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THE PROSPECT FOR GEOTHERMAL POWER

by

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ABSTRACT

The relatively small fraction of the earth's crust which is now accessible to man by drilling from the surface contains a supply of thermal energy potentially capable of satisfying the world's total energy needs for many thousands of years. At present, however, only that small fraction of this vast resource is considered useful which exists near the earth's surface in the convenient forms of natural steam or superheated water of relatively low salinity.

Research and development are now in progress by both industry and government to learn to use economically the energy contained in the more saline superheated waters, the lower temperature but less highly mineralized natural waters, the combination of heat and temperature and dissolved natural gas contained in geopressured water, and the abundant heat contained in dry hot rock. There is every reason to suppose that the problems associated with utilization of these energy sources will eventually be overcome. The problems are, however, sufficiently formidable to make it unlikely that even ten years from now, more than 1 to 2% of the United States' requirement for electrical power will be satisfied by energy from geothermal sources. With continued technical and commercial development, this fraction should increase to 15 to 20% of the Nation's electrical needs by the year 2000, and should be supplemented by a supply of relatively low-grade geothermal heat sufficient to supply a somewhat larger fraction of the Nation's nonelectrical energy requirement.

INTRODUCTION

Geothermal energy is the natural heat in the earth's interior. Most of it apparently originates in the slow decay of naturally occurring unstable isotopes of such elements as uranium and potassium. Because rocks in general are poor thermal conductors, most of this heat is retained for a very long time in the core, mantle, and deep crust of the earth. The rest is conducted only very slowly to the earth's surface, which has two principal results. First, the normal heat flux through the earth's surface is very low, averaging only about 1.5 $\mu cal/cm^2$ - sec. Second, the normal temperature gradient in the earth's crust (the "geothermal gradient") is relatively high, on the average about 25°C/km.

With existing rotary drilling equipment and techniques, holes can now be drilled into the earth more or less routinely to depths of the order of 6 km. Assuming a mean surface temperature of 10°C and a "normal" geothermal gradient the temperature at the bottom of a 6-km hole should be about 160°C -- and such temperatures are routinely encountered in deep oil and gas wells. This is certainly sufficient for many nonelectrical uses such as space-heating and low-temperature chemical processing. However, with existing technology, it is too low for the economical generation of electricity.

When improvements in drilling technology permit deeper holes to be made at reasonable cost; when lower-temperature power cycles make lower-grade heat economical for generating electricity; and when increasing scarcity and price have caused the competitive position of fossil and nuclear fuels to deteriorate further, then geothermal energy may become attractive for power production even where the geothermal gradient is only normal. In the meantime, however, except for nonelectrical applications, the earth's heat will in general be useful only where the geothermal gradient is relatively high, so that higher than normal rock temperatures exist at economically drillable depths. There are, fortunately, many places in the world where this is the case. They are usually associated either with convective transfer of heat in a hydrothermal reservoir, or with relatively recent vulcanism, or both.

HYDROTHERMAL RESERVOIRS

Many of the sedimentary rocks in the earth's crust are sufficiently permeable so that water from rain or melting snow can move slowly through them over long distances, and this is also true of some naturally porous or highly fractured metamorphic, volcanic, and igneous rocks. Carried downward by gravity, ground water migrating through such rock reaches the upper surfaces of less permeable rocks, extracts heat from them, and rises buoyantly to assist conductive processes in transporting heat upward toward the earth's surface and downstream along the aquifer which carries the main flow of the water. Over thousands or millions of years, an equilibrium situation is attained in which, locally, the geothermal gradient may be either somewhat greater or somewhat less than normal, according to details of the heat transport by the horizontal and vertical flow of water. However, if both the upward flow of water toward the earth's surface and its more or less horizontal flow along the aquifer are impeded by the presence of a less-permeable formation or a fault structure, or by precipitation of minerals from the water itself, then a hydrothermal reservoir is created in which the fluid is trapped except for convective circulation of the heated fluid through the porous rock constituting the reservoir.

