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PROGRESS OF THE LASL DRY HOT ROCK GEOTHERMAL ENERGY PROJECT*

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Under sponsorship of the Division of Applied Technology of AEC, Los Alamos Scientific Laboratory is investigating the possibilities and problems of extracting energy from geothermal reservoirs which do not spontaneously yield useful amounts of steam or hot water. The system for accomplishing this which is being developed first is a pressurized-water circulation loop intended for use in relatively impermeable hot rock. It will consist of two holes connected through the hot rock by a very large hydraulic fracture and connected at the surface through the primary heat exchanger of an energy utilization system. Preliminary experiments in a hole 2576 ft (0.7852 km) deep, extending about 470 ft (143 m) into the Precambrian basement rock underlying the Jemez Plateau of north-central New Mexico, revealed no unexpected difficulties in drilling or hydraulically fracturing such rock at a temperature of approximately 100°C, and demonstrated a permeability low enough so that it appeared probable that pressurized water could be contained by the basement rock. Similar experiments are in progress in a second hole, now 6701 ft (2.043 km) deep, about 1.5 miles (2.4 km) south of the first one. Here the bottom-hole temperature is about 146°C, and again no unexpected difficulty was encountered in drilling or hydraulically fracturing the granitic basement rock. At least below about 4250 ft (1.295 km) the permeability of the basement rock is also very low at this location, and again the rock appears competent to contain a pressurized-water circulation system.

I. INTRODUCTION

Many areas are known in the United States and elsewhere in the world in which geothermal gradients are relatively high but the formations accessible by drilling from the earth's surface do not yield commercially useful amounts of natural steam or hot water. In the same sense that an oil or gas well is considered a "dry hole" if it does not produce enough oil or gas to pay out the cost

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of drilling, a geothermal well drilled into such a formation is considered a dry hole if it does not produce enough steam or superheated water to pay for the well. Similarly, the natural thermal reservoir into which such a well has been drilled can be described as a "dry geothermal reservoir" even if (as is usually the case) it is not completely devoid of moisture.

There are several reasons why, in this sense, a geothermal reservoir may be "dry." One is that, because of faulting or an overlying impermeable formation or simply an extremely arid climate, very little water ever reaches the hot rock. In this case a dry geothermal reservoir might, locally, be converted into a productive wet one by developing a water-flooding system: drilling one or an array of holes through which cool water would be injected and a second array through which heated water or steam could be recovered. A second possible reason for a geothermal reservoir to be dry is that the permeability of the rock composing it is too low to permit whatever fluid it contains to flow into a well at a usefully high rate. Here a stimulation technique such as acidizing or fracturing the rock either hydraulically or by use of explosive might make the reservoir economically productive. A third possibility is that the reservoir is deficient in both moisture and permeability, and it is with this possibility that the LASL "Dry Hot Rock" Geothermal Energy Project is initially concerned. It is hoped that the other possibilities listed, and several variations of them with the geologic environment, can also eventually be investigated in a continuing, long-range program directed toward making this vast energy supply economically useful.

II. MAN-MADE CIRCULATION LOOPS

A variety of methods have been suggested for extracting energy from dry hot rock in the earth's crust. The simplest of these, and probably the most economical, appears to be to imitate nature by using water as a heat-transport fluid—injecting it into the geothermal reservoir at one point; permitting it to circulate over a sufficient surface area to be heated essentially to the temperature of the rock; and then recovering it at a second point as either hot water or steam. Again, a number of variations of this general method are possible, and eventually several of them should probably be tried in the field. The most straightforward of these appears to be to drill two separated holes from the surface downward into the hot rock and then to permit water to circulate through the formation continuously from one hole to the other. However, if the initial permeability of the rock is high enough to permit this circulation to occur naturally, then the rate of water loss from the system into the surrounding formations can also be expected to be high. To conserve both water and heat, it would be preferable to create the circulation loop in rock whose inherent permeability is low enough so that it will effectively contain the circulating heat-transport fluid. This permeability requirement is probably met by many deeply buried shales, limestones, dolomites, and both igneous and metamorphic rocks—although that remains to be demonstrated by *in situ* experiments.

When hot rock of low permeability has been found, the principal problems that remain are those of drilling the necessary holes and creating between them a connection whose impedance is low enough to permit a high rate of fluid circulation, and whose surface area is large enough to permit a high rate of heat extraction to be maintained for a usefully long time. At least to depths of the order of 20,000 ft (6 km) and rock temperatures of the order of 300°C, the necessary drilling can evidently be done with existing equipment and techniques. Several methods then exist for creating a connection between the holes, including chemical leaching to increase the permeability of the rock locally; fragmentation by detonation of either chemical or nuclear explosives; and hydraulic fracturing. Of these, hydraulic fracturing is the method that will be tried first in the LASL project.

