LA-UR-73-1695

Conf-740209--1

ARTIFICIAL GEOTHERMAL RESERVOIRS IN HOT VOLCANIC ROCK*

by

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(A talk to be presented at the U.S.-Japan Cooperative Science Seminar on "The Utilization of Volcano Energy" in Hilo, Hawaii, on February 4-8, 1974. Sponsored by the Japan Society for the Promotion of Science and the United States National Science Foundation.)

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*This work is being done under the auspices of the U. S. Atomic Energy Commission.

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I. INTRODUCTION

If there exists a sustained, reliable heat source in or near a volcano, it must be at some depth since lava pools in volcanic craters are only intermittently full. Lava lakes may be a partial exception to this rule, but their life appears to be limited to a few tens of years. There may exist more permanent pools of lava at depths of a few kilometers. Even these must have transient fluctuations as pressure builds up and recedes. However, if changes in the properties of the lava, such as viscosity, are not too great, and if rock movement does not destroy the energy extraction system too frequently, these pools may be attractive energy sources. Additionally, the rock surrounding such pools of lava may store heat over long times, and be relatively free of short term temperature fluctuations. This will only be true if the transport of heat out of the rock by steady or intermittent flow of water is sufficiently slow.

If such masses of rock at elevated temperature exist around underground lava pools, it may be possible and even advantageous to extract the heat from the rock instead of the lava. The means for doing this will be quite different from those designed to extract energy directly from molten magma. In general, the temperature of the rock will be lower, a much larger area of control between the heat exchange fluid and the rock will be necessary, and problems of solution, precipitation, and corrosion may be expected to decrease as the temperature is reduced.

The Los Alamos Scientific Laboratory is conducting an experiment about 4 kilometers west and south of the ring fault of the enormous Jemez Caldera in the northcentral part of the state of New Mexico. The experiment is designed to demonstrate that geothermal energy may be extracted from hot rock which does not contain circulating hot water or steam, and which is relatively impermeable. If successful, the experiment will help free the geothermal energy program from dependence on fortuitous geologic circumstances and show that man can engineer systems which provide the necessary circumstances for extraction of geothermal energy where nature has failed to do so. The purpose of this paper is to describe some recent results from the Los Alamos Program and discuss the circumstances under which artificial geothermal reservoirs might be created in the basaltic rock of Hawaii.

II. NATURAL GEOTHERMAL RESERVOIRS

When the requisite geological features fortuitously occur together, a natural geothermal reservoir is formed. These features are shown in Fig. 1. A source of heat, such as a recent magmatic instrusion, lies below a permeable zone containing water which has been heated by circulation over the heat source. Overlying the permeable zone is a layer of impermeable cap rock. The major mechanism for heat loss from the reservoir is conduction through the cap rock, although some heat may be lost through springs or geysers. A source of recharge water, usually an inflow of ground water from the sides, must exist. If the recharge rate is sufficiently slow, there may be a vapor phase overlying a liquid phase and a well drilled through the cap rock may deliver dry steam. More commonly, the well delivers hot water, which may boil in the wellbore as it nears the surface. At the surface, the unboiled water may be allowed to flash to steam at or slightly above the design pressure of the turbines. If the water is saline, the well bore may clog rapidly with salts which are precipitated when