The details of heat and fluid flow within a hydrothermal reservoir evidently must vary with its temperature and pressure, its horizontal and vertical extent, the nature and degree of interconnectedness of its porosity, and the rates at which fluid escapes from it and is resupplied to it. In general, however, the main body of a hydrothermal reservoir is a nearly isothermal region within which the geothermal fluid circulates more or less freely, extracting heat continuously from the hot rock beneath it and depositing this heat in the impermeable rock above it. There is usually evidence at the earth's surface of the presence of such an underground reservoir in the form of steam vents, geysers, or hot springs, and also in the relatively high geothermal gradient maintained in the overlying rock by the transport of heat upward by the reservoir fluid and its deposition in the impermeable rock above the reservoir.

Dry Steam Reservoirs. When the temperature in a hydrothermal reservoir is high and the pressure relatively low, then the fluid contained in it may be superheated ("dry") steam. This steam can be extracted through wells drilled downward into the permeable reservoir, piped to a turbine, and used directly to generate electricity. There are, of course, some difficulties in developing and exploiting even a dry steam field, resulting particularly from drilling problems, abrasive particles carried by the steam, noncondensible gases (particularly CO_2 and H_2S) contained in it, silica and certain unpleasant volatile substances (such as boron and arsenic compounds) transported by it, and the high noise level created by escaping steam. However, these problems can be and are being controlled, and natural dry steam is an attractive and economical energy source. The two largest geothermal power developments in the world -- Larderello, Italy and The Geysers, in California -- are based on the use of natural dry steam.

Unfortunately, the hydrologic situation which creates a dry steam field is evidently rare. The Geysers area is the only one in the United States known to contain enough natural steam to merit commercial development. It now supports a generating capacity of about 400 MW electrical. By 1985 this should increase to about 1500 MW, and when the field is fully developed it may continuously provide as much as 3000 MW electrical.

Dry steam is a sufficiently attractive and economical energy source so that there is now active exploration by many organizations and individuals for new steam fields. Undoubtedly some will be discovered, but it appears unlikely that as many as five more of them will be found in the United States or that, individually, any of them will be as productive as is The Geysers field. It is therefore probably optimistic to predict that, by 1985, geothermal steam will support a generating capacity of 2000 MW, supplying about 0.2% of the Nation's electrical power; and that by the year 2000 this will have increased to 14,000 MW, representing about 0.5% of the Country's projected electrical requirement.

Superheated Water. As might be supposed from the rather common occurrence of hot springs, "liquid-dominated" hydrothermal reservoirs are very much more common than are "vapor-dominated" ones; that is, naturally occurring hot water is much more common than is steam. Where the geothermal water is sufficiently superheated it can be permitted to flash in part to steam, and the steam then used to drive turbines and generate electricity. This is being done on a relatively large scale at Wairakei, New Zealand, and Cerro Prieto, Mexico, and on a smaller scale in several other places in the world. It has not so far been attempted commercially in the United States, principally because of the chemical problems associated with the use of geothermal water.

Hot water under high pressure is an extremely good solvent for many natural minerals, and the long contact period provided by convective circulation within a hydrothermal reservoir usually assures that the water is essentially saturated in most of the minerals which it has encountered. Particularly when the solubilities of these minerals are high -- as is true, for example, of the chlorides and carbonates contained in the "evaporates" of the Imperial Valley of California -- the content of dissolved solids in the geothermal water may be very high. Thus, the natural hot brines of the Imperial Valley often contain as much as 25 to 30% by weight of dissolved solids. As a result they are extremely corrosive, and precipitate large amounts of minerals when they are cooled, reduced in pressure, or flashed to steam. Further, the brine left from the flashing operation is still more concentrated in these minerals (which in general are relatively common ones that do not justify recovery treatments) and represent a difficult disposal problem.

As the temperature of geothermal water decreases, so in general do its mineral content, the chemical problems associated with its use, and the efficiency of any power cycle used to generate electricity from it. The choice then, in attempting to use natural hot water as an energy source for a power plant is between very serious corrosion and scaling problems and very low generating efficiencies.

The energy resource represented by geothermal water in the United States is tremendous, and both industry and government are seriously attacking the chemical and mechanical problems involved in exploiting it economically and efficiently. Good progress is being made, and it is probably safe to predict that by 1985 at least 5000 MW electrical will be generated from this source, representing about 0.5% of the Nation's electrical needs, and that by 2000 this will have increased to 80,000 MW, or about 2.7% of our projected requirement for electrical power. Particularly when reservoir temperatures are relatively low, it is rational and efficient to use this geothermal heat directly for such things as space-heating, air-conditioning, agriculture, and chemical processing, thus conserving fossil and nuclear fuels for more demanding applications. It is reasonable to predict that these nonelectrical uses of natural hot water will grow at least as rapidly as does their electrical use, and eventually will represent at least an equal contribution to the Nation's total energy requirement.