III. HYDRAULIC FRACTURING

Hydraulic fracturing is a method of well completion that has been used extensively for about 35 years in oil- and gas-bearing formations of relatively low permeability, to increase the rate at which petroleum or natural gas flows into a well. It is done hundreds of times a week by commercial oil-field service companies, with no evident hazards or undesirable environmental effects. It is accomplished by using "packers" (temporary seals) in a well to isolate the zone in which it is desired to produce a fracture, and then using a high-pressure pump at the surface to pressurize this zone sufficiently to crack the rock around the wellbore. The pumping pressure required to fracture the rock is normally from a few hundred to a few thousand pounds per square inch (of the order of 2 to 20 MPa), and once a crack has been formed it is in general easier to extend that crack than to form a new one. The result of hydraulic fracturing is, then, believed normally to be a single "penny-shaped" crack, extending outward from the well to distances of the order usually of a few hundred feet (100 to 200 m) but occasionally — as a result simply of continuing to pump fluid into the crack — to distances as great as half a mile (0.8 km) or more. If the fracture is formed near the earth's surface, then the fluid pressure required to create it is also usually sufficient to lift the overburden above it, and the plane of the fracture is therefore expected to be horizontal. However, at depths greater than about 2000 to 3000 ft (0.6 to 0.9 km), the least compressive stress in the rock — against which the crack will naturally open — is in general horizontal, so that the plane of a deep penny-shaped crack is expected to be vertical.

Not much is known from direct observation about the detailed geometry of a large hydraulic fracture. However, with the usual assumptions that a deep hydraulic fracture is vertically oriented, circular in outline, and elliptical in cross-section, and with realistic values of the properties and geothermal gradient of the rock containing the fracture, it is possible to construct what are believed to be good computer models of heat flow and fluid flow in such a crack. In rock of relatively low permeability it should be possible to hold the crack open simply with fluid pressure, without the use of particulate proppants. If this can in fact be done, our computer analyses indicate that impedances will be low enough to permit buoyant circulation of water in the crack; that very little short-circuiting will occur between the injection and the recovery hole; and that efficient extraction of heat from the crack surfaces will be possible. Under these conditions, and in spite of the expense of drilling deep holes in hard rock, the cost per unit of heat extracted from dry hot rock should be low relative to that of heat from almost any other energy source.

IV. THE LASL PROJECT

Under sponsorship of the Division of Applied Technology of the U.S. Atomic Energy Commission, Los Alamos Scientific Laboratory has undertaken to investigate the possibilities, problems, and economics of creating and operating such an energy extraction system. Initial field investigations are in progress on the Jemez Plateau of north-central New Mexico, about 20 air miles (32 km) west of the city of Los Alamos. The particular area being studied now is just outside of the western rim of the Valles Caldera, within which volcanic activity has occurred as recently as 40,000 to 50,000 years ago. This is recent enough in geologic time so that hot rock still exists at moderate depths, and contributes substantially to terrestrial heat flow in the area.

Because of its accessibility and inherent geologic interest, the region of the Valles Caldera has been studied intensively for many years by the U.S. Geological Survey, the New Mexico Bureau of Mines and Mineral Industries, several universities, and a number of other organizations and individuals. On the basis of information from these sources, supplemented by that from our own geologic and heat-flow studies, LASL has concentrated its attention on an area close to but outside of the caldera rim, where heat flow is relatively high, depth to the crystalline basement rock is moderate, geology is uncomplicated, and no large or active faults have been found.

