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This steam was produced when superheated water was vented to the atmosphere from the production well (EE-2) of the

Engineering (Phase II) Hot Dry Rock Geothermal Energy System at Fenton Hill, New Mexico, U.S.A.

The hot dry rock geothermal energy program

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Almost everyone is aware that the Earth's interior is extremely hot, and we can see evidence of this in the form of hot springs, geysers, steam vents, or molten lava from erupting volcanoes. But few of us have considered that the Earth's internal heat is one of our largest supplies of energy. In fact, almost anywhere it is already possible to drill holes deep enough to reach temperatures sufficiently high to

heat homes, generate electricity, or serve many other human needs.

This heat—geothermal energy—is produced mostly by disintegration of naturally occurring unstable forms of uranium, thorium, and potassium. Because the rocks, soils, and gravels that make up the Earth's outer crust conduct heat poorly, much of that heat remains stored in solid rock at considerable depth. In most places, a hole drilled

from the surface passes first through layers of sediments and fractured rock that are kept cool as groundwater circulates through them. Then, below the level of active groundwater circulation, temperature begins to increase quite rapidly—as typically occurs in any insulating material between a hot body and its cool surroundings. This temperature increase and the increasing pressure of the material above it cause

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the rock to become progressively drier as well as hotter—the typical “hot dry rock” (HDR) situation. On a worldwide average, the rate of temperature increase with depth (the “geothermal gradient”) is about 17°F per thousand feet (30°C per kilometer). However, it is often much greater than that where the crust is thin or has been disturbed by volcanism or by large-scale earth movements.

These movements—which cause earthquakes—usually involve the sliding of one part of the crust past another part along a large fracture surface called a “fault,” accompanied by considerable fracturing of the rock on both sides of the fault. Where these fractures have not been sealed by heat, pressure, and mineral deposition, they may permit surface water to seep down far enough to reach hot rock. The heated water expands and, rising buoyantly, it may reach the Earth’s surface as hot water or steam. Heated water may also remain trapped in porous formations or open fractures, forming “hydrothermal reservoirs” of hot water or (very rarely, where the pressure is low enough to permit boiling) of steam. These reservoirs can be useful and economical sources of thermal energy, but unfortunately they are rare. At depths where usefully high temperatures exist, the usual geologic environment is hot dry rock. In the HDR geothermal energy program, we are learning to imitate nature by creating and controlling artificial hydrothermal reservoirs in that kind of rock.

Magnitude of the HDR energy resource

Figure 1 is a preliminary map of geothermal gradients in the 48 adjacent United States showing hot spots where the measurements do not appear to have been affected by groundwater movement, the presence of hydrothermal reservoirs, or recent volcanism. This map indicates that areas with above-average gradients cover not less

Fig. 1. Map of conductive geothermal gradients in the United States.

than 20% of the land area of those states. (The percentage is probably even greater in Hawaii, and it may also be in Alaska.)

Estimates of the amount of potentially useful heat that this represents vary widely, depending on the assumptions made concerning temperatures required, practical drilling depths, the nature of the subterranean geology, and the effectiveness of the recovery method. One estimate by the U.S. Geological Survey in 1979 is that, to a depth of 23,000 feet (7 kilometers) in hot dry rock regions beneath the United States, there are about 4.7 quadrillion megawatt-hours of heat at temperatures above the mean annual surface temperature. In other units, this is 16 million quads (1 quad equals 1 quadrillion Btu), equivalent in energy to about 2800 trillion barrels of oil. That is approximately 100,000 times the energy content of the proved United States reserves of crude oil (estimated by the U.S. Department of Energy in 1983 to be 27,735 million barrels).

However, much of the heat at shallow depths is at temperatures too

low to be worth recovering. Therefore, a much more conservative estimate by the National Research Council in 1979 is that, to a depth of 19,700 feet (6 kilometers), there are more than 105,000 quads at temperatures between 175°F and 360°F (80°C to 180°C), a temperature range suitable for space heating and many other direct uses, and 222,000 quads at temperatures above 360°F, which is suitable for generating electricity. The total, 327,000 quads, is equivalent to 56 trillion barrels of oil and represents about 4000 times the total amount of energy used in the United States in one year.

The supply of useful energy represented by hot dry rock at accessible depths in the Earth’s crust is so great that economical recovery of even a small fraction of it would contribute significantly to the world’s energy future.

Extracting heat from the rock

In 1970, a Los Alamos group proposed that heat could be recovered from low-permeability hot rock in the

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Earth's crust by drilling two deep holes, connecting them at depth through large cracks produced by fluid pressure in one of the holes ("hydraulic fracturing"), and then circulating water through the cracks under sufficient pressure to prevent boiling. This is a "recirculating pressurized-water heat-extraction loop," similar in principle to the cooling system of an automobile engine but operating at much higher temperatures and pressures. Because it would be completely contained, the system was expected to be conservative of water and to have little or no environmental effect.