Geopressured Reservoirs. Particularly along the Gulf Coast of the United States, very large regions are underlain by "geopressured" reservoirs containing relatively pure but quite low-temperature geothermal water under high pressure, usually with a significant content of dissolved natural gas. Together, the thermal energy in the water, the mechanical energy available from its natural pressurization, and the calorific value of its dissolved gas, represent a tremendous energy supply. The economics of extracting and using this energy appear to depend very strongly on the gas content of the water, and are quite uncertain. However, both industry and government are working actively to develop methods of simultaneously utilizing the heat and pressure of the water and efficiently separating the gas from it. These problems are difficulty but they appear to be straightforward, and the incentive of increasing costs and scarcity of energy from other sources should lead to their solution within a very few years. By 1985, the author expects geopressured reservoirs to produce energy at a rate equivalent to about 4000 MW electrical, representing approximately 0.4% of the Nation's needs. By the year 2000 this should increase to perhaps 100,000 MW electrical, or between 3 and 4% of the Country's projected electrical power requirement.

Dry Hot Rock. By far the largest reservoir of accessible geothermal energy is the heat content of crustal rocks which are at usefully high temperatures but do not produce significant amounts of either steam or hot water. These "dry" hot rocks range in temperature from essentially atmospheric to above 1000°C (in molten lavas and magmas). Serious attempts to develop economical methods of extracting energy from dry hot rock are just beginning, and are directed initially at the recovery of heat from rock of relatively low permeability at intermediate temperatures--say 200° to 300°C. The method proposed is to drill two holes downward into the hot rock, connect them at depth through a very large crack system produced by hydraulic fracturing, connect them at the surface through the primary heat exchanger of an energy utilization system, and flow pressurized water around this loop. It is believed that the pressure difference created by the density difference between cool water flowing down one hole and hot water rising in the other will maintain circulation of the pressurized water without pumping. Further, it is hoped that thermal contraction of the rock near the point at which cool water enters it will produce cracks that extend the circulation pattern outward and downward into previously uncooled rock, greatly increasing the useful life of the system.

There are many uncertainties concerning the creation and operation of such a system, concerned particularly with impedance to fluid flow through the hydraulic fracture, stability of very large cracks held open by pressurized water, and the corrosion and scaling problems associated with dissolution of minerals at depth and their reprecipitation higher in the system. However, many options exist to overcome these problems and those associated with geologic environments other than essentially impermeable rock. These include, for example, the use of particulate proppants to hold the crack open if this cannot be done simply with fluid pressure, the production of steam instead of hot water, the use of a down-hole pump in the hot leg of the system to reduce system pressure elsewhere, and the drilling of an array of injection and recovery holes to permit large-scale water-flooding of hot formations having relatively high permeability.

The problems of man-made geothermal-energy systems are large engineering problems, and they appear to have straightforward engineering solutions. It is the author's opinion that, at least for relatively impermeable rocks at intermediate temperatures and depths, these problems will have been solved within a few years and that by 1985 systems of this type will support a generating capacity of the order of 2000 MW, or about 0.2% of the Nation's total requirement. Because of the flexibility possible in locating man-made systems, their development should be rapid--once feasibility has been convincingly demonstrated--and by the year 2000 they should provide about 200,000 MW electrical (6 to 7% of the projected United States requirement for electrical power). They should also by then provide very large amounts of relatively low-grade heat for nonelectrical uses, conserving fossil and nuclear fuels for other applications which geothermal heat cannot serve efficiently.

SUMMARY

It is unlikely that, by the year 1985, geothermal energy systems of all types will produce more than 1 to 2% of the electrical power required by the United States. However, by the year 2000 this should increase to perhaps 15 to 20%, and it should continue to expand thereafter. These proportions may be larger if reasonably efficient lower-temperature power cycles are developed and demonstrated soon. Particularly if effective man-made systems can be created at reasonable cost in relatively permeable formations, the production of geothermal heat for nonelectrical purposes is likely eventually to represent an even greater contribution to the Nation's total energy requirement than will its use for generating electricity.