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THE LOS ALAMOS HOT DRY ROCK GEOTHERMAL PROJECT

KEY WORDS: Drilling; Energy; Geology; Geothermal energy; Hot rock; Hydraulic fracturing; Power; Pumping; Rocks; Wells.

ABSTRACT: The greatest potential for geothermal energy is the almost unlimited energy contained in the vast regions of hot, but essentially impermeable, rock within the first six or seven km of the Earth's crust. For the past five years, the Los Alamos Scientific Laboratory has been investigating and developing a practical, economical and environmentally acceptable method of extracting this energy. By early 1978, a 10 MW (thermal) heat extraction experiment will be in operation.

In the Los Alamos concept, a man-made geothermal reservoir is formed by drilling into a region of suitably hot rock, and then creating within the rock a very large surface for heat transfer by large-scale hydraulic-fracturing techniques. After a circulation loop is formed by drilling a second hole to intersect the fractured region, the heat contained in this reservoir is brought to the surface by the buoyant closed-loop circulation of water. The water is kept liquid throughout the loop by pressurization, thereby increasing the rate of heat transport up the withdrawal hole compared to that possible with steam.

THE LOS ALAMOS HOT DRY ROCK GEOTHERMAL PROJECT

By Donald W. Brown,[1] and Roland A. Pettitt,[1] A.M. ASCE

INTRODUCTION

As a consequence of man's ever-increasing demands for energy and mineral resources, countless numbers of exploratory holes have been drilled deep into the earth's crust all over the world. Although the sought-for resources have most often not been found (the proverbial "dry" holes), what almost always has been found are bodies of essentially dry rock at elevated temperatures. In the Gulf Coast region of the United States for example, typical bottom-hole temperatures for the deeper dry holes often approach or even exceed 200°C -- a minimum temperature level which is considered feasible for the generation of electric power (5).

Such widespread drilling experience clearly attests to the existence, within presently attainable drilling depths, of vast regions of crustal rock at suitably elevated temperatures -- suitable for many of our space heating and process heating needs, and oftentimes even for the generation of electric power. These identified regions of hot rock beneath the earth's surface represent, in fact, our most abundant and broadly distributed energy resource, <u>if</u> an economical and environmentally acceptable means

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of extracting a reasonable amount of the contained thermal energy can be devised. Such is the primary objective of the Los Alamos Hot Dry Rock Project.

HOT DRY ROCK POTENTIAL IN THE WESTERN UNITED STATES (2)

Although several regions of the eastern United States have recently been identified as having a significant potential for the development of hot dry rock geothermal reservoirs at moderate temperatures (3, 6), the greatest potential for this type of geothermal energy lies in the western third of the United States. If one considers the thirteen westernmost states including North and South Dakota, this region possesses a significant potential for the near-term utilization of man-made hot dry rock geothermal reservoirs.

The U. S. Geological Survey (4) has identified 1.8 million acres (2000 square miles) of western lands as "having a significant potential for geothermal development," based primarily on an association with recent vulcanism in the area. However, from a survey of all available regional heat-flow data, it has been estimated that a much larger and more widely distributed portion of this 13-state area -- almost 95,000 square miles -- is underlain, at depths of about 16,400 feet (5 km), by hot rock at or above 550°F (290°C). It should be pointed out that these latter areas are not necessarily associated with recent vulcanism.

Using the numerous measured heat-flow values in conjunction with temperature vs depth predictive techniques, one is in a position to estimate, in a quasi-statistical fashion, the very large hot-dry-rock geothermal-energy potential for the western United

States. Table I lists the estimated probability, in the form of a percentage distribution, of a given temperature range for two specified depths -- 16,400 and 19,700 feet (5 and 6 km) -- for the 13-state region being considered. A mean depth to basement of 8200 feet (2.5 km) was used, along with appropriate mean-thermal-conductivity values for sedimentary and crystalline basement rock,* in deriving the temperature ranges listed in this table.

From an examination of Table I, one can conclude that a hot-rock reservoir temperature level in excess of 550°F (290°C) can be achieved by drilling to a depth of about 5 km anywhere within a 95,000-square-mile broadly distributed region of the western United States. This area is over 30 times greater than the total "Known Geothermal Resource Area" listed by the U. S. Geological Survey for potential naturally-occurring hot water or steam geothermal development.

Obviously then, if a practical, yet economical method of extracting energy from these known reservoirs of hot rock can be developed, as appears probable based on the results of the Los Alamos Project so far, this hot rock geothermal resource is very large.

PRESENT TECHNOLOGY (9)

The principal problems associated with developing this vast energy resource are primarily ones of economics and engineering.

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*0.005 cal/cm-sec-°C for sedimentary rock, and 0.007 cal/cm-sec-°C for crystalline basement rock.

TABLE 1.—Probable Distribution of Hot Rock Reservoir Temperatures for the Western Third of the United States[a]

Probable Areal Distribution	Heat Flow Range HFU[b]	Reservoir Temperature Range Corresponding to a Drilled Hole Depth of: 16,400 ft (5 km)	19,700 ft (6 km)
20%	< 1.6	< 316°F (158°C)	< 356°F (180°C)
30%	1.6-2.1	316-397°F (158-203°C)	356-451°F (180-233°C)
33%	2.1-2.6	397-478°F (203-248°C)	451-545°F (233-285°C)
10%	2.6-3.1	478-560°F (248-293°C)	545-639°F (285-337°C)
7%	> 3.1	> 560°F (293°C)	> 639°F (337°C)

[a]Based on a mean sedimentary thickness of 2.5 km overlying the top of the crystalline basement rock.