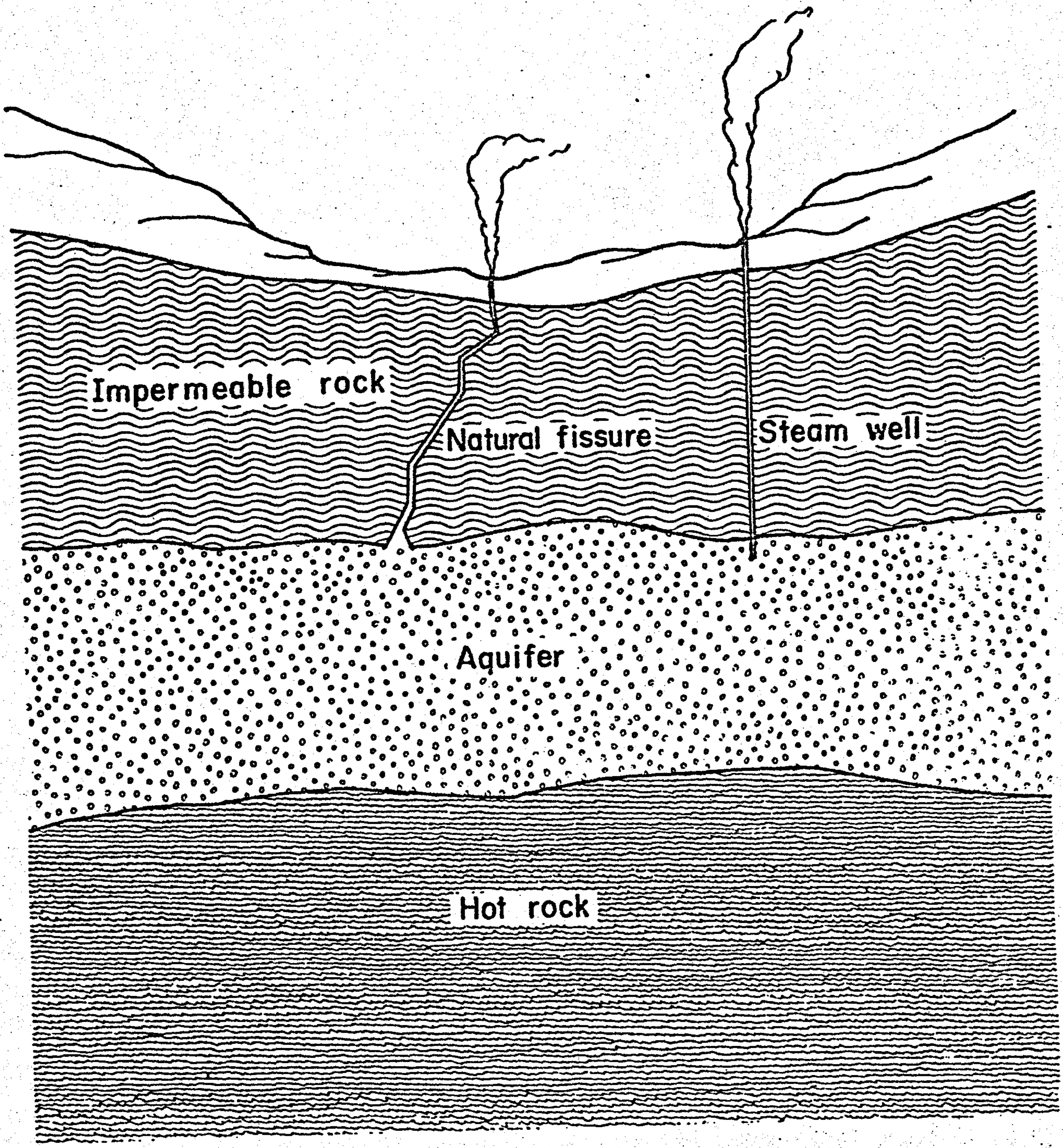


Fig. 1. Natural geothermal reservoirs.

part of the water is vaporized. In such case, a downhole pump may be required to pressurize the upper part of the wellbore and prevent boiling. Another alternative is to pass the water through a heat exchanger. The heat is transferred to a working fluid, which may be pure water or an organic vapor. This working fluid drives the turbine. In such a system, the geothermal water is never allowed to flash to steam, and may be reinjected back into the reservoir along with any noncondensible gases such as H_2S which are dissolved in it with obvious environmental advantages.

III. ARTIFICIAL GEOTHERMAL RESERVOIRS

A. Area of Contact Between Fluid and Hot Rock

A natural reservoir may be viewed as a hot-rock heat exchanger. Most of the energy in such a reservoir, as much as 85 to 90 percent of it, is in the rock (White 1973). Rock is a poor heat conductor: if the temperature at a rock face is lowered it may take a year for the resulting cooling wave to penetrate 6 to 10 meters into the rock. Thus, a hot-rock heat exchanger for geothermal use must provide a few square kilometers of contact area between the rock and the circulating fluid if it is to deliver tens of megawatts of geothermal heat energy (Smith et al, 1973). If a mass of rock contains pre-existing fractures, a large contact area is available naturally. If the rock is relatively impermeable, large cracks may be created by the process of hydraulic fracturing, which is described below.