In our first deep exploration of this area, a hole ("GT-1") was drilled in 1972 to a total depth of 2576 ft (0.7852 km), penetrating about 470 ft (143 m) into the Precambrian basement. Rock temperature at the bottom of this hole was about 100.4°C. The Precambrian section investigated consisted of granitic rocks typical of the southern Rocky Mountains, which showed extensive high-angle fracturing. However, the fractures were in general well sealed with calcite or chlorite, and measured <u>in situ</u> permeabilities were very low. Using our own equipment and relatively low pumping rates, we produced a series of small hydraulic fractures at pumping pressures of about 1200 to 1700 psi (8.3 to 11.7 MPa). Breakdown pressures correlated well with the apparent competency of the rock as observed on core samples. Using much larger equipment and higher pumping rates, an oil-field service company subsequently produced two larger fractures in the basement rock at pumping pressures of about 2500 psi (17.2 MPa). In a long series of pressurization and depressurization experiments, we measured an apparent surface energy of the <u>in situ</u> rock of about 100 J/m^2, a least horizontal compressive stress in the lower part of the hole of about 2000 psi (13.8 MPa), and a permeability of newly exposed fracture surfaces of a small fraction of a millidarcy. The fractures produced appeared to be essentially vertical, with a northwest-southeast orientation. These results were encouraging with regard to the existence under the Jemez Plateau of a dry geothermal reservoir, the possibility of drilling into and hydraulically fracturing it to produce a man-made geothermal energy system, and the probability that a pressurized-water circulation loop could be contained by it without excessive loss of the heat-transport fluid.

To confirm these observations at another location and to permit similar measurements to be made at greater depths and under conditions of higher temperature and pressure, a second exploratory hole ("GT-2") has been drilled during 1974 at a location about 1.5 miles (2.4 km) south of the first one. Its present depth is 6701 ft (2.043 km), although we hope to deepen it further, and we are now engaged in a series of hydrologic, hydraulic-fracturing, and pressurization and depressurization experiments in it. Some geologic surprises were encountered in the volcanic and sedimentary section above the crystalline basement rock, and the lithology of the Precambrian basement section is considerably different from that observed in GT-1. However, the fracture pattern in the basement rock is quite similar to that seen in cores from the previous exploratory hole. In GT-2 a highly permeable region of unsealed fractures was encountered in the granitic section at a depth of about 3570 ft (1.088 km), with some evidence of additional unsealed fractures at two or three other horizons in a zone several hundred feet deep which contained this region. Both above and below that zone the natural fractures in the basement rock are well sealed with such minerals as calcite and quartz, and measured in situ permeabilities again are very low (of the order of 20 microdarcies or less). There is some evidence that the natural fractures are both less frequent and more tightly closed at greater depth in the section.

At the location of GT-2, heat flow is evidently a little less than at GT-1. Since the effects of cooling by the drilling fluid have largely disappeared, the geothermal gradient through the Precambrian section of GT-2 from about 2400 to about 6700 ft (0.73 to 2.04 km) has become nearly constant at approximately 50°C/km. Rock temperature at 6701 ft (2.043 km) is about 146°C, and we are now projecting with reasonable confidence to a temperature of at least 200°C at a depth of 10,000 ft (3.05 km).

In our first hydraulic fracturing experiments, at a depth of about 6600 ft (2.01 km) and a pumping rate of 120 gpm (454 ℓ/min), fracture has occurred at a pumping pressure of about 2500 psi (17 MPa). As was true of several of the experiments in GT-1, fracturing has apparently occurred by slow opening and extension of favorably located preexisting cracks rather than by the sharp breakdown of competent rock. As fracturing theory predicts, crack extension then occurs at slowly decreasing pressure. The largest fracture so far produced was made by injecting about 900 gal (3400 ℓ) of water. It is being further extended today. So far no attempt has been made to prop the fractures produced in GT-2, and fluid return has generally been very slow when pressure in the hole was reduced and the crack was permitted to collapse. However, about 70 to 75% of the water injected has usually been recovered within a few hours, and the rest can be accounted for either by permeation of newly exposed crack surfaces or by entrapment of fluid in a crack which has sprung shut in the region of stress concentration near the borehole, or by some combination of the two. The system represented by the hole and the fractures extending from it appears to be a very tight one.

Experiments in GT-2 will continue for some time at the present depth, after which it is hoped that the hole can be extended and generally similar experiments can be undertaken in the deepened hole.

V. CONCLUSIONS

While two exploratory holes represent a very small sample, it so far appears that the Precambrian basement rock underlying the Jemez Plateau of northern New Mexico satisfies our definition of a "dry geothermal reservoir." No unexpected difficulties have been encountered in drilling or hydraulically fracturing this rock, and except for one zone about 1000 ft (0.3 km) below the Precambrian surface, its permeability is extremely low. In general it appears competent to contain pressurized water, and no reason has so far been discovered to believe that a man-made, pressurized-water circulation loop cannot be created and operated within it substantially as has been described above. Therefore we are still very optimistic that the LASL Geothermal Energy Project will be successful in developing economical methods for extracting thermal energy from dry hot rock in the earth's crust.