[b]HFU - $\mu cal/cm^2$-sec, corrected for Pleistocene climatic effects.

For any given geological setting -- shallow or deep, sedimentary or igneous -- which of the potentially available methods will be most efficient and economical, and at the same time environmentally acceptable?

Except in areas of active vulcanism, which are rare and appear somewhat hazardous for initial investigations, hot dry rock is normally encountered at considerable depths under thick insulating layers of cooler rock. Obviously, some method of in-situ energy extraction is most appropriate for the development of this resource. For similar reasons, drilling appears certainly to be the obvious choice for entering the geothermal reservoir. Fortunately, drilling equipment and techniques are already available which are used more or less routinely to penetrate hot, hard rock to depths of the order of 20,000 ft (6 km), and which produce holes large enough in cross section for the significant transport of a heat transfer fluid. While improvements in drilling technology and economics would certainly be welcome, existing drilling technology is adequate for development of hot dry rock energy systems and must be the immediate basis of that development.

Typically, rocks are poor conductors of heat. Therefore, within the hot rock, a very large heat-transfer surface must be exposed if thermal energy is to be extracted from it at a high rate for a usefully long time. As a method of developing new surfaces, drilling is prohibitively expensive. An economical energy system requires in fact that drilling be minimized, and that the necessary heat-transfer area exist or somehow be created outside the borehole in the form of connected openings large enough to permit heat extraction from their surfaces. It appears that the best possibility for efficient, economical extraction and transport of heat is to circulate a fluid from the borehole through these openings, in imitation of a natural hydrothermal system. And while other fluids would have advantages, particularly with regard to dissolution and reprecipitation of minerals, the total volume of fluid and the makeup requirements for fluid loss and thermal contraction of the rock are so great that a very inexpensive heat transfer fluid is evidently needed. Again in imitation of natural systems, water is the obvious fluid to be used for extraction and transport of the geothermal heat.

If the rock constituting the reservoir has a high natural permeability, as may be the case in porous sediments or fractured igneous or metamorphic rocks, injection of water from the borehole into the formation and circulation through it to extract heat should not be difficult. The problems of confining the circulation to the region from which it is desired to extract heat and of recovering the heated fluid from the formation can probably be handled by the reservoir-management techniques which have been widely used for secondary recovery of petroleum. This, however, in general requires a stratigraphy in which at least the upward flow of the reservoir fluid is prevented and requires also the drilling of an array of holes in which injection holes are surrounded by recovery holes and *vice versa*. Very large energy extraction systems of this type are probably possible, but convincing small-scale experiments to demonstrate their feasibility will be hard to arrange.

At least initially, it appears simpler to investigate energy extraction from hot dry rock whose initial permeability is low.

Here the problems of containing and recovering the fluid are replaced by those of producing flow passages and heat-transfer surfaces. Many options exist with regard to creation and operation of a heat-extraction system in such rock, including

- creation of circulation paths by chemical leaching, by explosive fragmentation, by hydraulic fracturing, or by some combination of these methods;
- alternate injection and recovery of fluid through a single hole, or continuous circulation through coaxial pipes in the same hole, or continuous flow of the fluid between two or more holes;
- transport of the energy to the surface by steam, by hot water, by a mixture of the two, by a second fluid, or--using some type of conversion device--in a form other than heat.

Several of these possibilities appear to deserve investigation, in a variety of geologic environments. However, the only large-scale experimental study of systems of this type now in progress is the ERDA-supported Hot Dry Rock Geothermal Energy Project at Los Alamos Scientific Laboratory. Initially, this is an attempt to create a pressurized-water circulation loop in hot granite by hydraulic fracturing between two boreholes. The feasibility of drilling into, hydraulically fracturing, and containing pressurized water has been demonstrated in granite at depths up to 9600 ft (2930 m) and temperatures up to 385°F (196°C). However, continuous extraction of energy has so far not been attempted except on a very small scale, and a convincing demonstration of a successful energy extraction system is still several months away.

Modified systems will subsequently be developed for other geologic environments, but these are several years farther into the future.

HOT DRY ROCK GEOTHERMAL RESERVOIR

In the initial Los Alamos concept, a man-made geothermal reservoir would be formed by first drilling into a previously-identified region of suitably hot rock, and then creating within this hot rock a very large surface area for heat transfer using conventional -- albeit large scale -- hydraulic fracturing techniques developed by the oil industry. After forming a circulation loop by drilling a second hole into the top of the fractured region, as shown schematically in Fig. 1, the heat contained in this reservoir would be convected to the surface by the buoyant circulation of water, possibly without the need for pumping. The water in the earth loop would be maintained as a liquid throughout by pressurization at the surface, both increasing the amount of heat transport up the second (withdrawal) hole, and enhancing the rate of heat removal from the fractured reservoir, when compared to steam.

Preliminary experiments and analyses indicate that thermal stresses resulting from the cooling of the hot rock in such a man-made reservoir may gradually enlarge the initial fracture system so that its useful lifetime will be greatly extended beyond the planned 10 to 15 years provided by the original fractured reservoir. If these thermal stress cracks grow preferentially downward and outward into regions of hotter rock, as seems probable, the quality of the geothermal source may actually improve as energy is withdrawn from it.

