Klamath Falls, Oregon

"Medo-Bel Creamery, the only creamery we know of anywhere that uses geothermal heat in the milk pasteurization process." These are words that are used in each radio, television, and newspaper commercial and ad by Medo-Bel Creamery telling the story of geothermal uses by Medo-Bel.

The geothermal well located at the corner of Spring and Esplanade Streets in Klamath Falls, Oregon, was first drilled in 1945 by the Lost River Dairy to a depth of 750 feet. The well was designed by a New York engineering firm to insure maximum heat at the well head with a minimum of pumping time. This has been the only commercial well used in Klamath Falls.

The well is double-cased to 450 feet to insure a constant heat at the top of the well. With this double-cased method, the artesian water runs into the storm drain year around.

The water is pumped from the well with a new $7\frac{1}{2}$ hp pump, with a capacity of pumping up to 100 gallons per minute to the milk plant into the short-time pasteurizer where it goes through a series of plates with the milk on opposite sides. The milk travels through the plates at a rate of 800 gallons per hour and is heated to 172 degrees F for 15 seconds. If the milk temperature should drop below 165 degrees F, the short-time pasteurizer automatically recirculates the milk and will not let it through the pasteurizer.

The milk then goes to the homogenizer at 172 degrees F back to the short-time pasteurizer to cool by chill water to 38 degrees F as the milk goes into the cartons with no chance of cook on. This insures both flavor and longer shelf life.

With this method of pasteurization, Medo-Bel Creamery has been a constant winner of awards for outstanding dairy products in the Oregon Dairy Industries competition each year. In 1977, Medo-Bel was awarded a total of five certificates including gold awards for homogenized and 2% milk.

The only energy used in this pasteurization process is the $7\frac{1}{2}$ hp pump which costs approximately \$120 per month to operate the pasteurizer and heat the 30,000 sq. ft. building.

In comparison to other creameries, the procedure is the same except a gas- or oil-fired boiler is used in place of the well. Steam is generated and mixed with domestic water and run through the pasteurizer but all at a much greater cost. The danger here is that if the steam gets into the short-time pasteurizer, the milk will cook on the plates. This will result in a cooked flavor to the finished product. The cost of this method is for the fossil fuel plus the electric energy to run the system and the domestic water used to operate it.

At Medo-Bel Creamery, all pipes are overhead from the pump to the main building. The reason for not putting the pipes underground is to eliminate corrosion of the pipes from sweating. The sweating in the pipes is due to heat emitted from the hot pipes into the ground. Pipe corrosion seems to be the only problem and expense that we cannot seem to eliminate. I am hoping that with all the geothermal studies now underway that someone will come up with a metal or treated metal to minimize the problem of corrosion.

Geothermal heat in our area for heavy commercial use is limited to the limited heat of the water thus far. To use geothermal heat for heavy commercial use, we must find the eye of the volcano which is supplying the heat. When tapped, it would serve an unlimited amount of heat to be used in abundance. So far, geothermal wells are mostly used for heating homes and heating of commercial buildings.

To try and get enough heat from the limited heated wells requires the pumping of too much water out of the ground, thus creating another problem of water shortages in existing wells. Water level drops and temperature drops came simultaneously in 1977 in the Klamath Basin and was felt by the operation of Medo-Bel Creamery.

Downhole heat systems are never a problem because no water is pumped out of the ground and this does not affect the water table, but to pump back into the ground could result in putting cool water into a hot vein of water thus cooling the water of other wells. This can especially occur in an area like Klamath Falls which has a great number of hot wells in a small area. I am convinced that some wells are cooling because of this method.

I feel that much study and research should be done before any large-scale commercial geothermal development is attempted. This will insure existing capacities and temperatures of current wells are not affected adversely. In the operation of Medo-Bel Creamery, this is vital to its continued existence and success. It has enjoyed being the only dairy that uses geothermal heat in the milk pasteurization process.

Owner, Elmer Belcastro, standing next to the plate heat exchanger (pasteurizer).

CHANNEL CATFISH (ICTALURUS PUNCTATUS) PRODUCTION IN GEOTHERMAL WATER

Leo Ray

Fish Breeders of Idaho

Buhl, ID

ABSTRACT

Fish Breeders have been raising Channel Catfish (*Ictalurus punctatus*) in geothermal facilities for six years. The product produced is superior to other catfish on the market.

Concrete facilities and 6,000,000 gallons per minute of water allow densities of five to ten pounds per cubic foot of space and 10,000 pounds per second foot of water. Oxygen and ammonia are the principle factors limiting production. Disease is related to these factors.

Identifying the resource, facility design, financing, construction, production, processing, marketing and distribution are the main problem areas preventing expansion of geothermal fish farming.

INTRODUCTION

Fish Breeders of Idaho, Inc. has been raising channel catfish (*Ictalurus punctatus*) in high density concrete raceways for six years. The water is supplied by artesian geothermal wells. The total flow is 6,000 gpm at 90°F. Cold water from springs and streams is used to cool the hot water to 80°F to 85°F., the ideal production temperature.

The quality of channel catfish produced in the clean water is far superior to any other catfish on the market. A fish is like a sponge; it tastes like the water in which it is raised. The geothermal water produces a quality that has allowed Fish Breeders to introduce catfish into the gourmet markets and obtain high prices for catfish.

FACILITIES

Fish Breeders is located in the Snake River Canyon near Buhl, Idaho. The elevation is 3,000 feet. Yearly temperatures are from -10°F to 105°F. Ambient water temperature seldom exceeds 75°F. The climate is too cold and the growing season too short to grow catfish commercially without hot water. Geothermal water changes a non-commercial area to a 365 day optimum growing season.

The fish farm is located on a hill. Approximately 80 feet of elevation is used in the farm. This is very important in aerating and reusing water.

The production facilities are concrete. Each section is 24 feet long, 10 feet wide and 4 feet deep. The space utilized by the fish is 770 cu. feet. The sections are arranged four in a series with a 2 foot drop between each section. The raceways are in pairs with a common center wall. The water passes through four sets of raceways, each raceway having four sections (16 section total), from the top of the hill to the bottom. The upper end of the farm is used for catfish production. The lower end of the farm is used for Tilapia production.

WATER SUPPLY

Four artesian geothermal wells supply 6,000 gpm of 90°F water. This water is mixed with cold water that varies from 32°F to 74°F to obtain a temperature of 80°F to 85°F. The geothermal water is used direct. No heat exchangers are utilized. The wells were drilled by Fish Breeders and are approximately 700 feet deep. The water flows through each raceway at 1,500 to 2,000 gpm.

STOCKING RATE

There are two densities to consider in producing catfish; pounds per cubic foot of space and pounds per second foot of water. Both are interrelated, but the degree of interrelationship is unknown. They will be considered separately in this report. The pounds per cubic foot of space is primarily limited by social factors. The pounds per second foot of water is primarily limited by water quality.

Channel catfish are social animals. In their natural environment they tend to congregate in groups. Eggs are laid in a mass. Sac fry congregate after hatching. Fingerlings, and even adults, spend much of their time in schools. They do not establish individual territories like shrimp or lobster. This is one major factor that makes them ideal for high density production. Channel catfish do establish a social pecking order. Stocking at high densities appears to interfere with this pecking order and reduces fighting.

Normal stocking densities are from 5 to 10 pounds of fish per cubic foot of space. Lower densities are used for small fish. Densities up to 20 pounds per cubic foot of space have been tested, but at this time are not recommended for commercial production.

The pounds of fish that can be produced per second foot of flowing water is limited by water quality. Water analysis of the water entering the raceway, compared to water analysis of the same water leaving the raceway, tells what the fish have put in the water and what the fish have taken out of the water. The factors of greatest importance are the oxygen removed and the carbon dioxide and ammonia added.

Oxygen removed is the first factor that limits production, however, oxygen is easily replaced by running water over waterfalls. At the same time oxygen is replaced, carbon dioxide is removed. Theoretically, oxygen can continuously be replaced and most of the carbon dioxide removed, by a chain of waterfalls. A two-foot drop will replace approximately 50% of the oxygen removed. There are ways of increasing the breakup and aeration of the water to achieve saturation in a two-foot drop, however, this is usually not done.

Ammonia is not easily removed by waterfalls and will continue to accumulate until it becomes the principle limiting factor in raceway production. The ammonia can be in an ionic state or a gaseous state. The gaseous state is very toxic to fish and can be partially aeriated out of the water. The ionic state is less toxic, remains in the water and changes to nitrates. The amount of ammonia that will be in the gaseous state is related to pH, temperature and water chemistry. The amount of ammonia that fish can tolerate is dependent on these same factors plus the oxygen and carbon dioxide levels. The higher the oxygen level, the more ammonia fish can tolerate. The level of ammonia that fish can tolerate is between .5 ppm and 2.0 ppm.

The amount of oxygen removed, carbon dioxide produced and ammonia produced is dependent on the amount of food fed in the raceway, not the amount of fish in the raceway. 5,000 pounds of fish could be fed 1% body weight (50 pounds of feed), and the ammonia, carbon dioxide and oxygen levels would be basically the same as if 2,500 pounds of fish were fed 2% body weight (50 pounds). The limiting factor is the same amount of feed can be fed per second foot of water, and the amount of fish that can be stocked is dependent on the percent body weight that is fed.

Oxygen required to metabolize 50 pounds of feed is approximately 2 ppm from one second foot of water. In a raceway with four sections and one second foot of water, the water will be aeriated three times, once between each section. Fifty pounds of feed can be fed in each section. This gives a total of 200 pounds of feed that can be fed in the entire raceway. Assuming 50% reoxygenation and saturation of 8 ppm, the oxygen at discharge would be 3 ppm. This is an absolute minimum level for production. A total of 8 ppm oxygen would be utilized in metabolizing the 200 pounds of feed.

Approximately .2 ppm ammonia would be deposited in one second foot of water from metabolism of 50 pounds of feed. Feeding 200 pounds of feed in one second foot of water, the ammonia in the discharge would be .8 ppm.

Maximum recommended inventory for commercial production of channel catfish on water at Fish Breeders is about 10,000 to 15,000 pounds per second foot of

water. Yearly production will usually be three to four times the carrying capacity.

Disease is usually a major concern in fish production. It should not be. 99% of all diseases are secondary expressions of poor water quality, poor feed quality and poor management (the human element). If good water quality is maintained, good feed is used and labor handles fish properly, disease should not be a problem.

In order for a commercial hatchery to obtain maximum profit, production must be pressed to the limit. This means carrying inventory will be increased to the point disease will develop because of overloading. It is management's job to balance carrying capacity to water quality and stay below the point where disease is a problem.

Here is summarized the problems expected in starting a geothermal fish farm. These factors have prevented a faster growth rate in geothermal fish farming.

Identifying the Resource. The extent of most geothermal sites considered for fish production have not been identified. Surface springs show a potential but do not tell the complete story. Wells must be drilled before the volume, temperature and water chemistry is determinable. These must be known before a production potential can be analyzed. Considerable money must be spent before a decision can be made recommending a site for geothermal fish farming. The person with a geothermal resource must first identify that resource, and then see if it is suitable for fish production.

Facility Design. People interested in building fish farms usually examine government hatcheries for models to copy. This is a poor place to study a good design. Poorly designed commercial farms go broke and disappear. Poorly designed government fish farms continue to operate indefinitely, consuming tax dollars.