B. Hydraulic Fracturing

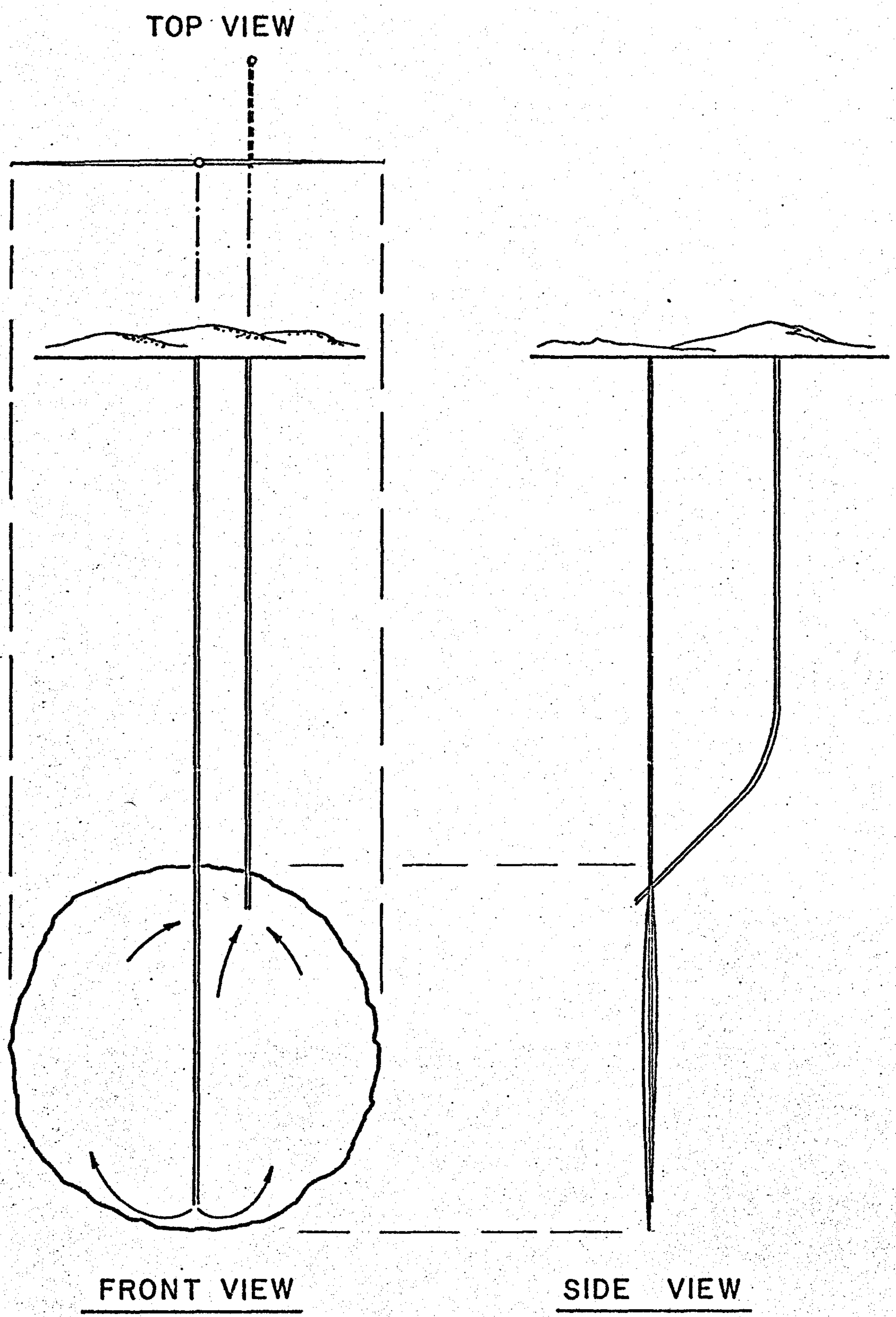
To create a hydraulic fracture, a fluid is pumped at high pressure into an isolated section of a wellbore, where it is allowed to contact the surrounding rock. If the well is cased, the pipe in this pressurized region is perforated by methods familiar in the petroleum industry, so that the pressure may be applied to the rock. As the pressure increases, the rock goes into tension and eventually cracks. The crack may be enlarged to form a large, pancake shaped fracture by pumping more fluid into it. If the crack is deeper than a few hundred meters, it will usually be oriented so that it opens against the least principal earth stress. This stress is usually horizontal, and the crack is vertical (Hubbert, 1957).