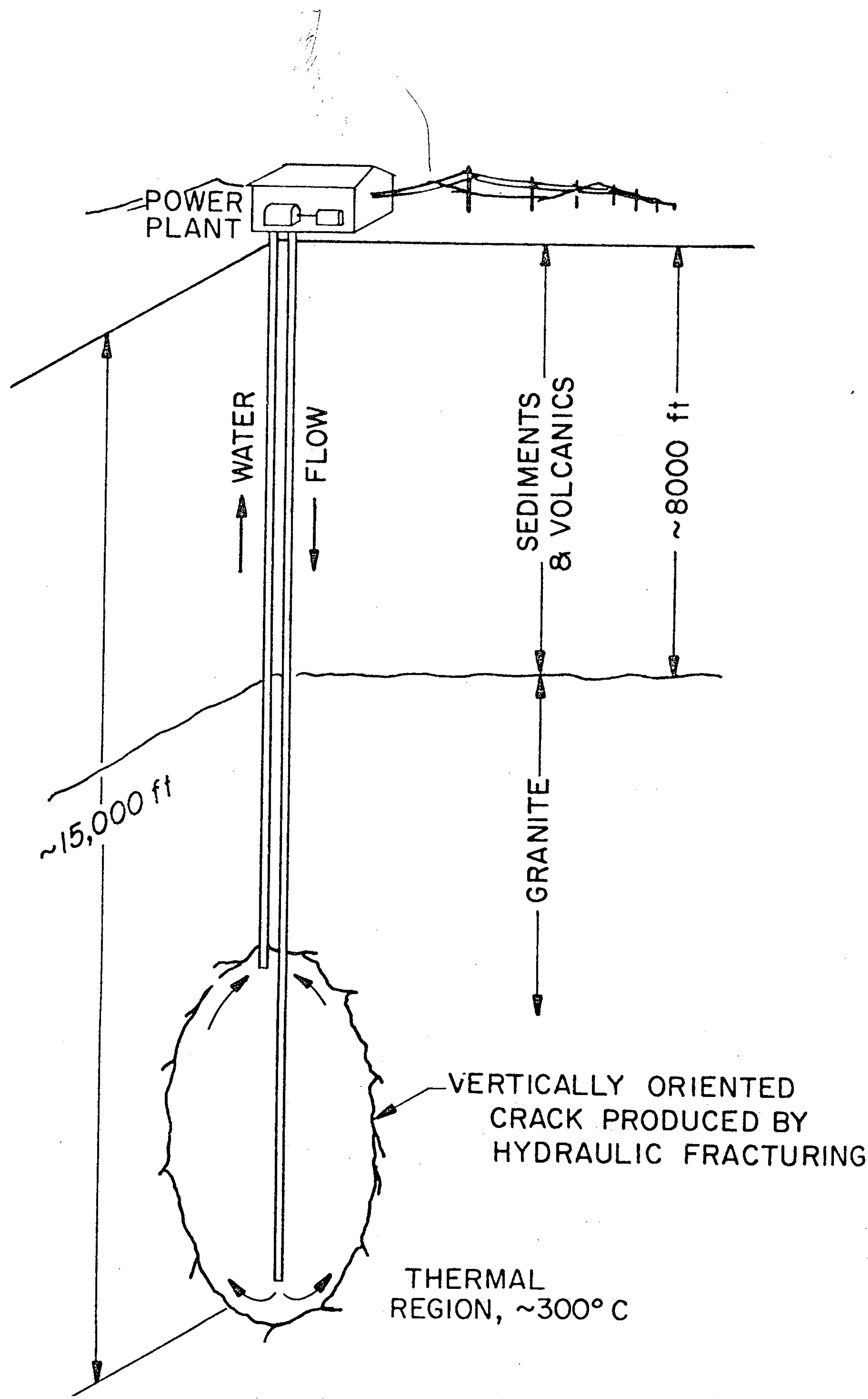

FIG. 1. - A possible hot dry rock geothermal energy system produced by drilling and hydraulic fracturing.

SITE SELECTION

The initial geothermal source demonstration area is located on the Jemez Plateau, a part of the western arm of the Rocky Mountains that extends into northern New Mexico (Fig. 2). About a million years ago, the adjacent Valles Caldera was formed when a huge volcano erupted violently and then subsided into its own empty magma chamber. The Jemez Plateau is part of an apron of volcanic ash ejected during the eruptions. A subsequent series of smaller volcanic events is now represented by a number of rhyolite domes along the inner periphery of the caldera. As a result of this relatively recent vulcanism, a large amount of heat is still retained in rocks underlying the entire area within a few kilometers of the surface.

In 1971, a field investigation was undertaken to determine whether a location accessible to the Laboratory could be found at which the geothermal gradient, geology, and hydrology indicated the probable existence of a usefully hot, dry geothermal reservoir at an economical drilling depth. Temperature-gradient measurements made in a series of holes drilled to depths of about 100 ft (30 m) and the available geological, geophysical, and hydrological information suggested that such a reservoir might exist beneath the Jemez Plateau. Additional field studies produced further encouraging evidence (8), including heat-flow measurements in holes drilled 650-1000 ft (200-300 m), which confirmed heat flow values of about 5 heat flow units (HFU)* on the west side of the caldera.

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*HFU = $\mu cal/cm^2$-sec. The worldwide average heat flow is 1.5 HFU.