An engineer's dream is too often a fish culturist's nightmare. The KISS rule is the only rule to follow. KEEP IT SIMPLE STUPID. There has been little communication between fish culturists and engineers. This lack of communication has resulted in a situation where there are few, if any, engineers who understand the management of fish culture well enough to design a commercial fish farm. I cannot recall a commercially viable fish farm that was designed by an engineer. The entire industry has been designed and built by the fish farmers themselves. This does not mean there is no room in the design work for engineers. It means engineers are not in tune with the problems of fish culture and, therefore, behind the times.

Financing. Financing is difficult. Geothermal is considered high risk. Fish farming is considered high risk, and high density production even a higher risk. Capital expenditure is high, operating expenses are even higher. An executive of a large company looking at fish farming said they consider some businesses as cash generating and others as cash consuming. They considered fish farming as cash consuming. It is a good description of fish farming.

Contrary to common opinion, most fish farms that have gone broke did not do so because of underfinancing. Those started underfinanced have had a high success ratio, while those adequately financed "spent it like they had it" and went broke. Too many mistakes were made too fast, and the investors ended up very disenchanted. Bankruptcy followed because of a lack of willingness, not ability, to refinance and do what was necessary to succeed.

Construction. If engineering follows the KISS rule, construction is simple. There is no substitute for good facilities. Concrete is usually best. The facilities will probably be the first fish farm the contractor has ever built.

Production. Trying to achieve more production than the water quality will allow causes most production problems. If the rules laid down earlier in this paper are followed, production should not be a problem. Keep good water quality, good feed quality and keep labor stress down.

Experienced personnel are not available. Personnel must be trained. There are many degree students graduating, but most do not have any experience. They need experience if they are being hired to run a new farm.

Processing. A processing plant will not be available in most situations. A producer will need to build a processing plant. Very little machinery is available for processing. Most of the labor is hand labor.

Marketing. No money is made raising fish until the fish are sold.

A common misconception is there is an unlimited market for fish products such as channel catfish. The truth is, there is an unlimited potential market for channel catfish and other good fish. The potential is unlimited. The existing market is full. There is no room for additional production without additional marketing. Markets must be developed, and they cannot be developed without fish. The fish must be raised before the market can be developed.

There were approximately 150,000,000 pounds of catfish sold in the U.S. in 1978. This production breaks down as follows: Brazilian imports 30,000,000 pounds; wild catfish harvested commercially in the U.S., 30,000,000; channel catfish raised on farms, mainly in Mississippi and Arkansas, 90,000,000; and 500,000 pounds raised in high density geothermal facilities. These catfish figures are listed in order according to quality and price, with the poorest quality listed first. There is a considerable difference in quality of product and price. The Brazilian fish sell as low as 60 cents per pound, and the geothermal produced fish sell for \$2.85 per pound, wholesale. In catfish, as in any other product, one gets what he pays for.

Distribution. Most geothermal resources are not near large market areas for fish. Distribution can be a major problem. The easiest market to develop is the fresh market. This complicates distribution, for the fresh market delivery must be avail-

able on a dependable weekly basis. In Idaho, Fish Breeders are in a good distribution area because of the 25,000,000 pounds of trout raised within 15 miles of the farm. Each production and market situation will have to be viewed individually to solve the distribution problem.

These are the main problems in establishing a geothermal fish farm. No phase can be left out. A project will need to master each phase to be successful.

IN SUMMARY

If you want to raise fish to get rich, you will probably go broke. If you want to raise fish because you like the challenge of fish culture, you will probably get rich. The best advice is to start small and grow slow.

THE USE OF GEOTHERMAL FLUIDS TO HEAT A LARGE GREENHOUSE COMPLEX

Kenneth L. Boren

GeoProducts Corporation

ABSTRACT

Geothermal fluids are being used to heat 30 greenhouses near Susanville, in Northeastern California. Cucumbers and tomatoes are grown in a hydroponic system requiring no root medium such as dirt or gravel. A high quality ground water supply is used for irrigation, while a shallow geothermal well supplies hot water for the heat-exchange type heaters. Thermostats and humidistats control the greenhouse environment. Nutrients are supplied in the irrigation water circulated through the root system that is contained in polyethylene growing tubes. A high quality fruit is produced and sold in the Los Angeles market. The complex has been planned for expansion to 205 greenhouses, and the next units are scheduled for construction this year.

HYDROPONIC VEGETABLE CULTURE

A large greenhouse complex is producing vegetables in a controlled environment with all heating requirements supplied by geothermal fluids. In Northeastern California, near Susanville, GeoProducts Corporation of Oakland has installed the first 30 greenhouses of a planned 205-greenhouse complex.

The greenhouses utilize hydroponic growing techniques to produce a high quality produce - currently tomatoes and European cucumbers. The plants - about 850 per greenhouse - are grown in flexible polyethylene growing tubes. There is no growing medium such as dirt, gravel or peat moss; instead, the plant roots are enclosed in the tube with the plant stem protruding from a pre-cut slit. The plant is supported by twine extending from an overhead support grid. As the plant grows, it is pruned to leave only one main stem, thereby concentrating the plant's strength in the budding area where the fruit develops.

Each greenhouse has two 450-gallon fiberglass tanks buried under the concrete floor. A nutrient solution is maintained in this reservoir and

periodically pumped into the end of each growing tube. The nutrient solution flows through the tube by gravity and drains back into the nutrient reservoir. Water for the nutrient solution is supplied by a nearby cold-water well producing from 110 feet. The well is not contaminated by geothermal fluids and produces an excellent quality water. The system uses very little irrigant water - only about 10% as much as row crop systems.

HEATING AND COOLING

The greenhouses are in an area of high temperature variations from summer to winter. Summer temperatures exceed 100°F several times a year and winter temperatures reach -20°F. Elevation of the site is 4000' and average precipitation is only about 6", so evaporative cooling provides excellent summer cooling. Winter heating is provided by two off-the-shelf heaters with copper coils. Geothermal water at about 190°F is circulated through the coils and a fan forces air across the coils and into a series of polyethylene convection tubes. The convection tubes are perforated, and carry the heated air to all areas of the greenhouse to maintain the desired temperatures.

Hot geothermal fluid is pumped through the main supply lines and into the heating coils by a 40hp. turbine pump. A motorized valve at each heater controls the rate of flow required to maintain the greenhouse environment. The valves are controlled by thermostats which are adjusted vertically to match approximate fruit levels. During coldest periods, each greenhouse is designed to use about 10gpm of 190°F geothermal fluid with a system pressure of 25 psi. Effluent from the heaters leaves the greenhouses at 120° F and flows into an existing drainage ditch where the site's rancher allows his range cattle to drink it. Eventually, it seeps underground and into Honey Lake, an alkali sink devoid

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of aquatic life which drains the entire valley.

GEOHERMAL SYSTEM

The geothermal resource is derived from an underground hydrothermal system believed to be heated by a deep-seated magma chamber. Volcanism of Pleistocene-to-recent age exists near the site, and the area's abnormal heat flow can be traced to this source. While the main reservoir is believed to be as deep as 5000 to 6000 feet, the hot fluids circulate to shallow zones through an extensive fault system. Where the intruding geothermal fluids intersect a ground water zone, mixing occurs and the shallow water wells drilled in these areas might encounter water zones varying from 68°F to boiling temperatures. Where the faults intersect the surface, hot springs exist, often at boiling temperatures.

Geothermal fluid for the greenhouses is supplied primarily from a shallow (627') well drilled into a fault through which the hot fluids are escaping the deep hydrothermal system. The hottest zone in the well is at 100 feet, where 216°F has been measured. Average temperature at the bottom of the pump setting (200') is 210°F. The well is pumped with a turbine pump designed by Valley Pump Company. About 300 gpm of geothermal fluid is supplied to the greenhouses during peak periods. The hot water is pumped to the greenhouses through 175 feet of transite line buried 36 inches without insulation.

MARKETING

The cucumbers are individually wrapped and individually labeled, as are the tomatoes, with the company's logo, Honey Lake Farms. Marketing is done through a large produce broker in Los Angeles. The fruit has excellent taste and visual qualities and an unusually long shelf life with virtually no loss from spoilage. Market demand for the produce has been excellent even though prices are well above the prices received for field crops. Expansion of the complex is planned to begin this summer in units of 25 greenhouses.

View of GeoProducts greenhouses near Susanville, California. This is the first 30 of a proposed 205 greenhouse complex.

Interior of a GeoProducts greenhouse near Susanville, California, planted with tomatoes.

THERMAL WATER OF HOT SPRINGS NATIONAL PARK ARKANSAS - THEIR ORIGIN, NATURE, AND
IMPLICATIONS FOR THE GEOTHERMAL DEVELOPMENT.

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and Benard Goodman

U. S. Department of Interior - National Park Service
Hot Springs National Park, AR 71901

ABSTRACT

The 47 hot springs has a combined flow of approximately 1,000,000 gallons per day at 143° fahrenheit. Source of the hot springs artesian-flow system is by infiltration of rainfall in the outcrop area of the Bigfork chert, the Arkansas Navaculite, sandstones and shales with the water emerging after 4,400 years. The radioactivity through radon gas emanation is 0.81 millicurie per liter. Chemical analysis milligrams per liter

Silica (SiO ₂)....42.0	Sulfate (SO ₄).....8.0
Calcium (Ca).....45.0	Chloride (Cl).....1.8
Sodium (Na).....4.0	Fluoride (F).....2
Potassium (K).....1.5	Oxygen (O).....3.0
Bicarbonate (HCO ₃)165.0	Free Car. Di.(CO ₂)10.0

Existing water usage heating restrooms, Administration Building and Therapeutic bathing as known world wide in Hot Springs, Garland County, Arkansas.

INTRODUCTION

The thermal springs of Hot Springs National Park in Arkansas has been a Natural resource of international renown for many years. The springs were known to President Thomas Jefferson who initiated the first scientific study in 1804, marking the first beginning of an era of scientific curiosity as to the origin heat source of the springs.

Public interest in the hot springs has been focused primarily on therapeutic values of the waters, and in serving such interest, this also has been the focus of Federal Management since the area was established as the Hot Springs Reservation in 1832 and was designated as a National Park in 1921 and is preserved and protected for present and future generations.

Geothermal energy has been utilized for many years in a minor fashion through radiators heating small structures (restrooms) on bath house row and in October, 1975 the National Park Administration Building was converted from natural gas heat to geothermal heating. With the gradual decline in bathing only about 1/3 of the thermal waters are utilized for therapeutic purpose.

SPRING DEVELOPMENT INCLUDING HISTORY
AND PRESENT USE

The 47 thermal water springs including 2 exhibition springs are in a belt about one-fourth mile long and a few hundred feet wide along the southwest slop of Hot Springs Mountain.

Excavation and covering of springs to increase and concentrate flows and to protect springs from contamination, have so altered the natural spring environment that it bears no resemblance to the original conditions.

Water flow from 45 spring to a collecting line system including a 12 inch collecting line to a 300,000 gallon reservoir and pumped to high level reservoir in order to be redistributed to individual bath houses with approximately 60 pound pressure, this process includes cooling a portion of this water from 143° to 90° for use in the bath house.

The chemical quality of water from the Hot Springs in Arkansas has been a great interest to man, probably since the hot springs were discovered.

The purpose of many investigations have been to support some therapeutic claim for the water, or to determine whether the chemical concentration of the water has been changed.

GEOTHERMAL ENERGY FOR HEATING OF THE
ADMINISTRATION BUILDING-HOT SPRINGS NATIONAL PARK

With the energy crisis, it was necessary to look at all possible ways in which to conserve energy. An inhouse dialogue ensued over some months between the Superintendent, Chief of Maintenance and Utilities Foreman, leading to the conclusion that the thermal water heating should be pursued as a realistic alternative to the use of natural gas.