C. Circulation System

A second well is drilled a few hundred feet away from the first, and deviated by standard techniques to intersect the fracture near the top as shown in Fig. 2. Cold water is injected through the first pipe, circulates through the crack, and hot water returns to the surface through the second pipe. The water may be allowed to flash to vapor in the reservoir, but this entails several disadvantages. The first is that dissolved materials may be deposited on the walls and close off the circulation system. The second is that the viscosity of steam increases with temperature, so that it will preferentially choose the colder of two otherwise similar paths, while the opposite is true for water. The third disadvantage of steam is that in a given wellbore, with a given temperature and driving pressure, a steam well delivers much less energy to the surface than a hot water well (Smith et al, 1973). The favored operating mode for the circulation system is one in which the heat conducting fluid is kept under sufficient pressure so that it never vaporizes. The fluid passes through a heat exchanger at the surface and is then reinjected into the crack. A second working fluid, which may be water, is heated in the heat exchanger to drive a turbine or to provide process heat, etc. Problems of precipitation and scale formation are thus concentrated at the heat exchanger.

D. Earth Stress Balance

The internal pressure in the crack varies with depth, as does the external earth stress. If the difference between earth stress



TOP VIEW

FRONT VIEW

SIDE VIEW

SYSTEM FOR CIRCULATING LIQUID COOLANT THROUGH CRACK

Fig. 2. Artificial geothermal reservoir.

and internal pressure were constant, the pressure difference required to extend the crack is given by the equation (Sack, 1946).

$$P-S = \{\pi \alpha E/[2R(1 - \nu^2)]\}^{1/2} \qquad (1)$$

P - pressure of fluid in crack.
S - least principal earth stress, normal to crack.
α - energy required to form unit area of crack surface.
R - radius of crack.
E - Young's modulus of rock.
ν - Poisson's ratio of rock.

If the difference between internal pressure and the least principal earth stress is greater than this, the crack will grow. It is very desirable to hold the crack open by pressure, in order to reduce resistance to flow. In order to do this, the difference between internal pressure and earth stress near the top of the crack should match the corresponding difference at the bottom of the crack as nearly as possible. The pressure must be greater than the earth stress to open the crack, yet the difference anywhere inside the crack cannot exceed (1) or the crack will not be stable. The difference between P and S at the top and bottom of the crack may be reduced by controlling the density of the circulating fluid. This density may be controlled by choosing fluids other than water, if lower density than that of water is needed, or by dissolving substances in water to increase its density. In some cases, it may be desirable to increase the density with suspended solids. In order to determine the required density, the earth stress should be measured vs depth in a number of small fractures before the very large fracture is created.

E. Measurement of Earth Stress

Figure 3 shows data from which the earth stress in a Los Alamos exploratory hole was determined. The pressure data were taken after a hydraulic fracture was made in granite at a mean depth of 760 meters and the well was shut in. Approximately 4000 liters of water were injected, at a pressure about 240 bars above the estimated overburden weight.

The first plateau in Fig. 3 is interpreted as showing that a horizontal fracture had been created as well as a vertical fracture (numerous small vertical fractures had previously been created at lower pressures in the same wellbore). For approximately 3 hours, the pressure was maintained near the estimated overburden pressure, while water was passing into the vertical fracture, which continued to grow, and out of the wellbore through a leaking packer. When the horizontal fracture emptied, the pressure dropped to a value above the least principal stress S. Just as the vertical crack closed, the pressure was S = 137 bars, in reasonable agreement with a value of 147 bars obtained by a different method.

F. Limit on Size of Stable Crack

As R increases, Eq. (1) shows that the value of P-S at which a crack extends is reduced. At the same time, deviation of the least principal stress, S, from values that may be compensated by adjusting the density of the circulating liquid becomes more probable. It is thus likely that a maximum stable crack radius exists. If this radius does not provide sufficient heat transfer surface, a method of producing multiple parallel fractures exists, as shown in Fig. 4 (this method was independently suggested by Barry Raleigh of the U.S.G.S.).

G. Thermal Stress Cracking

Another possible way out of the limit on the size of a single crack arises from thermal stress cracking. As energy is withdrawn from the rock, the rock is cooled and contracts. This