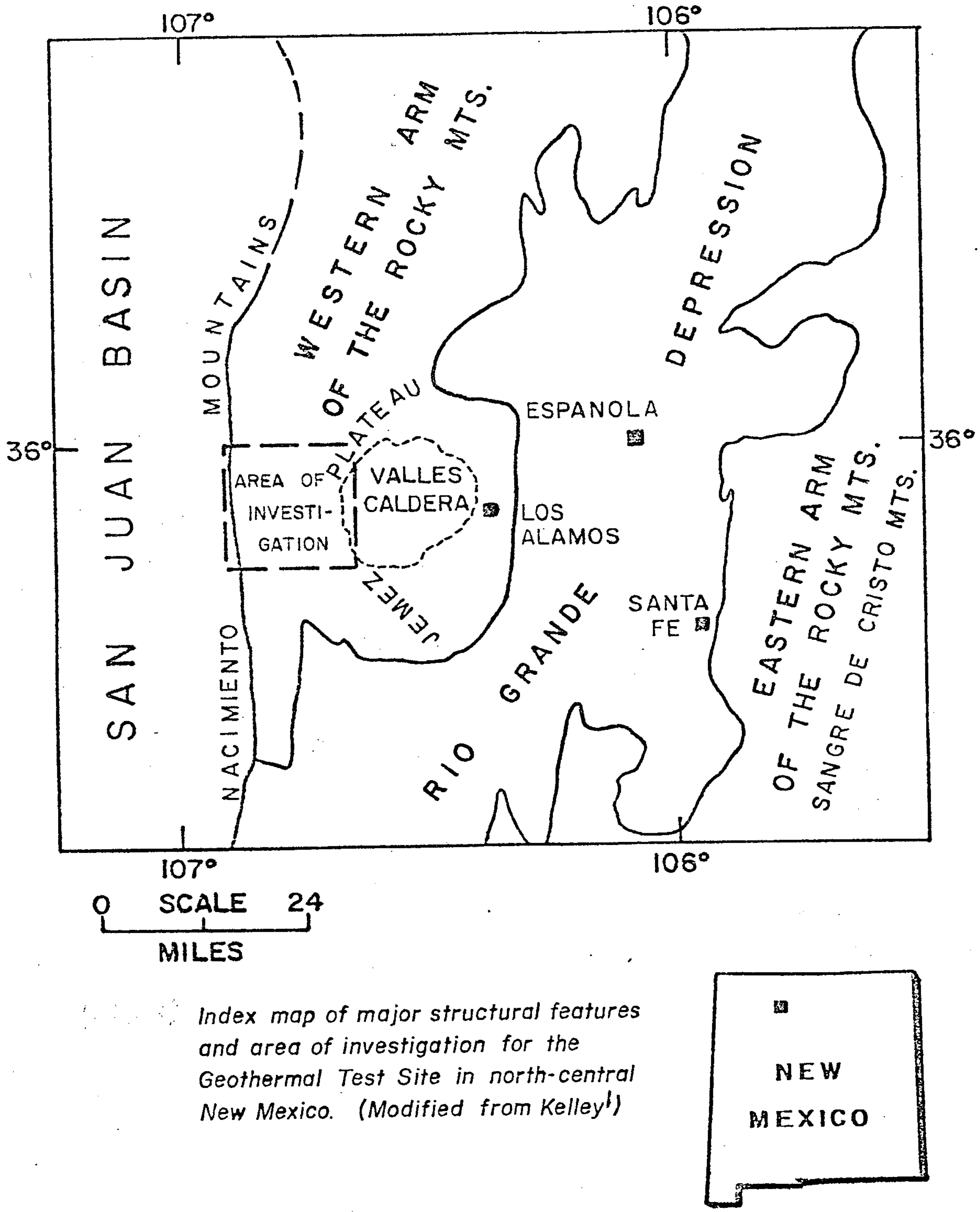

FIG. 2. - Major structural features and area of investigation in north central New Mexico.

To investigate the feasibility of the LASL energy extraction concept and to verify the existence of a dry geothermal reservoir under the Jemez Plateau, a slim exploratory geothermal test hole (GT-1) was drilled in Barley Canyon on the west side of the caldera in 1972 to a final depth of 2576 ft (785 m). It penetrated about 500 ft (150 m) into the basement granitic rock and reached a temperature of 212°F (100°C). The initial permeability of the hot basement rock was very low, so that it appeared capable of containing a pressurized-water circulation system, and of being fractured hydraulically at moderate pumping pressures.

On the basis of these studies and field experiments, a site on the Jemez Plateau about 20 air miles (32 km) west of Los Alamos was selected as being appropriate for development of the first hot dry rock energy experiment. This has been officially identified as the "Fenton Hill Site," or TA-57 (Technical Area 57). It is a gently sloping area on top of a mesa that was burned over in a forest fire in 1971, so site preparation involved minimal leveling and no destruction of standing timber. It is immediately adjacent to an all-weather state highway and to power and telephone lines, and is crossed by a forest road. Access is convenient, power is immediately available, and communications to and from the site are good.

Fenton Hill is situated on the Jemez Plateau about 1 mile (1.5 km) west of the outermost ring fault of the Valles Caldera and about 8 miles (13 km) west of the center of the caldera. The caldera, in turn, sits astride the western edge of the Rio Grande Rift (Fig. 2).

The site is within a large coherent block bounded by faults and capped by the Bandelier Tuff, a welded ash flow. The closest fault with surface expression is the ring fault east of the site. About 2400 ft (0.73 km) of Cenozoic and Paleozoic rocks overlie the Precambrian granitic rocks which form the basement of the Rio Grande Valley and the Jemez Mountains. The predominantly volcanic Cenozoic rocks consist of the Bandelier Tuff, the Paliza Canyon Formation and the Abiquiu Tuff. The Paleozoic rocks are mainly shales (Abo Formation) and the limestones (Magdalena Group) of Permian and Pennsylvanian age.