With the assistance of Davis & Pitts, an Engineering firm we installed a hot water coil with cleanable tubes in our existing forced air system alone with the necessary controls and devices for the new system costing approximately \$3,000.00.

The average thermal water use per month for heating the 5,460 square foot building is approximately 170,895 gallons estimated cost of 7 cents

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per 1,000 gallons and is required about five months each year during the winter months.

The heat reclaim for energy conservation of the administration building was put in to effect in October, 1975 replacing the need for a natural gas fired boiler.

The thermal water coil was installed in the existing 24 inch x 24 inch return air duct to heat 4,550 cubic feet per minute of air from 65° fahrenheit to 105° fahrenheit when provided with 26.0 gallons per minute of 140° fahrenheit water.

Existing installation and performance with blower moving 4,550 cubic feet per minute of air with a average of 171,000 gallons per month using 140° fahrenheit water keeps the building at a desired temperature.

Note the water use is considerable less than planned.

Controls for the System as follows:

1. The fan is the same one that existed in the previous system. It blows a given number of hours, depending on the setting on an automatic timing device. It's operation is basically no different than it was in the old system.

2. The Element is heated by the thermal water pipes into the "radiator" type unit. This is the same "HOT" water that the concessioners have available in their "hot" taps (Approximately 143° fahrenheit). The temperature of the heated air is controlled, however, by two thermostat controlled valves. These two valves control the flow of water into the unit.

3. The two thermostats operate with one having priority over the other.

A. Supply Duct Thermostat This thermostat is attached to the supply duct and measures the temperature of the heated air therein. It can open or close an electric motorized modulating valve, provided that the "building thermostat" has opened the valve on the water supply line nearest the source.

B. Building Thermostat The existing thermostat located in the administration building, has priority, in the sense that it can close the prior valve on the hot water supply line if the heated area reaches the desired temperature before the supply duct thermostat is satisfied.

Materials and Description as follows for the conversion:

The Coil shall be copper tube, aluminum fin in casing for installation in return air duct, and is of cleanable tube design with removable headers for cleaning from either end. Coil is a Bohn #5CC4A 15T x 48.

4 stand for four rows -- A stands for 8 fins

Tube wall shall be 0.035,

Tube size shall be 5/8 inch diameter

Maximum air pressure drop shall be 0.585" H₂O

Controls (Honeywell, Inc.)

1 - T991A thermostat set up for heating only

1 - M945A valve motor, 24 volts

1 - V5011A valve, 1" size, Maximum 8 psig pressure drop at 26 g. p. m.

1 - Q618A linkage

1 - Rodale switch with box and cover

1 - AT72D1477 transformer 115/24 volt

Geothermal heat will be utilized for the National Park Service Buildings (Existing Bath Houses) being renovated for use as a Visitors Center and a Amphitheatre and possibly using the cooled water for other therapeutic purposes.

After the use of the 143° fahrenheit waters for heating buildings has been cooled to 90° temperature; it can be utilized as the cool water supply for existing bath houses.

UTILIZATION OF GEOTHERMAL ENERGY WITH AN EMPHASIS ON HEAT PUMPS

by

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Abstract

While there are uses for low temperature (≤ 120 degrees Fahrenheit) geothermal sources for space heating and other relatively low temperature applications, many commercial users and industries require higher temperatures. These higher temperatures (140 degrees to 220 degrees Fahrenheit) are obtainable through supplementary heating using oil, gas or electricity; however, the cost is high particularly where direct electric heating is used. Since 1975 low temperature waste heat sources (such as water normally cooled in cooling towers) have increasingly been used in conjunction with heat pumps for hot water production and space heating. This same concept can be applied to a low temperature geothermal source to amplify the temperature to a usable value or amplify the amount of energy that can be usefully extracted from a limited geothermal resource.

There is a high level of interest in the application of industrial water-to-water heat pumps for use with geothermal water in the 60 degrees to 120 degrees Fahrenheit range, considered available from wells less than 3000 feet deep. The heat in this water can then be temperature amplified to increase the deliverable temperature by as much as 80 degrees to 90 degrees Fahrenheit. The heat pump can be economically used either a) to upgrade a geothermal resource already obtained where the flow and/or temperature are insufficient to meet the utilization needs, or b) as an alternative to drilling much deeper wells to obtain needed higher use temperatures.

Background

The economy of the United States is based on a high consumption of energy; and, therefore, we are one of the countries most affected by the fast changing global energy situation. We are not, as a country, energy deficient as ample reserves of coal, oil shale and geothermal energy have been proven. However, the development of these resources has been delayed for a number of reasons. Relative to geothermal, two of the most important reasons are. . . 1) the economics of recovery, distribution and use in the face of today's relatively low gas and oil costs, and 2) geothermal is not broadly appreciated by many design engineers. These alternate sources of energy must

be developed, to both lessen the negative balance of payment impact between the United States and the OPEC countries, and to reduce this country's dependence on foreign oil.

There are considerable geothermal resources in the United States which could be developed and become a significant part of the total energy supply. It is to the advantage of the United States to rapidly develop geothermal resources in a manner consistent with the overall protection of the environment.

While geothermal reservoir temperatures can range quite high, this discussion is oriented to those that are more commonly considered available. Most geothermal sources have base temperatures below 300 degrees Fahrenheit, which is the current threshold temperature for economic electrical power generation. Of identified western United States natural heat sources (hot springs, fumaroles, etc.), approximately 85 percent have base temperatures less than 300 degrees Fahrenheit. Additionally, in the eastern United States there appear to be numerous, but not yet identified, low-temperature heat sources.

Water Temperature Versus Well Depth

The temperature gradient will vary by location; however, some reasonable assumptions can be made to examine the order of magnitude of the economic alternatives. A number of test sites (1) have indicated an average temperature increase of 1 degree Fahrenheit/100 feet. Preliminary test drilling at a Maryland site (2) is indicating an increase in geothermal temperature of $2\frac{1}{2}$ degrees Fahrenheit/100 feet of well depth. These two ranges of temperature gradient are plotted in figure 1. For purposes of further analysis, a reasonable mean of $1\frac{1}{2}$ degrees Fahrenheit is used and plotted in figure 1 using the formula:

$$T = 55 + 0.015 Z$$

where T = °F and Z = depth in feet.

Temperature of Formation Water vs. Well Depth

Figure 1.

Use Temperature

For extensive direct use in industrial process heat applications and most large space heating uses, the required hot water temperatures range upward from 135 degrees Fahrenheit. Using the Figure 1 correlation, this indicates a well depth requirement in excess of 5000 feet for direct use.

To provide the 150 degrees Fahrenheit hot water extensively used in the food processing and metal fabricating industries, the indicated well depth would be over 6000 feet. The cost of drilling wells to these depths could be prohibitive considering the present (and even the ten-year projected) cost of conventional energy uses to heat process water and to supply space heating.

Temperature Amplification

Recent developments in the area of high temperature heat pumps represent a potentially attractive alternative to the deeper wells through temperature amplification of the geothermal source by electric heat pumps. Where the geothermal flow is limited, considerable cooling can be accomplished, thus, extracting many more Btu's from the geothermal water.

Using the nonreversible heat pump principle, the industrial heat pump recovers low grade heat in geothermal water in the temperature range of 60 degrees Fahrenheit to 120 degrees Fahrenheit and amplifies it to higher, usable temperature levels. The heat from the geothermal water is absorbed in the heat pump evaporator by the unit's working fluid which is then increased in temperature and pressure by the compressor. From here it

goes to the condenser where this heat is transferred to a delivery fluid for providing useful heat at temperatures up to 230 degrees Fahrenheit, with this 230 degrees Fahrenheit upper limit being the current state of the art.

The cycle diagram for such a system is shown in Figure 2.

Figure 2

The measure of efficiency, called the coefficient of performance (COP), of such devices currently available from Westinghouse Electric Corporation is shown in Figure 3. The ratio of the thermal equivalent of the Westinghouse Templifier (R) heat pump electrical input to the upgraded heat output (the COP) ranges from roughly three to six. For example, 150 degrees Fahrenheit hot process water stream can be delivered from a 95 degrees Fahrenheit geothermal source cooled 10 degrees Fahrenheit (or a 105 degrees Fahrenheit source cooled 20 degrees Fahrenheit, etc.) with a COP of about 4.5.

Coefficient of Performance (COP)

Figure 3

Usually temperature amplification is utilized in a range up to 80 degrees to 90 degrees Fahrenheit (output hot water minus leaving geothermal water) where a COP of about 3.5 is obtained. A COP of less than 3.0 is not normally used as the economics are not usually sufficiently favorable.

By applying Templiers to the process, usable water temperatures for source heat can be obtained at well depths 2000 feet (85 degrees Fahrenheit) to 3000 feet (100 degrees Fahrenheit)

and the captured heat temperature amplified to the higher use temperature.

Temperature Amplified Low Grade Heat-Closed Loop System

The objective in this example is to provide 450 gpm of 165 degrees Fahrenheit supply hot water to meet a 2.2 million Btuh heating load in a closed loop where the return hot water is 155 degrees Fahrenheit; a closed loop system being one in which the hot water is cooled by the load and then returned for reheating.

If we consider that the properties of the geothermal water are such that it should be used through a water-to-water heat exchanger to generate 165 degrees Fahrenheit fresh water to the load, in a conventional geothermal system the producing well temperature would have to deliver at least 170 degrees Fahrenheit at a 450 gpm flow rate. From Figure 1 this would require a well depth at mean gradient of approximately 7,700 feet.

A simplified example of the use of the heat pump process is shown in Figure 4. By the use of the Templifier heat pump, a more shallow well of about 3000 feet in depth could produce 100 degrees Fahrenheit water. If we take out 10 degrees Fahrenheit of heat, a flow of only 325 gpm is required to transfer 1.6 million Btuh to a 95 degrees Fahrenheit fresh water stream to supply the Templifier heat pump. Alternatively, if higher temperatures are available, lower gpm flows would be needed: 110 gpm at 120 degrees Fahrenheit or 55 gpm at 150 degrees Fahrenheit supply temperature. Or, if both higher flows and temperatures are available, a larger Btu per hour heating load could be served.

Schematic Diagram of Use of Low - Grade Geothermal Energy Temperature - Amplified for 165°F Heating Load

Figure 4.

Typically, such a heat pump, with 85 degrees Fahrenheit water leaving the evaporator, will produce 165 degrees Fahrenheit hot water at a 3.5 COP. Allowing for system losses, this 1.6 million Btuh of geothermal source heat will produce the required 2.2 million Btuh for the utilization load. The Btuh difference coming from the 184 kw per hour electrical input to the heat pump.

Thus, a 3000 foot deep well delivering 325 gpm of 100 degrees Fahrenheit water plus the Tempilifier heat pump will meet a load that would otherwise require a 7,700 foot deep well producing 450 gpm calculated as follows:

$$\text{gpm} = \frac{2.2 \times 10^6 \text{ Btuh Load}}{10^\circ\text{F range} \times 8.15 \text{ lbs/gal} \times 60 \text{ min/hr}} = 450$$

System Design - Open Loop System

An open loop system is one where incoming feed water is heated through a relatively high temperature range and then supplied to the process load and consumed or not returned for other reasons. Such an open loop system, where the incoming water to be heated is at a temperature below the geothermal source temperature, offers

significant additional opportunities.