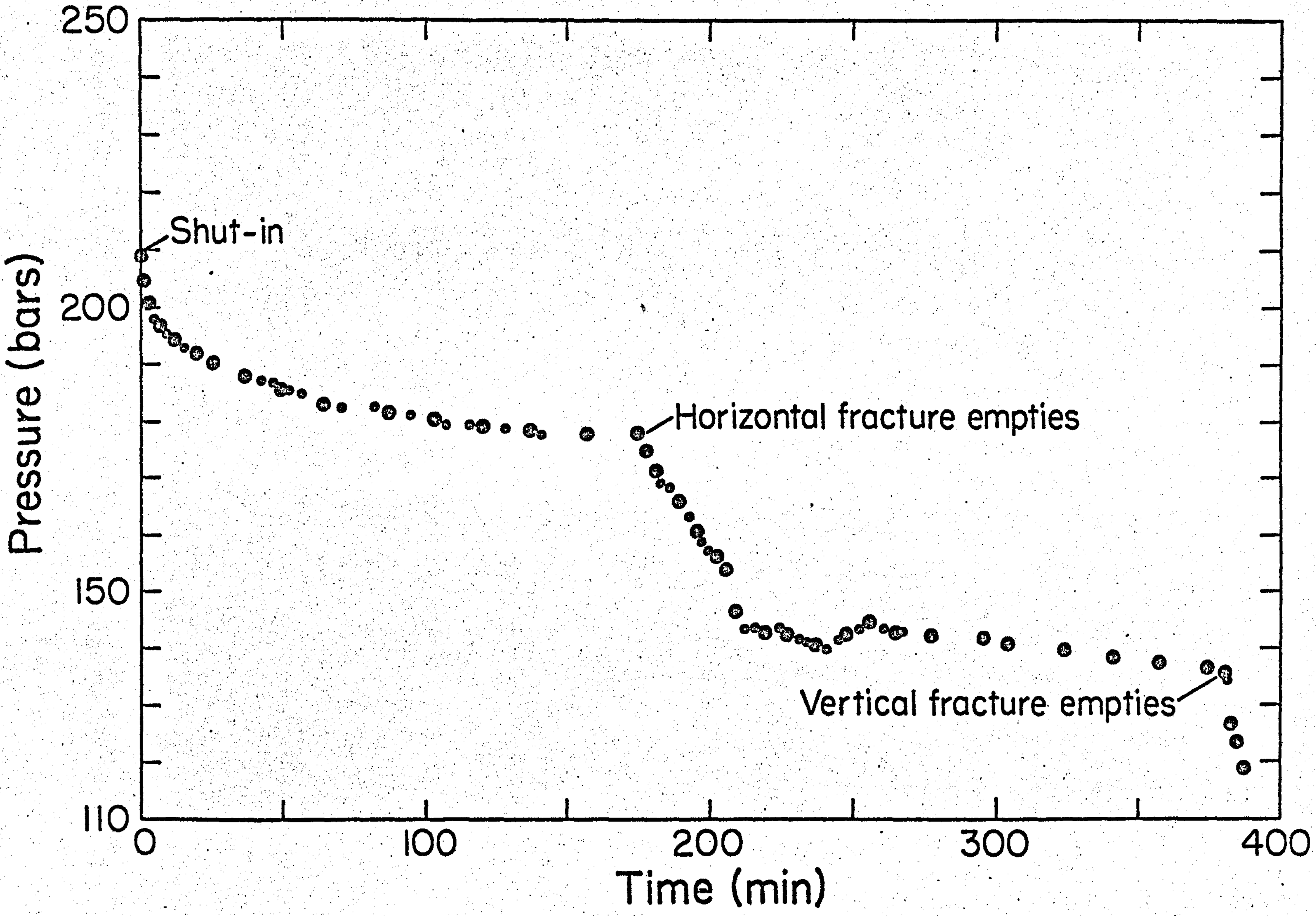


Fig. 3. Pressure vs time in well after hydraulic fracturing.