DRILLING AND TESTING PROGRESS

A Geothermal Energy Group at LASL was established March 1, 1973, and was given primary responsibility for the engineering aspects of the project, with scientific and engineering support to be provided by other Laboratory groups. It is the first project to investigate the feasibility of extracting geothermal energy from nonmolten hot rock in regions where the geothermal gradient is above normal but where neither natural steam nor hot water can be produced at economically useful rates from wells drilled into the geothermal reservoir.

To initiate large-scale field investigations of hot dry rock energy systems, the drilling of a second exploratory hole (GT-2) was begun in February 1974 at the Fenton Hill site. Many difficulties were encountered in drilling, cementing, and logging the hole; furthermore, it was necessary to drill the hole considerably deeper than originally anticipated to reach the target temperature of 392°F (200°C). Two heat flow values were obtained in GT-2 and GT-1. A heat flow of about 5 HFU was observed in the volcanic and sedimentary rocks; in the Precambrian rocks a value of 3.7 HFU was obtained. The difference apparently resulted from the flow of hot water along the Precambrian unconformity.

Hole GT-2.--The problems encountered in drilling the Permian-age red beds and the Pennsylvanian-age shales and limestones required that a string of 13-3/8-in.-diam (35-cm) casing be set to a depth of 1600 ft (488 m). The Precambrian granitic surface was reached at 2404 ft (733 m) and a second string of 10-3/4-in.-diam (27.3-cm) casing was set from the surface to 2535 ft (773 m). Drilling continued to 6700 ft (2042 m) using 9-5/8-in.-diam (24.4-cm) bits.

At this depth, a series of hydrology experiments was performed to determine the permeability of the lower granitic rocks. Hydraulic fracturing experiments were also conducted using methods and equipment developed by the oil-well services industry. Although the rock at this depth seemed to be broken by extensive natural fractures, water leak-off was slight.

As a result of these experiments, the Fenton Hill site was judged suitable for further development of the geothermal project. The hole was deepened to 9619 ft (2932 m), and a 608-ft-long (185-m) liner was cemented into the bottom section of the hole to facilitate seating of packers for future fracturing experiments. A 38-ft (11.6 m) section of hole was left uncased at the bottom. The equilibrium bottom-hole rock temperature was 386.6°F (197°C).

Later, additional fracture experiments were performed through perforations in the liner and in the open hole below the liner. A near-vertical, 400-ft-radius (122-m) fracture was thought to have been created near the bottom of the hole.

Hole EE-1.--The second hole was located 252 ft (77 m) northeast of GT-2 (Fig. 3). Drilling began in May 1975 and was