To get the most energy out of the geothermal source with the least electrical input to the heat pump, it is necessary to transfer as much heat as possible directly by means of a heat exchanger. The remaining temperature amplification can then be provided through use of a heat pump. As the geothermal source may be in limited supply, it is desirable to drop its temperature as low as possible to maximize the energy extracted from the source. If we are to heat an incoming low temperature return or feed water supply at temperature (T_u , in) to the use level desired (T_u , out,) the geothermal source at temperature (T_g , in) is then cooled to (T_g , out) to achieve a heat balance.

Working with Westinghouse, a study (3) of several potential system designs has been conducted at the Johns Hopkins University Applied Physics Laboratory.

The five systems considered are shown in Figure 5, each using an incoming feed water temperature (T_u , in) of 60 degrees Fahrenheit and a geothermal discharge temperature (T_g , out) of 70 degrees Fahrenheit for comparison.

Open Loop Tempilifier® Heat Pump Systems

Figure 5

Using COP performance derived from Figure 3 and a heat exchanger effectiveness of 0.90 (a reasonable compromise between heat exchanger cost and performance), the systems were examined at the above selected conditions.

The operating characteristics of Systems 1 and 2 show less efficiency than Systems 3, 4 or 5 except at very low source temperatures. For System 1, all of the temperature lift must be supplied by the Templifier (R) heat pump. At very low geothermal source temperatures this incurs little penalty; however, at high geothermal source temperatures the penalty can be severe unless the geothermal supply is quite limited compared to the required hot water heat load. A similar situation exists for System 2 since in order to fully extract the energy from the source, the heat pump again is providing most of the temperature amplification.

Considering the cost of electric power, a critical operating parameter is the amount of power required to deliver a specific amount of energy ($\text{kw-hr}/10^6 \text{ BTU}$).

Taking a geothermal inlet temperature, (T_g , in) of 120 degrees and a delivery (use) temperature, (T_u , out) of 160 degrees Fahrenheit, the results enable us to compare the energy efficiency of the systems as shown in Table 1.

Table 1
Heat Pump/Heat Exchanger Open Loop Systems

System	$\text{kw-hr}/10^6 \text{ BTU}$	System COP	$\text{Wg gpm}/10^6 \text{ BTU}$
1	88.4	3.3	27.9
3	60.8	4.8	31.7
4	40.7	7.2	34.5
5	35.0	8.4	35.2

It is seen that Systems 4 and 5 are better than 3 by almost a factor of two and are $2\frac{1}{2}$ times better than System 1. As electrical energy per million BTU is not the only consideration, a comparison of the source requirements of the three systems shows that System 5 also requires only a small increase in the flow of geothermal water (11% more than System 3 and 26% more than System 1). The cost of the additional heat exchangers required in System 5 is small compared to the heat pump cost. Thus with similar capital costs and lower energy costs the preferred system is number 5.

Keep in mind these are for the specific conditions stated previously and for large centrifugal Templifier heat pumps having COP's approximated by Figure 3. For analysis of other conditions for System 1, 3, 4 and 5, magnetic cards for a TI59 programmable computer have been developed in which the inputs are (T_u , in); (T_u , out); (T_g , in); W_u (use water flow gpm), E (heat exchanger effectiveness) either W_g (geothermal flow gpm) or (T_g , out) (outlet geothermal water temperature).

The computer then outputs the optimum various cycle point temperatures and heat flows (Btuh) as well as the heat pump and overall system COP and the heat pump KW. The program also can adjust for the heat pump COP factor (C).

From this information the installed cost of the Templifier and heat exchangers can be estimated and an economic evaluation made of the geothermal heat pump system versus a geothermal - boiler system or against today's conventional systems.

Another computer program is available from Westinghouse to simplify these financial analyses and output net cash flow, present value of cash flow and return on investment over a ten-year operating cycle, taking into account such important elements as the relative investment, load factor, cost of capital, maintenance, tax rates, incentive tax credits and projected energy cost escalation.

Economics - Closed Loop System

In the example shown in Figure 4, a rough order estimate of the economics can be made by making several assumptions. For specific situations, these assumptions can be varied to suit, and the results recalculated using your numbers.

The nature of the geologic formation, diameter and depth are all contributors to well costs. For this analysis we will assume a 3000 foot well delivering 325 gpm can be completed for \$50 per foot; while a 7700 foot well depth for 450 gpm will cost \$65 per foot; and that the injection well (if used) will be identical to the producing well. Further, that electric power costs 3¢ per kilowatt-hour and efficiencies are 60 percent for the pump and 90 percent for the driving motor. Finally, the process heating load occurs for 4000 hours per year - a typical two shift industrial operation.

The incremental pumping costs between 325 gpm from a 3000 foot well and 450 gpm from a 7700 foot well is computed to be 870 kwh per well at an annual pumping cost of \$104,400 ($=870 \text{ kw/h} \times 4000 \text{ hr/yr} \times \$0.03/\text{kwh}$).

The Templifier heat pump annual operating cost calculates at \$22,100 ($=184 \text{ kw/h} \times 4000 \text{ hr/yr} \times \$0.03/\text{kwh}$). The required evaporator pump operation is estimated with a 50 foot head at \$700.

From this data Table 2 is constructed which demonstrates the economic opportunity for significant savings in both the first cost and in the annual operating cost.

Table 2 - Economic Analysis; Closed Loop System

2,200 Mwh Load:	Geothermal/Heat Pump		Geothermal Only	
450 gpm, 165 degrees Fahrenheit	325 gpm, 3000 Foot Well		450 gpm, 7700 Foot Well	
<u>Delivery Hot Water</u>	<u>Injection Well</u>		<u>Injection Well</u>	
<u>Capital Cost</u>	<u>With</u>	<u>Without</u>	<u>With</u>	<u>Without</u>
Producing Well	\$150,000	\$150,000	\$500,500	\$500,500
Injection Well	150,000	0	500,500	0
Templifier installed*	85,000	85,000	-	-
Total	\$385,000	\$235,000	\$1,001,000	\$500,500
Incremental First Cost Saving	\$625,000	\$265,500	-	-
<u>Incremental Annual Operating Cost</u>				
Producing Well	\$ 0	\$ 0	\$104,000	\$104,000
Injection Well	0	0	104,000	0
Templifier Heat Pump	22,100	22,100	-	-
Templifier Evap. Pump	700	700	-	-
Total	\$ 22,800	\$ 22,800	\$208,000	\$104,000
Incremental Operating Cost Saving	\$185,200	\$ 81,200	-	-

* Includes Templifier heat pump, evaporator water pump and associated piping system on an installed basis.

Economics - Open Loop System

In an open loop system the incoming water can be heated through a heat exchanger, extracting the most heat it can from the geothermally heated source. Then the remaining heat can be supplied by a boiler to achieve the desired discharge temperature. The arrangement would be similar to System 3, except substituting a boiler for the heat pump condenser. This can then be compared to a geothermal heat pump system.

For a typical analysis let's assume the 4000 hour per year load requires heating 100 gpm of water from 60 degrees Fahrenheit to the use temperature of 160 degrees Fahrenheit; equivalent to 5 million Btu per hour. Additionally, assume we have a resource of 176 gpm of 120 degrees Fahrenheit geothermal source water of a quality that can be utilized directly; electricity cost is 3¢ per kwh. With a 5 degrees Fahrenheit approach in the heat exchanger, the incoming water can be preheated to 115 degrees Fahrenheit before going to the boiler or the heat pump.

Table 3 shows the computer program output for both the System 3 and 5 arrangement. When the boiler is used (instead of the heat pump) in the System 3 arrangement, the boiler must supply 90 or the 2.25 million Btu per hour otherwise supplied by the heat pump.

Table 3 - Geothermal Heat Pump System Computer Program Output

System 5		System 3	
User Side		User Side	
60.0	TIN	60.0	TIN
115.0	T1	115.0	T1
78.5	T2	60.0	T2
160.0	TOUT	160.0	TOUT
100.	GPM	100.	GPM
5,000,000.	QT	5,000,000.	QT
GEO Side		GEO Side	
120.0	TIN	120.0	TIN
99.3	T1	88.8	T1
80.6	T2	70.8	T2
70.1	TOUT	70.8	TOUT
176.	GPM	176.	GPM
4,392,960.	QT	4,326,080.	QT
Heat Exchanger		Heat Exchanger	
0.88	EFF1	0.92	EFF1
1,823,500.	Q1	2,750,000.	Q1
0.90	EFF2	0.	EFF2
928,000.	Q2	0.	Q2
Heat Pump		Heat Pump	
0.53	HPC	0.53	HPC
2,248,500.	QU	2,250,000.	QU
1,641,806.	QG	1,576,443.	QG
177.76	KW	197.35	KW
3.71	COP	3.34	COP
8.24	COP Total	7.42	COP Total

With this data, plus some reasonable estimates on incremental installed first cost, Table 4 can be constructed giving a rough-order

comparison of geothermal heat pump systems compared to a geothermal boiler system.

Table 4 - Economic Analysis, Open Loop System

	Geothermal/Heat Pump		Geothermal/Boiler
	System 5	System 3	System 3
<u>Capital Cost</u>			
Heat Exchanger 1	\$ 7,000	\$ 9,000	\$ 9,000
Heat Exchanger 2	8,000	-	-
Boiler Installed	-	-	25,000
Templifier Installed	85,000	85,000	-
Total	\$100,000	\$ 94,000	\$ 34,000
Incremental First Cost Addition	\$ 66,000	\$ 60,000	-
<u>Incremental Annual Operating Cost</u>			
Templifier	\$ 21,300	\$ 23,700	-
Electric Boiler	-	-	\$ 79,100
Incremental Saving	\$ 57,800	\$ 55,400	-

If these results are then fed into the Westinghouse economic analysis program, and we assume inflation at 7 percent and electricity escalation at 10 percent per year, together with the 46 percent corporate tax rate, 20 percent investment tax credit and a 10 percent cost of capital we find over a 10-year operating cycle - the results shown in Table 5.

Table 5 - Ten Year Economic Comparison Open Loop System

	System 5	System 3
Added First Cost	\$ 66,000	\$ 60,000
Annual Operating Cost Saving at Current Cost	57,800	55,400
Energy Saved per Year	1.93×10^6 kwh	1.85×10^6 kwh
Project Net Cash Flow	\$499,000	\$480,000
Present Value of Cash Flow	\$279,500	\$270,000
Return on Investment	118%	127%

From this it can be concluded that, in this case, the geothermal heat pump system 3 is the economically preferable investment that gives the greatest financial return (ROI) of the geothermal alternative, while system 5 saves the most energy and generates the highest cash flow. In both cases the heat pump application pays for itself in just over one year.

Other Economic Considerations

Other economic aspects which have not been considered here include development and depletion allowances. According to the Internal Revenue Service⁽⁴⁾, an operator developing geothermal properties may either deduct as expenses or charge to the capital account all intangible drilling and development costs incurred on wells begun after September 1978.

Additionally, geothermal deposits qualify for percentage depletion. The applicable percentage through 1980 is 22 percent, decreasing by 2 percent yearly through 1983. After that the rate is 15 percent.