The first such system (Fig. 2) was completed in 1977 at Fenton Hill, New Mexico, about 20 air miles west of Los Alamos. It was operated successfully for several months in 1977 and 1978 and was then enlarged by additional hydraulic fracturing. The longest continuous run of the enlarged system lasted nine months and produced

pressurized hot water at about 275°F (135°C) and heat at rates up to 17 million Btu per hour (5 million thermal watts). Some of the heat was used to operate a small (60 kilowatt) experimental power plant, generating electricity that was used at the site. Quality of the recirculated water remained good, water loss decreased with time, and there were no detectable environmental effects from system operation. Because the rock around it contracted as heat was extracted from it, both the volume of the fracture system and the surface area available for heat extraction increased with operating time. In a populated area, this Phase I system could have heated several hundred homes for many years. It was a convincing demonstration of the technical feasibility of constructing and operating a hydraulically fractured HDR system in low-permeability crustal rock and using thermal energy from it beneficially. However, the system did not produce heat at a high enough temperature or rate to support an efficient commercial electrical power plant. To approach those more demanding requirements, a deeper and hotter Phase II system has since been constructed at the same site.

The Engineering (Phase II) system

The usual stress condition in the Earth is such that, at depths greater than a few thousand feet, hydraulic fractures are substantially planar and vertical and oriented in a specific compass direction. This is the behavior usually reported for hydraulic fractures made to increase fluid production from deep oil, gas, and water wells, and it was also the case in our Phase I system. Since we expected similar fracturing behavior in a deeper Phase II system, the new wells were drilled as shown in Fig. 3—to

provide space for a number of thermally isolated vertical fractures connecting them. However, when large hydraulic fractures were made at various depths in the two wells, they grew in three dimensions rather than in a single plane and were inclined rather than vertical; most important, they did not connect the wells. This unusual behavior is probably related to the presence of a cooling magma body beneath a large volcanic center, the Valles Caldera, located a few miles east of Fenton Hill.

When rock is fractured hydraulically, some of the energy involved is released as a sound wave—similar to the acoustic signal generated by a tiny earthquake. Using very sensitive geophones and seismometers, we can determine the source locations of the signals and then produce a three-dimensional map of the fractures we had created. Because our map showed that additional hydraulic fracturing would probably not connect the two wells, the upper well was directionally redrilled as shown in Fig. 4, through a region where a high concentration of source locations indicated that extensive fracturing had occurred. At depths around 12,000 feet, the redrilled well intersected several major fractures produced from the other well, providing good flow connections between them.

In preparation for a much longer flow test now scheduled to begin early in 1988, a one-month flow test of this Phase II heat-extraction loop was run during May and June 1986. A total of 10 million gallons of water at 70°F (20°C) was injected into an 800-foot-long uncased section of the redrilled well at depths around 12,000 feet, where the initial rock temperature was about 460°F (240°C). At a pumping pressure of 4000 psi (pounds per square inch), the injection rate was 285 gpm (gallons per minute). Rate of fluid production from the other well increased with time to 235 gpm—against a back pressure of

Fig. 2. The Research (Phase I) Hot Dry Rock Energy System at Fenton Hill, New Mexico.

Fig. 3. Drilling plan for the Phase II system.

500 psi, which we used to prevent boiling. Temperature of the produced water rose to 375°F (190°C), rate of heat production rose to 30 million Btu per hour—which could be converted to about 1500 to 2000 kilowatts of electrical power—and both were still increasing at the end of the test. Rate of water loss initially was very high, in part because of leakage through damaged casing in the production well, but it decreased with time to a final value of 26%. Much of this “loss” was water stored temporarily in fractures that were outside of the circulation paths, and a large fraction of it was recovered later when the system was vented.

Fig. 4. Trajectory of the redrilled well through source locations of acoustic signals indicating extensive fracturing. This view looks north along the narrow dimension of the fractured region.

Plans for the future

This was a very successful test of the world's first high-temperature HDR system. It demonstrated that such systems can be constructed and operated to produce superheated water at temperatures suitable for generating electricity. However, the economics of commercial power plants requires higher rates of heat production, reduced water loss, and a credible basis for

predicting useful lifetime of the heat source. Therefore, we currently plan to repair the production well, attempt to open the fractures to increase flow rate through them at moderate pumping pressures, reduce water loss, and then operate the system for a much longer time to demonstrate its reliability and longevity.

In the meantime, both commercial and governmental interest exists in HDR development in several promising areas across the United States, and we hope that cooperative arrangements for such developments can soon be made.

Support and cooperation

Throughout its history, the HDR Program has been sponsored principally by the U.S. Department of Energy and its predecessor agencies. However, hot dry rock is a worldwide energy resource, and there is strong international interest in its development and use. Under an International Energy Agency Agreement, agencies of the governments of West Germany and Japan have contributed both financial support and technical personnel to the Los Alamos project, and both now have excellent HDR projects in their own countries. Great Britain has an important complementary HDR program and exploratory projects are under way in several other countries. With this active international effort and the close cooperation maintained among its participants, HDR technology should soon be in a position to contribute significantly to the world's energy future.

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