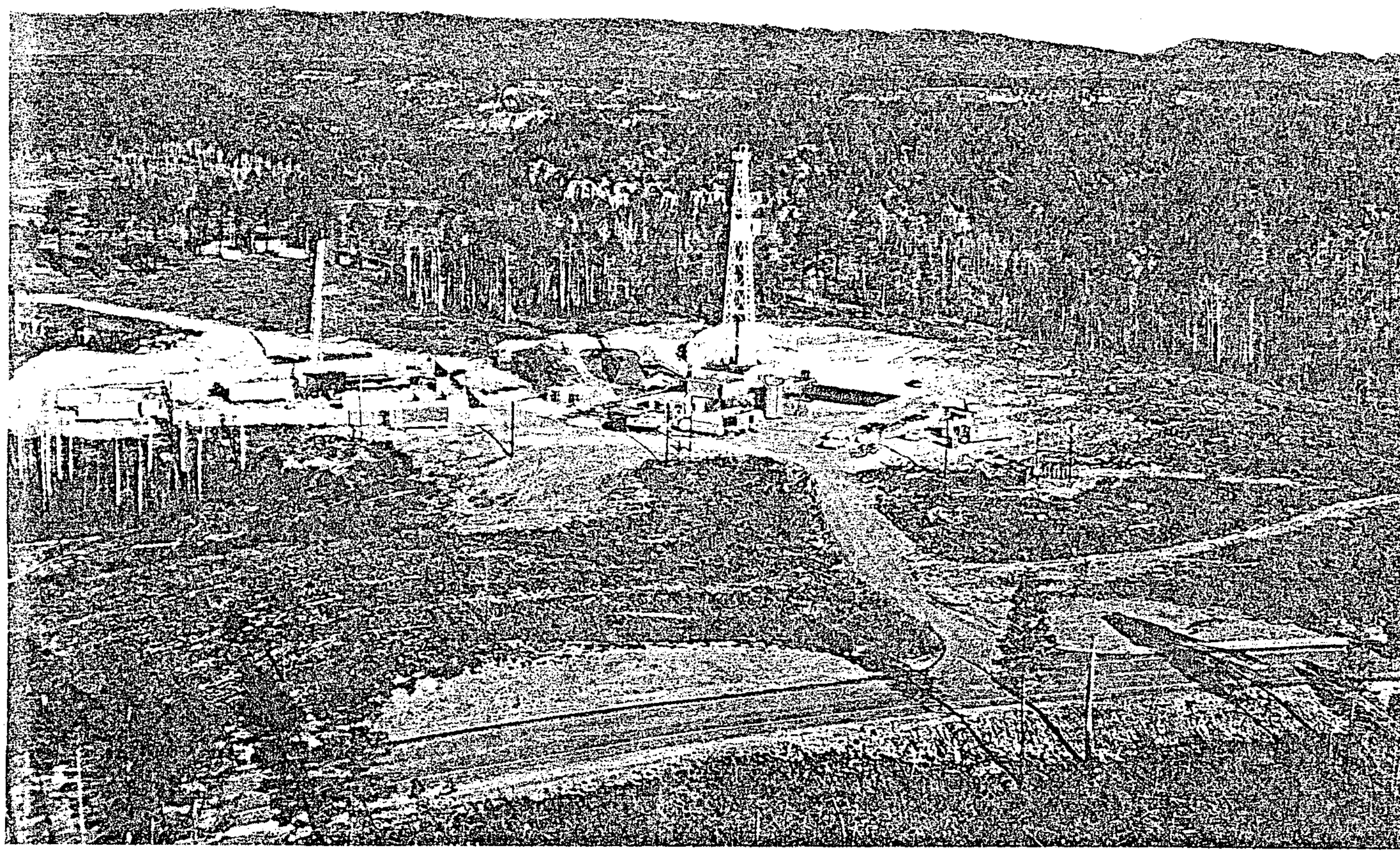

FIG. 3. - Aerial view of the Fenton Hill site (TA-57), looking west. Borehole GT-2 with the workover drilling rig is on the left, EE-1 in the process of being drilled is on the right.

completed in October at a depth of 10,053 ft (3064 m) and a bottom-hole temperature of 402°F (205.5°C). EE-1 was cased to 6420 ft (1957 m) with three strings of casing, the deepest being 10-3/4 in. (27.3 cm) in diameter.

Directional drilling techniques were used below this casing to angle EE-1 toward the presumed fracture at the bottom of GT-2. The hole was drilled through a 205° spiral, turning counter-clockwise from an initial northwest heading to a northeast heading (Fig. 4). On October 14, 1975 flow between the two drill holes was established, creating for the first time a man-made connection in hot, nearly impermeable basement rock. After circulation was established, EE-1 was cased to 9600 ft (2926 m) with a 7-5/8-in.-diam (19.4 cm) casing for subsequent pressurized flow and heat extraction experiments. Circulation tests between the two holes were then conducted to determine the dimensions and characteristics of the downhole reservoir system.

The predominant Precambrian rock in both holes is banded granitic gneiss. In one section, biotite schists are interlayered with the gneiss which is intruded by unfoliated monzogranite dikes. A relatively extensive and homogeneous biotite-granodiorite body was encountered at depth. Drill cores show numerous fractures, usually well sealed or healed.

Except for coring, all drilling in the crystalline basement was done with full-face tricone rock bits. For standard drilling, the bit rotational speed was 40 rpm; for directional drilling, it was 250 rpm. Penetration rates ranged from 2.8 ft/h (0.9 m/h) to a maximum of 38 ft/h (11.6 m/h). The maximum standard drilling interval for a single bit was 672 ft (205 m) in 75 h; the maximum directional drilling interval was 115 ft (34.4 m) in 5 h. These