Other Application Considerations

Some of the additional considerations in this application are items such as--

- In areas with limited geothermal water, expended water may have to be reinjected into the aquifer from which it came to maintain formation pressures to prevent aquifer collapse with loss of permeability and to prevent depletion.
- Investigations will be needed to prevent low temperature mineral precipitation in the aquifer that would plug the aquifer; how to screen out sediment from the water that would foul the heat exchangers and plug the aquifer.
- The prevention of scale within the heat exchanger and the Templifier heat pump evaporator itself must be solved, for most geothermal water carries relatively high mineral content compared with surface water. This mineral tends to form scale as soon as the water temperature is lowered. In some cases a separate closed fresh water loop may be needed to facilitate and minimize maintenance,

as illustrated in Figure 4.

- Experience has indicated that at least the supply well should be drilled and tested before completing the system design.
- In some cases the system can be designed to use the geothermal water as a heat sink for summer cooling and as the heat supply for winter heating.

Additionally, other aspects need to be examined for geothermal to take its potential place in the nation's energy supply, and work is proceeding on this through the Geothermal Resources Council and Geo-Heat Utilization Center.

Summary

With the growing need to utilize our geothermal resources to displace imported oil and gas with their rapidly rising costs and decreasing availability, it appears the geothermal heat pump system has an economic application for furnishing up to 230 degrees Fahrenheit hot water for process heat, space heat and service hot water in commerce and industry.

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DIRECT HEAT ACTIVATED COOLING ADAPTED TO GEOTHERMAL ENERGY

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ABSTRACT

Development in recent years of direct low temperature heat operated cooling equipment has the potential of improving geothermal economics by enabling more uniform seasonal load distribution and capital amortization. Source temperatures below 200°F and improved auxiliary power consumption are the primary advantages over previously available equipment. Of the various types of equipment on which development was undertaken, only absorption is beyond the developmental stage, being in current volume production.

Availability of these advanced absorption machines in small tonnage capacities (as low as 3 tons) facilitates the undertaking of demonstration projects at greatly reduced costs, freeing R & D monies for instrumentation, analysis and reporting expenses.

INTRODUCTION

Increasing concern over the cost and availability of energy has initiated investigation into alternate sources of, and more efficient methods of, utilizing energy. Coincident concern over ecological considerations and use of non-renewable resources has encouraged development of naturally occurring sources of energy. Of particular interest are solar and geothermal. The former because of technology development for solar application. The second because much of the solar technology is directly applicable and may, in some instances, prove to be a more economical application.

Both solar and geothermal immediately suggest the availability of heat for direct use in space, hot water and process heating applications. Higher source temperatures suggest electrical power generation application. Recent interest has also focussed on direct heat operated cooling equipment with the intent of amortizing the heat source development capital over the cooling season as well as the heating season.

Historically, absorption machines have been the most commonly used apparatus in direct heat operated cooling applications, and initial attention was directed to this equipment.

Initial solar cooling installations using low temperature heat employed modified versions of commercially available fuel-operated absorption air conditioners in residential application. In commercial structures, standard equipment (most derated to lower capacities to operate at the lower temperatures) was employed.

DEVELOPMENT REQUIRED

The operating experiences gained from these early installations indicated the requirement for a new generation of equipment designed specifically to operate within the parameters imposed by the new applications. Design objectives established were:

- 1) Full design capacity of the machine to be obtained at lower than traditional (230 - 270°F) source temperatures. Source temperatures below 212°F would be desirable.
- 2) Temperature Flexibility: A broader temperature range must be acceptable to the machine.
- 3) Parasitic power (power for such auxiliaries as pumps) to be reduced to absolute minimum. The capacity to parasitic ratio determines the advantage, if any, the heat operated system will have over a conventional electrically driven system.
- 4) Maintenance requirements must be minimized. The possibility of over-concentrating the absorption machine must be reduced.

RESULTING EQUIPMENT

To meet these objectives and bring the resulting equipment to the marketplace, machine development received federal funding in the absorption, Rankine and Brayton cycles. The latter two are in development with field testing of experimental units scheduled this year.

In early 1977 the first two machines designed to the new objectives rolled off the production line at Arkla Industries. The Model WF-36 was directed at the residential market and has a nominal design capacity of 3 tons. The Model WFB-300 was developed for the light and medium commercial market and has a nominal design capacity of 25 tons. The

capacity rating of both machines is taken with a source temperature of 195°F. Capacity varies with the source temperature. Specifically, the relationship to the design objectives are detailed as follows and in the accompanying tables:

1) Full design capacity obtained with source temperature of 195°F, 17°F below the 212°F target. This makes it possible to avoid the use of pressure code vessels, reducing the system costs.

2) Temperature Flexibility: A source temperature range of 350 - 400°F with capacities as indicated in the accompanying tables, in addition to a relatively high turn-down.

3) Parasitic Power at Full Capacity:

- 25 Ton: Absorption cycle electric - 300 watts.
Auxiliary Pumping: 9.6 GPM/ton
- 3 Ton: Absorption cycle electric - 250 watts.
Auxiliary Pumping: 10 GPM/ton

Development timing necessitated the use of an off-the-shelf solution pump on the 3 ton machine not allowing optimization of the pump for power consumption. A new pump is currently completing development.

4) Maintenance: Use of relatively dilute solution eliminates dilution cycle requirements and over-concentrating resulting from unintentional shut-downs and under-firing conditions. Use of inherently self-cleaning dripper fluid distribution instead of spray nozzles eliminates clogging problems and reduces solution pump horsepower. Use of air-tight construction normally associated with low-maintenance requirements of residential type construction eliminates periodic solution sampling and avoids motor driven purging mechanisms.

WF-36 PERFORMANCE AT 45°F CHW

FIGURE 1: CAPACITY & COP TABLE FOR 3-TON MACHINE.

WFB-300 PERFORMANCE AT 85°F CONDENSING

FIGURE 2: CAPACITY & COP TABLE FOR 25-TON MACHINE.

FIGURE 3: WFB-300 CYCLE.

The Arkla SOLAIRE 300 Water Chiller operates on the absorption principle. Solar heated water is the energy source, circulating in a closed loop between the unit's generator and the solar collectors. In a second closed loop, the refrigeration tonnage is delivered by chilled water which circulates between the unit's evaporator coil and a refrigeration load. In a third water circuit, condensing water flows through the unit's absorber and condenser coils, carrying away the waste heat.

To begin the cycle, solar heated water enters the generator tubes. Its heat vaporizes part of the

water refrigerant in solution, separating it from the lithium bromide absorbent.

The vaporized refrigerant passes to the condenser where it gives up its latent heat to the condensing water and is liquefied. It then flows through a "U" tube and through the flash chamber into the evaporator, wetting the outer surfaces of the evaporator coil tubes. There it is again vaporized as it absorbs the heat of the refrigeration load from the chilled water. The vapor then flows to the absorber where it is again liquefied as it combines with the absorbent in the process that gives the cycle its name.

The hot absorbent passes from the generator to the liquid heat exchanger where it gives up some of its heat. The pre-cooled absorbent then enters the absorber where it wets the outer surface of the absorber coil tubes and combines with the vapor refrigerant. It then gives up the remainder of its heat to the condensing water flowing inside the absorber coil tubes.

After the absorption process, the reunited refrigerant-absorbent solution drains into the solution sump. From there, it flows to the solution pump which moves it through the liquid heat exchanger where it is pre-heated before continuing on to the generator to repeat the cycle.

Refinements, in addition to the liquid heat exchanger, include:

1) The Concentration Chamber and Dump Valve. The chamber, by collecting and storing a portion of the liquid refrigerant, provides the optimum solution concentration for best unit performance when entering condensing water temperatures are in the normal range of from 75°F to 90°F. If condensing water temperature drops below 75°F, the dump valve opens and empties any stored refrigerant into the solution sump, diluting the solution. This dilution allows stable and continuous unit operation at the lower condensing water temperatures.

2) The Solution By-Pass Valve. This valve is opened for a timed interval during the initial minutes of any start, by-passing solution around the absorber coil directly back to the solution sump. This allows time for the evaporator to be fully wetted with liquid refrigerant before the absorber becomes active.

3) The Hot Water Control Valve. This valve, in addition to acting as an on-off device, modulates the flow of hot water (input energy) to the generator according to the entering and leaving chilled water temperatures. If either or both temperatures drop below preselected points, the valve reduces hot water flow through the generator by diverting some hot water into its by-pass. Thus, input energy is adjusted to match the refrigeration load.

SYSTEM APPLICATIONS

Five different methods of applying these machines

have been proposed in various private and federally funded projects. The basic types of systems are briefly outlined as:

1) Conventional Central Station: The conditioned structure has its own heat source and central HVAC plant which provides all conditioning and DHW (domestic and service hot water). This is the most common application.

2) District Heating & Cooling - 4 Pipe: A central heat source plant simultaneously providing hot and chilled water in separate circuits to numerous, physically independent structures. Each structure retains independent control over its requirements.

3) District Heating & Cooling - 2 Pipe: As in number 2), but hot water only is circulated during the heating season and chilled water only is circulated during the cooling season. DHW is available from the central plant only during the heating season. This system also places restraints on the individual structure's ability to determine heating or cooling requirements during intermediate seasons (Spring and Fall) when frequent changeover may be required.

4) District Hot Source - 2 Pipe: The central heat source provides only heat to the individual structures during all seasons. Each structure has its own central HVAC and DHW system. Each structure independently determines its own requirements. Provides the economy of a 2-pipe system over a 4-pipe system while providing operating mode selection for the individual user. The latter might increase the probability of successful marketing of this concept.

5) Cogeneration: Efficient electrical generation requires relatively high temperature sources. To increase overall system efficiency the heat rejected from the generation cycle may be used directly to activate the absorption cycle, assuming the heat engine's condensing temperature is within range of the absorber's generator temperature. Such a system has been in use at Sandia Labs employing a derated Arkla 100-ton machine (no longer produced). Additionally, NASA is using the cooling water from a diesel generator set to operate a WFB-300 which provides cooling for a tracking station. Such systems, already demonstrated are directly applicable to geothermal applications which have sufficiently high temperatures.

The significance of these applications is their potential, however limited, of providing energy-intensive work utilizing a virtually untapped ecologically favorable resource. In some areas, it may be possible that the economics are favorable with currently available technology and hardware. The following table was prepared as a "glance" in that direction, but a more detailed analysis with hard number should be examined for a proper determination.

FIGURE 4

FIGURE 5: DIAGRAM OF 3RD GENERATION MACHINE.

CURRENT DEVELOPMENT

Although equipment currently in development may be years from the marketplace, it is interesting to see what's "down the road". Arkla is currently in development of the "3rd" generation of residential cooling equipment for a direct low temperature application. It is a novel departure from traditional concepts in that it has been "turned inside out", using the external shell surfaces for heat rejection. Distributing the cooling (condensing) water directly over the machine eliminates the cost of a separate cooling tower, reduces pumping energy and decreases scaling by reducing heat flux. Prototypes have achieved design goals. The previous schematic of this evaporatively cooled chiller shows its basic configuration. Please note that it is a "cut-away" of concentric shells. The heat exchange tubing is circularly wound.

Beyond the 3rd generation machine it is difficult to predict events. If sufficiently high temperatures are made available, it may be practical to develop double-effect absorption machines for the lower tonnage market. They are currently available above 500 tons. The double effect machine requires 300°F internal operating temperatures, but offers higher efficiencies than single effect machines. Arkla currently has double effect experience in-house. A 15-ton machine designed by an engineer on the Arkla development staff achieved its design COP of 1.20. This is contrasted to the single effect machines which typically attain COP's in the range of .66 to .72. (Note that the WF-36 achieves .80 in off-design conditions of 185°F source, 80°F condensing, 45°F CHW).