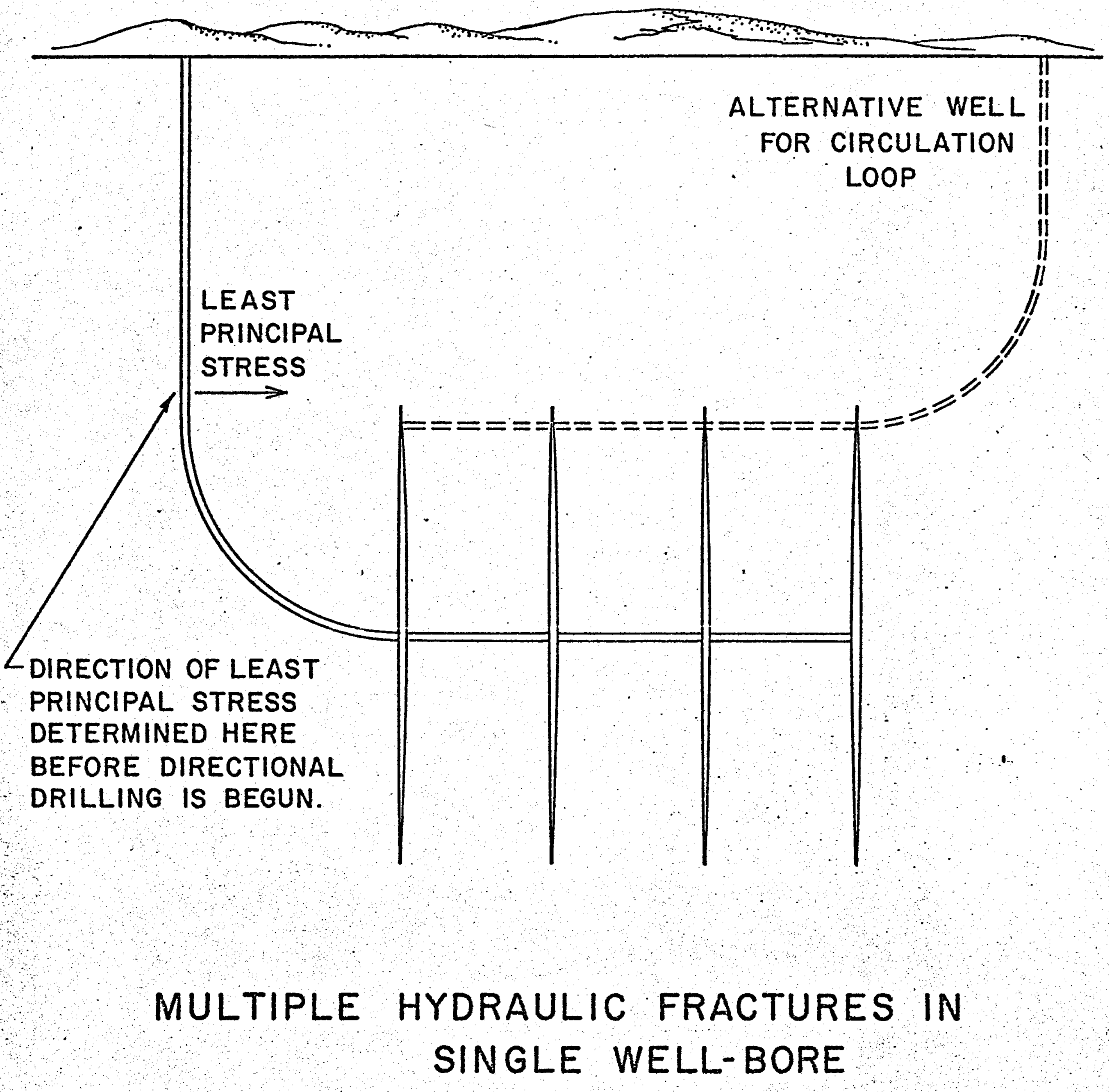


Fig. 4. Multiple hydraulic fractures in single wellbore.

contraction eventually causes new cracks in the face of the original one. Computer calculations (Harlow and Pracht, 1972) show that the reservoir grows fasted where the coldest water encounters the hottest rock, i.e., downward and outward from the face of the crack. Experiments are needed to determine the actual rate of growth of artificial reservoirs by this mechanism.

H. Other Options for Creating Artificial Reservoirs

If the variation of earth stress with depth is erratic, as might well be the case near a volcano, a mode of operation known as the "Huff-Puff" method may be used, as was suggested by Robert Rex (Private communication, 1971). In this system, water is pumped into a crack for some time, and then allowed to return through the same pipe which should be insulated from the surrounding rock. If the upcoming water is coöled in a heat exchanger and flows into a second large fracture, continuous power generation can be achieved with a small additional storage volume on the surface.

If reservoirs are leaky and cannot sustain the overpressure necessary to keep the surface water in liquid form, a downhole pump may be used in the hot line.

Finally, if the reservoir of hot rock is truly porous, one or more injection wells near the withdrawal well may be used. Such a system obviously grades over into a conventional hot water well with reinjection.

REFERENCES

R. A. Sack, "Extension of Griffith's Theory of Rupture to Three Dimensions," Proc. Phys. Soc. of London 58, 729 (1946).

M. King Hubbert and David G. Willis, "Mechanics of Hydraulic Fracturing," Pet. Trans. AIME 210, 153-166 (1957).

M. C. Smith, R. M. Potter, D. W. Brown, and R. L. Aamodt, "Induction and Growth of Fractures in Hot Rock," Geothermal Energy, Paul Kruger and Carel Otte, Eds. (Stanford University Press, 1973), p 251-268.

Donald E. White, "Characteristics of Geothermal Resources," Geothermal Energy, Paul Kruger and Carel Otte, Eds. (Stanford University Press, 1973), p 85.