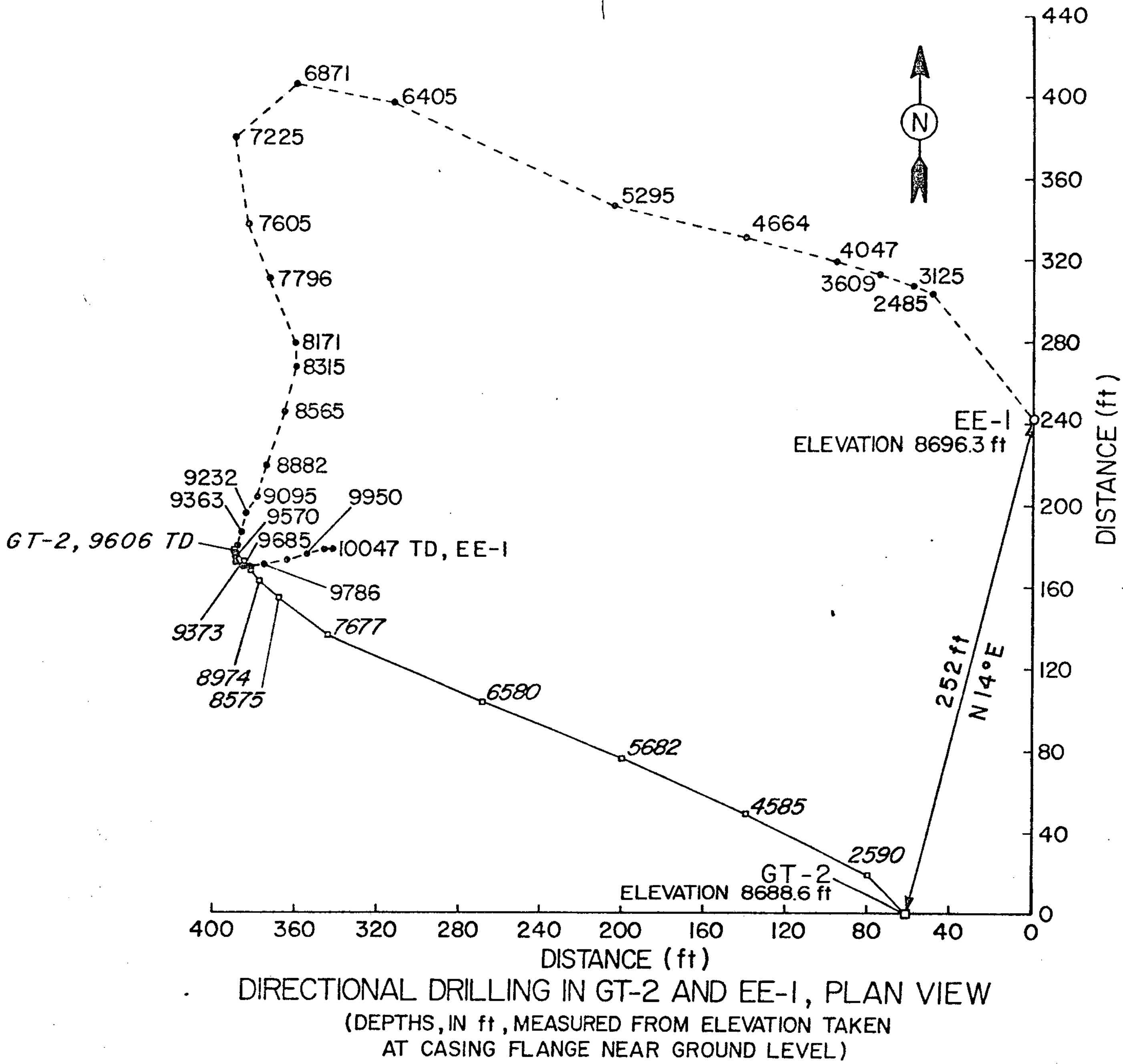

FIG. 4. - Plan view of the paths of the drill holes. EE-1 was directionally drilled below 6886 ft (2099 m) to intersect the fracture zone at the bottom of GT-2.

two holes constitute the bulk of existing drilling experience in hot granitic rocks using conventional oil-field equipment.

Redrilling Hole GT-2.--Because of inaccuracies in locating the fracture when the intersection was attempted, EE-1 missed the fracture by about 27 ft (8 m). However, as a result of additional hydraulic fracturing experiments, the two holes were connected. The impedance to the flow of water in that fracture system was too high, though, for the proposed 10-MW(t) heat extraction experiment. Therefore, beginning in April 1977, GT-2 was directionally redrilled to connect it with a fracture produced from EE-1.

A cement plug was set in GT-2 at a depth of 8300 ft (2530 m), and after several attempts, the hole was sidetracked using 9-5/8-in.-diam (24.4-cm) diamond bits, followed by tri-cone bits. The first trajectory apparently intersected the EE-1 fracture near its upper edge, and the resulting impedance was still too high to be useful. A second sidetracking was successful in obtaining an impedance that appeared to be acceptable.

On June 3, 1977 during a 20-h pumping experiment, cold water pumped down EE-1 at 1000 psi (6.89 MPa) was heated to 266°F (130°C), and the rate of water recovery was 85% of the injection rate. The temperature and the recovery rate are expected to increase as the system is operated (Fig. 5).

The hole was completed by cementing a string of 7-5/8-in.-diam (19.4-cm) casing from 8572 ft (2612.8 m) to the surface.

THE FUTURE

By January of 1978, the 10-MW(t) heat extraction experiment will be operating (Fig. 6). The experiment will be conducted for several months to determine the mechanical, physical, and chemical

FIG. 5. - Steam flow from GT-2 during the pumping experiment of June 3, 1977.