For general information, the following table has been abstracted from DOE information and is intended to demonstrate design objectives of the various R & D programs. The absorption curves, however, represent developed technology and have been overlaid on the DOE data.

FIGURE 6

CONCLUSION

Current efforts in new energy technology represent an investment in the future. It would appear that Geoheat represents a relatively untapped resource which is available for near-term utilization in some areas. If so, increased development effort in this area represents a sound investment.

This dictates the requirement for geothermal demonstration programs for problem solving, technology development and feasibility determination. Where cooling is required, absorption technology should be applied and evaluated. Finally, the economics should be evaluated from the initial cost and savings potential to determine ROI.

As is occurring with solar, the increased level of activity has a significant impact on legislative action and may provide a degree of "self-help" in this area.

Arkla is well-situated to provide technical assistance in applying absorption cooling to this area and welcomes inquiries from individuals preparing demonstration projects.

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GEOHERMAL ENERGY MARKETS ON THE ATLANTIC COASTAL PLAIN

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ABSTRACT

A Geothermal Energy Market Study (GEMS) has been performed in four selected areas on the Atlantic Coastal Plain. The GEMS efforts have fallen into two categories: market definition, wherein current requirements for thermal energy are assessed, and market penetration, wherein the economics are investigated and projections are made of the extent to which geothermal energy will be used in the defined markets. In the market definition phase, a survey and analysis of potential energy markets for low- to moderate-temperature (up to 250°F) geothermal resources has been completed for southeastern New Jersey, the Delmarva Peninsula, the Norfolk area of Virginia, and for eastern North Carolina. Data have been obtained and analyzed for space and water heating requirements in the residential, commercial and military sectors and for crop drying and space heating requirements in the agricultural sector. In addition, over five hundred companies in the four areas have been contacted for information on energy consumption, and about 175 of these companies have been identified as having process heat requirements that could be satisfied by potential geothermal resources. A final report of the results of the study will be published early in 1979. Current plans are for survey activities to be continued into potential resource areas of South Carolina and Georgia beginning in the spring of 1979.

INTRODUCTION

The Applied Physics Laboratory of The Johns Hopkins University (APL/JHU) has performed a Geothermal Energy Market Study (GEMS) for four areas on the Atlantic Coastal Plain that offer promise of potential geothermal resources. This work is part of a larger program being sponsored by the Department of Energy (DOE) to explore and assess potential geothermal resources on the Atlantic Coastal Plain, to identify potential markets for these low- to moderate-temperature hydrothermal

geothermal resources, and to encourage the early commercialization of these resources, especially where usage of substantial quantities of fossil fuels can be supplanted by geothermal energy.

The Applied Physics Laboratory has served as the Eastern Region Operations Research Contractor for DOE's Division of Geothermal Energy for the last three years. In this capacity APL has prepared several planning documents, one of which (Ref. 1) was a preliminary development scenario for the postulated geothermal resources on the Atlantic Coastal Plain. In order to more fully assess the potential markets in the resource areas, the Geothermal Energy Market Study was begun in early 1978 to 1) identify existing energy requirements for space and water heating and for industrial process heat at temperatures below 250°F in each of the resource areas identified by VPI&SU, 2) determine the technical feasibility of supplying these energy requirements with expected geothermal resources, 3) estimate the costs, and the economic viability, of supplying geothermal energy for these applications, and 4) estimate the penetration of geothermal energy into those energy markets that are technically and economically attractive. The first two efforts comprise a market definition study, in which data had to be collected from a variety of sources, including a detailed survey of over 500 industrial companies in the four resource areas. Analyses of these data and engineering studies of the compatibility of energy requirements with expected resources have been performed and selected results are given below. The latter two efforts above comprise a market penetration study and assistance in these efforts has been provided by the Center for Metropolitan Planning and Research (The Metro Center) of The Johns Hopkins University. Some of the results of these efforts will be presented in the next paper by R. Weissbrod and W. Barron. A final report will be published in the near future and will contain more complete discussions of

the results of the GEMS efforts.

To date, the four resource areas of southern New Jersey, the Delmarva Peninsula, the Norfolk area of Virginia and eastern North Carolina (see Figure 1) have been included in the GEMS work. Activities are planned to begin in the resource areas in South Carolina and Georgia in the spring of 1979. Once the market studies are complete in an area, the development of a resource-specific prospectus is begun. The purpose of the prospectus is to inform and aid participants and to facilitate the commercialization of geothermal resources. The prospectus identifies near-term and potential long-term users, outlines the necessary tasks required for resource development and applications engineering, lists legal, institutional, and environmental issues that must be resolved, and plans and schedules these activities for development in the resource area. The prospectus is prepared with the cooperation and consultation of many of the parties that would be involved. One such prospectus for the Delmarva Peninsula is nearly complete and will be described in more detail in another paper by F. C. Paddison.

MARKET DEFINITION

The largest requirements for thermal energy at temperatures below 250°F are in space and water heating for the residential and commercial sectors; however, due to the diffuse distribution of such requirements, expensive community distribution networks must be provided to satisfy many individual small loads. In addition, the seasonal and hourly variations of these loads place additional constraints on a community distribution system, all of which manifest themselves in higher costs for delivered energy. Thus, it is necessary to identify areas with high population densities so that distribution systems can be limited in size and cost.

Obtaining space and water heating data for the residential and commercial sectors on a local basis is not practical. Individual building loads can vary drastically, even

between identical buildings, since the occupants may have different schedules and activities. A survey to obtain such data, even if limited to very high density areas, would be prohibitively expensive and time consuming. However, useful data can be obtained on a more aggregated census tract or minor civil division level where a large number of buildings are included, since averages for space and water heating are fairly accurate when applied to larger populations. For these reasons, a model developed by J. Karkheck et. al. (Ref. 2) was selected for estimating the space and water heating loads.

Under this model space heating is given on a per capita basis as a function of the number of annual heating degree-days as well as by building type, i.e., single family or multi-family residences or commercial buildings. Water heating for both the residential and commercial sectors is estimated on an average per capita basis. Table 1 summarizes the parameters used.

Heating degree-day information was obtained from the National Climatic Center for selected cities and interpolated values were developed on a county basis. Census Bureau population and housing data were obtained and water and space heating demands were calculated. The results of these calculations were mapped as shown in Figures 2 - 5 to display the spatial distribution of these energy loads.

In the military sector, data on space and water heating for military installations were obtained from the DoD Defense Energy Information System (DEIS) I and II reports. Figure 6 shows the locations of the major military facilities in the four resource areas and the magnitude of their heat loads. Also included in Figure 6 is the heat load for the NASA facility at Wallops Island, Virginia, which is located on the Delmarva Peninsula.

The principal agricultural applications of interest are crop drying and

Table 1

Annual Space and Water Heating Requirements

<u>Space Heating</u>	
Single Family Residences	5640 Btu/Degree(F)-day/person
Multi-family Residences	3740 Btu/Degree(F)-day/person
Commercial Buildings	1000 Btu/Degree(F)-Day/person
<u>Water Heating</u>	
Residential	6.00x10 ⁶ Btu/person
Commercial	1.75x10 ⁶ Btu/person

space heating. Data have been obtained from the Bureau of the Census and the Department of Agriculture on crop-drying requirements. Of the four resource areas, North Carolina appears to have the greatest crop drying requirements (for tobacco), and the Delmarva Peninsula, one of the largest poultry-producing areas in the U.S., has the greatest requirements for space heating. Estimates of heat for crop drying in each resource area are given in Table 2. Nearly all crop drying is done at temperatures of less than 200°F; however, since crop drying is highly seasonal, it would be most practical to use crop drying as an off-peak use of a geothermal system that is dedicated to another use, such as space heating.

Table 2

Crop Drying Requirements

Resource Area	Btu per year
Southeast New Jersey	0.024×10^{12}
Delmarva Peninsula	0.450×10^{12}
Norfolk, Virginia	0.50×10^{12}
Eastern North Carolina	0.950×10^{12}

In areas of large poultry production, space heating of poultry houses appears to be a large potential market. For example, on the Delmarva Peninsula, poultry house capacity exceeds 82,000,000 chickens and production exceeds 380,000,000 chickens per year. Annual heating bills for the 6300 broiler houses exceed \$6,000,000 for well over one trillion (10^{12}) Btu. However, because of the wide distribution of poultry houses in rural areas, as shown in Fig. 7, only a fraction of this energy can be economically supplied by geothermal resources, i.e., where such resources co-exist with large concentrations of poultry houses. Again, it would probably be most economical to have this use tied into a dual-purpose district heating system.

Estimates for energy consumption for process heat and space and water heating in the industrial sector are usually obtained from the average energy consumption per employee for particular industries and the number of employees at each plant. This approach in the past has served to provide qualitative estimates for county totals; however, on a single plant basis, these estimates can be grossly inaccurate, e.g., a warehouse and a factory with equal numbers of employees will appear to have the same energy requirements, when in reality their energy consumption is markedly different. Therefore, to provide accurate estimates of energy demand, a detailed industrial survey was undertaken in each of the four areas.

Because the potential resources were expected not to exceed 250°F, not all of the two digit SIC (Standard Industrial Classification) industries were likely prospects for geothermal energy applications. Thus, an initial screening identified six industries that had significant process heat requirements at temperatures below 250°F. These included the foods and kindred products, textile, tobacco products, lumber and wood products, pulp and paper, and chemicals industries. As the survey progressed in the four areas, the largest and best suited industries were found to be the foods and lumber industries. Within the food industry, poultry processing, vegetable canning and crab processing are the largest heat-consuming activities. The first two often are comprised of large companies that could use nearly the entire thermal output of one or more geothermal wells and thus are attractive candidates for early commercialization of geothermal resources. On the other hand, the large number of crab processing plants in the areas are often small concerns that require steam at 250°F, are scattered in sparsely populated areas, and thus are not attractive candidates.

In total, over 500 companies have been contacted, of which 25 to 35% have energy requirements compatible with potential resources. In order to compare the industrial market with resource locations, the supplantable energy consumption and the location of each company can be represented graphically by a symbol showing that portion of a nominally sized geothermal well that the company would use. A nominal geothermal production well is defined as a well that produces 500 gpm of water whose temperature is reduced 50°F by extraction of thermal energy, thus producing about 10^{11} Btu per year. Figures 8 - 11 show these data for the four resource areas. About one-half of the industrial market shown in Figure 9 for Delmarva is related to the poultry industry, which is the largest single geothermally compatible industry in any of the four areas.

A summary of the magnitudes of potential markets in each of the four areas is given in Table 3.

Clearly the largest market areas overall are found in Norfolk, Virginia and New Jersey; however, the residential/commercial markets are the most difficult to serve in the short term. Likewise most agricultural markets are quite diffuse and probably are best served by incorporating them into dual purpose

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community systems. Military markets are the most attractive in the short term for several reasons: 1) they are "captive" markets, 2) they are large, high density consumers who would need a large number of geothermal wells to satisfy their energy demands, 3) they currently use hot water or steam distribution systems which may minimize conversion costs and time, and 4) they are under directives to reduce energy consumption and are exploring alternate energy sources. Furthermore, a definite commitment by the federal government in developing such resources on such a large scale would provide a great deal of confidence and encouragement in local resource areas for private concerns to become involved in a commercialization of geothermal resources. Unfortunately, there is a great deal of reluctance in some corners to explore this sector; therefore, the sector of the greatest short term potential for geothermal energy applications is the industrial sector, which was investigated in the most detail in this study. As Table 3 indicates, the Delmarva Peninsula has the largest industrial market, a majority of which is made up by the large poultry industry, which is extremely well suited to direct-use applications of geothermal energy. In addition, grain drying facilities are often co-located with processing plants, further increasing potential short term markets.

Figure 12 illustrates a typical system that might be used to deliver geothermal energy to either a community district heating system, or a large industrial user, or both. Hot geothermal brines are brought to the surface by the down-hole pump, stored temporarily in an accumulator to allow for load-leveling, passed through a heat exchanger to heat a fluid in the secondary loop, and then the cooled brine is reinjected either into the original aquifer or into a shallower, cooler aquifer. In the secondary loop, chemically-treated water is heated at the heat exchanger, and passed through a topping system, which provides higher temperatures to allow for peak load conditions or to match higher temperature applications. After the heated water has been piped to users for space, water or

process heating, the cooled water is returned to the well for reheating. An alternate approach might use pure water in an open secondary loop where the water is consumed or disposed of by the user.

Estimating costs of geothermal energy that is delivered by such systems can be a complex task because of the large number of variables and the uncertainty of resource characteristics. Thus, it quickly becomes apparent that computer models are essential to allow the bracketing of costs as a function of resource and market types and to permit studies of the sensitivity of cost to various parameters. APL and the Metro Center have developed such computer models and the results of these studies are presented in the next paper.

CONCLUSIONS

The Geothermal Energy Market Study has defined the potential markets for geothermal energy in each of four resource areas on the Atlantic Coastal Plain. Computer models have been developed to estimate the effects of various resource and market characteristics on the economic costs of geothermal energy. Efforts are in progress to develop methods to determine the market penetration potential for geothermal energy in each resource area. The GEMS results will be useful in justifying further DOE exploration efforts on the Atlantic Coastal Plain, in identifying those resource areas where sufficient markets exist to warrant further resource exploration and development, and in identifying and informing potential near-term users for geothermal energy.

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Table 3
Total energy demand by sector in each resource area (units of 10^{11} of Btu/yr).

	RESIDENTIAL AND COMMERCIAL	MILITARY	AGRICULTURE	INDUSTRIAL
S. E. NEW JERSEY	290	25	0.2	5.2
DELMARVA	125	8	14.5	14.8
NORFOLK AREA	280	97	0.5	8.3
E. NORTH CAROLINA	80	15	9.5	9.0

Fig. 1 The four resource areas surveyed in the geothermal energy market study.

Fig. 3 Residential and commercial space and water heating demand on the Delmarva Peninsula.

Fig. 2 Residential and commercial space and water heating demand in southeastern New Jersey.

Fig. 4 Residential and commercial space and water heating demand in the Norfolk area of Virginia.

Fig. 5 Residential and commercial space and water heating demand in eastern North Carolina.

Fig. 6 Military space and water heating demand in the four resource areas.

Fig. 7 Poultry house capacity by 5 mi x 5 mi grid areas for the Delmarva Peninsula. Based on data reported by 11 of the 13 companies. (Base map courtesy of the Delmarva Poultry Industry, Inc.).

Fig. 8 Industrial process heat demand below 250°F in southeastern New Jersey.

Fig. 9 Industrial process heat demand below 250°F on the Delmarva Peninsula.

Fig. 11 Industrial process heat demand below 250°F in eastern North Carolina.

Fig. 10 Industrial process heat below 250°F in the Norfolk area.

Fig. 12 Illustration of heating from a hydrothermal resource for community or industrial users.

COST ANALYSIS OF HYDROTHERMAL RESOURCE APPLICATIONS IN THE ATLANTIC COASTAL PLAIN

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INTRODUCTION

An economic analysis of the supply and demand conditions for unconventional energy resources must, because of circumstances, be somewhat unconventional itself. The lack of a statistical data base, the variable nature of the resource, and the lack of an established market require that any analysis be, at least initially, fundamental in addressing those factors which have a major impact on the per unit cost. At the outset of the discussion, it is essential to be cognizant of the extreme localness of any geothermal market; it is difficult to imagine the equivalent in the geothermal market of the oil spot price. In the same light, one must be sensitive to the fact that the delivered cost of low temperature geothermal energy may change several hundred percent on the basis of the spatial density of demand alone, while the delivered price of home heating oil is only slightly influenced by the concentration of customers in a local market area.

In general, the unit cost of low temperature hydrothermal resources is very sensitive to such resource conditions as bottomhole temperature and in-well pumping energy requirements, and such economic conditions as the spatial concentration of energy demand and the level of risk assessed by lending institutions and potential equity investors. In order to accommodate changing resource and economic conditions and to estimate locally specific average costs, the Center for Metropolitan Planning and Research of The Johns Hopkins University, through its work with the Johns Hopkins Applied Physics Laboratory, developed a computer simulation model for the study of low temperature hydrothermal resources and the costs of developing and using those resources. The cost estimates derived from the model give an indication of the potential competitiveness of low temperature hydro resources relative to the costs of traditional space heating and process heating fuels.

This paper describes the model briefly, and then presents some of the cost estimates under varying resource and economic conditions. The sensitivity of changing different input conditions is outlined.

MODEL DESCRIPTION

The Geothermal Resource Economic Evaluation

System (GREES) calculates average costs per million BTUs of delivered thermal energy to the residential, commercial, or industrial user. Computationally, the determination of average cost is straightforward; however, the length of the computation necessitates the use of the computer. The annual capital and operating cost of each component of the system from the well to the user's doorstep or plantgate are summed, and the total annual cost is then divided by the number of BTUs required annually by participants on the system.

The GREES model is currently being expanded to include calculation of cost and revenue streams over the economic life of the system (about 15 to 30 years) and to incorporate user-specified changes in resource and economic conditions during this period. It does not include internal optimization routines, and deals with data at a relatively high level of aggregation. For example, rather than calculating distribution costs based on optimal pipe sizes for each segment of the distribution system, GREES calculates these costs on the basis of a user-specified systemwide average cost per mile of an insulated dual pipe system installed in the ground. Considering the preliminary nature of much of the data on resource characteristics and economic conditions, the ability to assess a broad range of possible conditions had a higher priority than did refinements in the calculations for costing specific system components. Also, an optimization model containing more detail useful for actually designing a district heating system is available in GEOCITY. While GEOCITY can accept a range of resource and economic factors, the GREES model is somewhat more flexible and its relative simplicity allows ready modification of the model as better information becomes available.

The cost of each individual component depends on the quality of the resource, the design of the system, economic conditions (e.g., interest rates and amortization periods), and the technical and economic interrelationship among components. As examples, the well cost is simply taken as a function of depth. However, costs which are dependent on the number of households served are dependent on other components: the number of households on the system is determined by the temperature at which the fossil fuel peaking system begins supplying, the net thermal energy delivered across the central heat exchanger (which, in turn, is a function of

the wellhead and reinjection temperatures), and the type of housing unit. A change in one parameter may affect several component costs. Changing average drawdown on the well will affect pump costs and pumping energy requirements. A change in design temperature affects expenditures for in-well pumping energy, purchase of fossil fuel, the size of the peaking boilers, the length of the distribution system, and the level of energy sold annually.

The accuracy of our system estimates are to a large extent dependent on the component cost information, and, broadly speaking, there are two types of estimates used. The first are taken from closely related activities and modified by engineering considerations so as to provide estimates for our specific use; oil drilling costs are used as a basis for well costs and heat exchanger data from other energy research are used as a basis for our main heat exchanger costs. The second source is in the fields of direct utilization and district heating systems where specific cost estimates appeared generally applicable. In some cases, information was available from both sources, and that judged to be the most reliable was incorporated into the model, although all estimates are reviewed and modified as new information becomes available.

In many cases, the input values may vary considerably. Where substantial uncertainty exists about the relevant input values, such as in the average cost of the distribution system of a given length, or where conditions are likely to vary from site to site, as in average drawdown in the well due to pumping, these values are user-specified inputs. If the user does not input a value for a specified parameter, its default value, usually chosen from the middle range of likely values, is automatically implemented. Since the model was originally designed for the evaluation of hydrothermal resources on the Atlantic Coastal Plain, the default values reflect expected conditions in this region. For example, the default "scenario" may be described as an area of townhouses in Salisbury, Maryland, of which 80 percent of the households in the service area are hooked up to a district heating system supplied by a single or multiple well system; all space heating requirements down to 36° F are served exclusively by geothermal energy, and additional energy requirements for colder temperatures (down to -5° F) are served by a fossil fuel peaking system which raises the temperature of the circulating water; the resource is tapped by a 5,500 foot production well which experiences an average drawdown of 50 percent (2,750 feet) during the heating season as the water is pumped to the surface at a maximum flow rate of 500 gallons per minute; the water temperature at the wellhead is 160° F; the water is reinjected to a separate aquifer lying at a depth of 2,500 feet, and hydrostatic pressure alone is sufficient to dispose of the water; the economic conditions include a 12 percent charge on borrowed funds, with the system capital components amortized individually over their expected lives; and the distribution system average cost is \$250,000 per mile. The parameter values which may be changed by the user are listed in Table 1, along with their default values.

Table 1. User-specified parameters and default values

Area under consideration	Salisbury, Md.
Wellhead water temperature	160°F
Depth of production well	5,500 ft.
Depth of reinjection well	2,500 ft.
Average drawdown in the well	50%
Reinjection temperature	85°F
Housing type	Townhouses
Market saturation level	80%
System design temperature	36°F
Minimum ambient temperature	-5°F
Distribution system cost per mile	\$250,000
Capital equipment lifetime	Years
wells	20
distribution system	30
central heat exchanger	10
in-well pumps	10
hookup equipment	30
peaking boiler	20
Interest rate	12%
Cost of purchased electricity	4¢/kwh
Cost of fossil fuel	\$4.50/10 ⁶ BTUs
Boiler cost	\$1,500/10 ³ BTU capacity

The relatively large number of values which the user may change offers the opportunity to conduct extensive sensitivity tests of specific resource and economic conditions as well as potential tradeoffs. The option of varying the design temperature permits analysis of changes in the size of the system and thus calculation of marginal costs.

MODEL RESULTS

The results of the model indicate that the key factors for the economic viability of low-temperature hydrothermal resources are (1) the combined impact of wellhead temperature and the level of pumping energy required to maintain a given flow rate; (2) the concentration of energy demand above a certain critical level; and (3) the length of the payback period and the interest rate on borrowed funds, i.e., the capital recovery factor.

The results of the model indicated an important potential tradeoff between wellhead temperature and the level of drawdown in the well. The hottest resource may not be the most attractive, if the aquifer has low permeability, less saturated thickness, or other features which result in high levels of pumping energy required to maintain the desired flow rate at the wellhead. As an example, the average cost of energy from a 4,000 foot well with a 150° F wellhead temperature and an average drawdown of 10 percent is less than the cost of energy from a 170° F resource with a drawdown of 50 percent, all other factors being equal. These results from the model are confirmed by the experience of the French in the Paris Basin. In exploration and reservoir assessment, the French are more concerned with potential flow rates than with finding the highest temperatures (Olivet et al., 1976). Drawdown being equal, of course, higher temperatures are preferable. The implication is

that, while "depth to the basement" is an important factor in resource assessment, this feature must be weighed against other geologic considerations.

For residential use, the concentration of housing units of a density at least that of detached single family homes on comparatively small lots (approximately 50 feet by 90 feet) and a market share of more than 60 percent of such homes is required for economic viability (Lind, 1978; Weissbrod and Barron, 1978). If the system can sign up at least half of the homes in neighborhoods of "single family dense" homes, townhouses, or apartments, the district heating system is potentially competitive. For market saturation levels above about 60 percent, reductions in average cost are more modest, but still important.