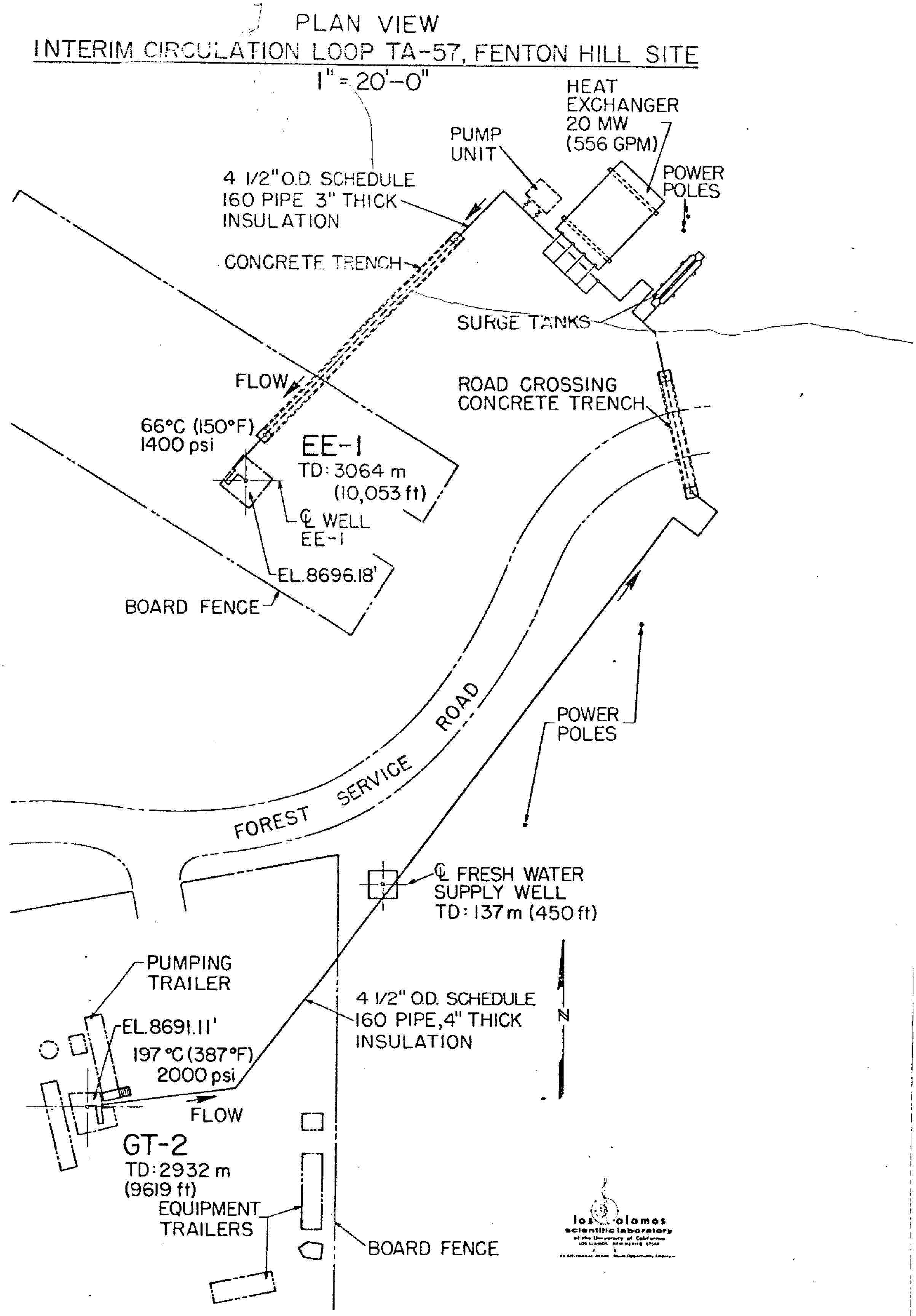

FIG. 6. - Schematic drawing of the surface facilities for the 10 MW(t) Circulating Loop.

properties of the reservoir and the heat exchange system. If it is successful, the system will be expanded to a 100-MW(t) experiment by drilling deeper to 12,500 ft (3810 m) where temperatures of 482°F (250°C) are expected. Such a facility could produce enough electricity for 10,000 consumers and would provide unique and useful information on the design and construction of a small-scale electric generating plant that uses this new energy resource.

PROJECTED DEVELOPMENT (10)

Clearly, no commercial production of energy from hot dry rock geothermal reservoirs will be attempted until at least one energy extraction system has been operated long enough to demonstrate its usefulness and reliability and to evaluate in detail its behavior and economics. If the Los Alamos project is successful, this may have been accomplished for one type of system by 1980. If that occurs, then the first demonstrations of the use of this type of geothermal energy both for generating electricity and for nonelectrical purposes could be in progress by 1981. These demonstration systems will probably be small, each producing of the order of 80 MW-thermal or 10 MW-electrical, and it will probably be necessary to operate them for 2 or 3 years before funds can reasonably be committed for construction of commercial-scale systems. However, again assuming success in the pilot-scale operations, it is quite possible that two to four commercial plants might be in operation by 1990, producing perhaps 600 MW-thermal and 80 MW-electrical. Thereafter, depending both on technical progress in the use of this and other forms of energy and on economic and environmental constraints, the rate at which new hot, dry rock systems could be developed would be controlled primarily by the rate at which deep holes could be drilled into hot rock.

ENVIRONMENTAL MONITORING

An environmental monitoring study of the project has been initiated and a report issued (7). Included in the report are descriptions of the work that has been done in three major monitoring areas: (1) water quality, both surface and subsurface; (2) seismicity, with a discussion of the monitoring strategy of regional, local, and close-in detection networks; and (3) climatology. The purpose of these programs is to record baseline data, define potential effects from the project activities, and determine and record any impacts that may occur.

The development of the hot dry rock geothermal energy resource and associated energy extraction technology is a new field of endeavor, with no established environmental guidelines. It is doubtful if the problems encountered and solutions devised in traditional geothermal systems will apply directly to hot dry rock development. Therefore, the impacts that are encountered in this project will be of particular value in making future environmental assessments for this type of energy resource development in other locations in different geologic settings.

To date, there have been no unacceptable impacts on the environment in any of the three monitoring areas.

SUMMARY

Over the past 5 years the LASL HDR Project has progressed considerably. At LASL and under subcontracts with industry, many new instruments were developed to operate in the high-temperature (200°C), high-pressure (400 bar) environment downhole, including acoustic detectors, gyroscopic survey tools, a mechanical acoustic source, temperature probes, self-potential (SP) and induced potential (IP) probes, and water samplers. Major technical achievements have been made in developing and modifying diagnostic and analytical techniques for mapping and characterizing the hot dry rock reservoir. Directional drilling and hydraulic fracturing in hot granitic rock were just two of many "firsts" achieved. For a detailed description of this work, see Reference 1.

The LASL Hot Dry Rock Geothermal Energy Project is the only U. S. field test of this huge geothermal resource. A man-made geothermal reservoir has been formed by drilling a deep hole into relatively impermeable hot rocks, creating a large surface area for heat transfer by fracturing the rock hydraulically, then drilling a second hole to intersect the fracture to complete the circulation loop. In 1974, the first hole was drilled to a depth of 9619 ft (2932 m) and a hydraulic fracture was produced near the bottom. In 1975 a second hole was directionally drilled to intersect the fracture. Although the desired intersection was not achieved, a better connection was made by redrilling into the fracture zone from the first hole. By January of 1978 a 10-MW(t) heat extraction experiment will be in operation.

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