Another factor which is very important in determining average cost is the interest rate charged on borrowed funds and the length of the repayment period. For example, under default conditions, a 12 percent interest rate and a 20-year repayment period result in average costs of \$5.70, while an 18 percent interest rate and a 10-year repayment period result in an average cost of \$8.40 per million BTUs. Both interest rate and length of the repayment period set by commercial lenders will be greatly influenced by the level of risk associated with the exploitation of hydrothermal energy at a particular site. The higher the level of uncertainty in regard to the long-term reliability of the resource and in regard to the competitiveness of the delivered energy, the higher the interest rate and the shorter the repayment period are likely to be.

The use of hydrothermal fluids for process heating in industrial or agricultural applications presents the opportunity for considerable cost savings due to the concentration of demand. Well-head costs are often less than one-third of the total cost of delivered energy through a district heating system. Thus, if the thermal energy can be used near the well by one or a few users, this

energy can be sold at much lower prices. While the cost of oil or gas is likely to be somewhat less for industrial users than for residential customers, cost savings are much less than they may be in the case of geothermal. Thus, process heating applications of hydrothermal energy may be competitive in areas where the space heating applications are not.

Process heating also offers the potential for greater utilization of the resource where the plant operates on a year-round basis or where several users have complementary demand schedules. The integration of interruptible process heating sales and sales to a community heating system may also provide for much higher utilization of the resource and hence lower average costs.

In the analysis of the hydrothermal resources on the Eastern Coastal Plain, the GREES model was used to estimate the cost of delivered energy under the range of conditions considered likely. Table 2 shows the results of some of the model runs made for the major cities in each of the initial study regions. Differences in climate between Atlantic City, N.J., and Norfolk, Va., result in a difference of about \$1.50 per million BTUs under base-case conditions. Other factors being equal, colder climates offer the opportunity for greater utilization of the resource and hence lower average costs.

Recent projections of the price of home heating oil indicate the likelihood of continued rises in the real dollar value of this fuel; that is, its prices will rise over and above prices in general. One set of projections made by the Energy Information Administration of the Department of Energy, and another by Brookhaven National Laboratory, show the real price for distillate fuel oil rising about 3 percent per year through 1990. Taking a retail price of \$4.50 per million BTUs for heating oil in 1978, by 1990, the price would be about \$6.50 in 1978 dollar values (Weissbrod and Barron, 1978). Assuming a home furnace is about 70 percent efficient and a hydrothermal-based community heating

Table 2. Results of Model Runs for Atlantic City, Salisbury, and Norfolk

Area	Well Depth	Wellhead Temperature	Drawdown	Housing Type	Market Saturation	Average Cost/10 BTUs
Atlantic City	5,500	160°F	50%	Row	80%	\$ 5.00
Salisbury	"	"	"	"	"	5.70
Norfolk	"	"	"	"	"	6.40
Atlantic City	4,000	130°F	50%	Garden	100%	\$ 4.70
Salisbury	"	"	"	"	"	5.30
Norfolk	"	"	"	"	"	5.90
Atlantic City	4,000	130°F	50%	Detached Dense	40%	\$ 7.50
Salisbury	"	"	"	"	"	8.80
Norfolk	"	"	"	"	"	10.00
Atlantic City	4,000	130°F	10%	Row	40%	\$ 4.80
Salisbury	"	"	"	"	"	5.70
Norfolk	"	"	"	"	"	6.60

system is about 90 percent efficient, the hydrothermal energy would need to be delivered at a price of about \$8.40 per million BTUs to meet the price of oil in 1990.

Natural gas prices will rise even more rapidly, but, starting from low controlled price levels, they will likely remain less expensive than oil. Electric space heating costs should rise much more slowly, but will remain much more expensive than oil or gas. The Energy Information Administration projects electricity prices in 1990 to be only slightly more expensive than current prices, while Brookhaven projects the price level to rise somewhat more rapidly. The cost of electric space heating is projected to be in the range of from \$12 to \$15 per million BTUs by 1990, again in 1978 dollar values (Weissbrod and Barron, 1978). It is against this set of projections for oil, gas, and electricity that price projections for hydrothermal energy should be compared.

The analysis based on the GREES model was supplemented by the study of space heating requirements for the major city in each of the three initial study areas. Studies of space heating requirements for housing units of various types and data from the 1970 Census of Housing were used to develop residential space heating requirements at the census tract level. Estimates of commercial requirements based on land area within each tract which is zoned commercial and studies of demand based on the numbers of employees were then developed and added to those for residential estimates. Finally, hot water requirements based on population were added. A computer mapping program used these data to develop maps of thermal energy requirements for each city. Figure 1 shows the map developed for Atlantic City. The map shows the peak requirements to be near the center of downtown Atlantic City, and then to fall slowly as one moves down the island. Much lower requirements for the mainland communities are evident on the left hand portion of the map. Maps such as these are useful in suggesting the layout of a distribution system and

Figure 1. Thermal energy requirements for Atlantic City, New Jersey

thus in the costs of supplying a particular area with a community heating system. The Atlantic City area map, for example, suggests that, until much greater development occurs on the mainland areas adjacent to Atlantic City, such areas would probably not be included in a community heating system.

Current information suggests that low temperature hydrothermal energy resources can be competitive under moderately favorable conditions. However, before these resources can be widely utilized, considerably more information will be required on the reliability of the resources under sustained exploitation, and on the factors which affect consumer decisions in regard to selection of heating systems. Refined versions of current models for economic evaluation can then be used for more accurate and detailed estimates of the competitiveness of particular resources. It must be remembered that the economic viability of low temperature hydrothermal resources will always be highly site specific. The evaluation of a resource at a particular site will require considerable amounts of local information even after improved modeling of "typical resources" is available.

IMPLICATIONS FOR MARKET PENETRATION

The cost analysis which has been completed to date is a necessary step in addressing what the market potential or market share of hydrothermal may ultimately be. For a traditional energy form, the usual approach would involve manipulating the data base and drawing conclusions based on the strength of the statistical tests. In this case, there is no data base with which to calculate meaningful market parameters. An alternate approach, which we attempted, is to take comparable situations from other fuels and attempt to extrapolate to a hydrothermal case. The results using this approach tended to negate the special characteristics of hydrothermal energy and to incorporate the characteristics of the other energy form, and this, we felt, would lead to false conclusions. The approach that we are currently experimenting with is to examine the attributes of the space heating market itself, and to draw some conclusions based on optimistic, neutral, and pessimistic resource and economic conditions. For instance, the residential space heating market, in any one year, may consist of new construction and retrofit based on current fuel boiler fatigue. We assume, based on local building conditions and the price attractiveness of hydrothermal relative to other fuels, that hydrothermal will capture a certain portion of this market. This case is extended for a number of years and the market share or potential is obtained.

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A PROSPECTUS FOR GEOTHERMAL ENERGY - THE ATLANTIC COASTAL PLAIN

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ABSTRACT

The Department of Energy is targeting and evaluating the not-so-obvious geothermal resource areas under the Atlantic Coastal Plain. These potential hydrothermal resources turn out to be areas of reasonable size from the State of New Jersey to the State of Georgia. The resources are evidenced by higher-than-normal thermal gradients; however, the sedimentary sequences are of limited depth, so that the expected temperatures at the bottom of the sedimentary pile are such that use will be limited to direct (non-electric) applications. A survey of the northern half of the Coastal Plain established the potential market for moderate temperature geothermal energy. This effort is being followed in each resource area by the preparation of a "how-to-apply" prospectus or scenario. Since each state is unique in its resource characteristics, its laws, regulations, environmental concerns and, further states differ in their method of planning for accommodating new energy forms and economic development of state and counties. The prospectus is accordingly prepared either by, or with the assistance of, local agencies. The prospectus outlines the applications engineering, and economic considerations and a road map through the institutional, environmental and legal requirements for his particular use. Finally, the prospectus identifies those issues which are yet to be resolved, either by the federal, state or local government. There results, therefore, a planning document with enough detail so that a potentially interested user (entrepreneur) can assess the resource's potential to his needs.

DISCUSSION

The Department of Energy has had prepared, through its Regional Operations Research Contractors or their equivalent, scenarios of known or suspected geothermal resource areas. These scenarios quantified the energy potential of the resource area and estimated the rate of development of the resource in respect to the energy

market in that area. These scenarios in aggregate were intended, first, to provide a quantitative measure of the geothermal potential of regional areas or the entire country, and, second, to identify early in the process potential problems in the realization of the potential. The reference is an example of such a scenario for the entire Eastern Coastal Plain.

At the time the resource definition program progresses to the point where the resource extent, temperature and hydrology are apparent, then a different need arises. This is to initiate the process of education as to what the resource is, its application, its economics and the laws and regulations required to provide for an orderly process of development.

The Department of Energy is dedicated to assisting in the development of and commercialization of geothermal resources by local interests. However, in the case of the Eastern United States, with little or no experience with moderate temperature hydrothermal geothermal resources, the Department of Energy commissioned the Eastern Regional Operations Research Contractor to aid in expediting the process of commercialization. This is being done by first conducting a survey in detail of the potential market for geothermal energy over each of the resource areas. The results of such a survey are presented elsewhere in these Proceedings. The survey was carried out initially in the Delmarva area of the State of Delaware, the Eastern Shore of Maryland and the Eastern Shore of Virginia, see Figure 1, and has been followed by a prospectus for geothermal energy development. A prospectus for each of the other coastal states, i.e., New Jersey, Tidewater Virginia, North Carolina, South Carolina and Georgia, are planned to follow.

The prospectus for the development of geothermal energy on the Delmarva Peninsula which is in an advanced stage of preparation, not only discusses in a

narrative form the description of the resource and its potential energy content, but also through workshops, discussion with local planning groups and the market survey, present and future uses and users are outlined in as much detail as possible at this time. The Reservoir Engineering Program status and or data, as appropriate, are given together with the mechanics for reservoir management and plans of the state for implementation. Applications engineering, if not covered in specific applications, is covered separately, as is, finally, an estimate of the cost of geothermal water at each resource area in the state. The range of expected costs for the industrial user of geothermal energy for process heat, as well for the multi-residence space heating are included. The requirements in each state and locality for a prospective developer in terms of legal, environmental and institutions are set forth together with an estimate of the time required for each and the order in which they must occur. A list of action items, i.e., issues, for either federal, state and/or local government is presented. Finally, state and federal, technical, planning and financial assistance programs applicable to that area are listed.

CONCLUDING REMARKS

A year ago there was little thought to geothermal energy in the east. Through the success of the Virginia Polytechnic Institute and State University's geologic program and the stimulus of local interest through inquiry about the potential of geothermal energy on the Atlantic Coastal Plain there is now considerable interest and action. A Geothermal Act was signed into law in Maryland in July 1978, and Delaware and Virginia are working with the National Conference of State Legislatures in considering geothermal legislation. In response to the recent Department of Energy's Program Research and Development Announcement (PRDA), eight proposals from a total of four Eastern Coastal States were submitted.

The prospectus and, to a great extent, the mechanics of its writing is an effective planning tool to aid and expedite the development of a specific geothermal resource. The prospectus cannot, however, ensure that all the regulations, etc., called out as required will be emplaced and worked out when the first applicant starts through the process. Accordingly, the prospectus will require revision until the process is well understood and guidance is no longer required.

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