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LOS ALAMOS HOT DRY ROCK GEOTHERMAL ENERGY EXPERIMENT

by

Roland A. Pettitt

I. INTRODUCTION[1,2]

In its broadest sense, geothermal energy is all of the heat in the Earth's interior. Most of this energy, unfortunately, is now useless to man because of difficulties in locating it and utilizing it. However, as these obstacles are overcome, power produced from geothermal sources should increase to the point at which it can satisfy a significant fraction of man's total energy needs.

Earth's physical nature is now widely enough understood so that it is probably safe to state categorically that, simply by drilling a deep enough hole, rock can be reached that is hot enough to be potentially useful as an energy source. There are many methods by which energy can be extracted from the hot rock at the bottom of such a hole and transported to the surface, and by which it can then be used beneficially. The problems of geothermal energy, therefore, derive not so much from questions about the possibility of recovering and using heat from geothermal reservoirs as from those about economics. How can this heat be recovered and used at a competitive price?

Until now, geothermal energy has been used commercially only where nature has created a geologic situation in which heat from Earth's interior is transported to the near-surface by convective circulation of steam or very hot water. A hydrothermal reservoir of this type usually leaks, thereby creating obvious surface expressions of its presence--fumaroles, geysers, or hot springs. Where these indications are found, holes are drilled and steam or hot water is recovered through them for use at the surface.

A. Present Uses of Geothermal Power

1. Dry Steam. When the hot fluid in a geothermal reservoir is superheated (dry) steam, it need only be permitted to issue from a drilled hole, be passed through a centrifugal separator to remove

any entrained particles, and be fed into a turbogenerator to produce electrical power. The world's two largest producers of geothermal power, at Larderello, Italy, and The Geysers in northern California, use natural dry steam in this way and provide relatively clean, very economical power.

2. Superheated Water. Natural hydrothermal systems in which the reservoir fluid is hot water are much more numerous than are those in which it is steam, as is suggested by the relatively common occurrence of hot springs in many parts of the world. The amount of thermal energy contained in subterranean hot water is enormous. Large-scale development of liquid-dominated geothermal systems has, however, been undertaken only at Wairakei, New Zealand, and Cerro Prieto, Mexico, for generating electricity and in Iceland, Hungary, and the Soviet Union for space heating, although there are smaller developments at several other places around the world.

3. Hot Dry Rock. Even in dry-steam or superheated-water reservoirs, much more than half of the thermal energy is contained in the reservoir rock. The heat is there even when steam or water is entirely absent. At sufficient depth, rock hot enough to be potentially useful as an energy source exists everywhere, and initial studies suggest that in many places it is at depths shallow enough to be reached at moderate cost with existing drilling equipment.

A recent survey[3] of all available regional heat-flow data indicates that about 7% of the western heat flow province of the United States--about 95 000 square miles in the 13 western states--is underlain, at a depth of 5 km (16 400 ft), by hot, but essentially dry, rock at temperatures above 290°C (440°F).

II. THE LOS ALAMOS CONCEPT

The Hot Dry Rock (HDR) Geothermal Energy Development Project is conducted by the Los Alamos Scientific Laboratory (LASL) under the sponsorship of the Energy Research and Development Administration (ERDA), Division of Geothermal Energy. The primary goals of the Project are (a) to investigate and develop methods of thermal energy extraction from naturally hot rock in the Earth's crust by manmade underground circulation systems, (b) to demonstrate the commercial feasibility of such systems, and (c) to encourage and assist further industrial development and widespread application of this new technology. At this time, the only large-scale HDR field experiment in the nation is conducted under this project.

For the last five years, the Los Alamos Scientific Laboratory has been actively investigating the potential for, and problems associated with, extracting geothermal energy in those parts of the United States that contain hot, dry rock at moderate depths.

In the Los Alamos concept, a man-made geothermal reservoir would be formed by drilling into an identified region of suitably hot rock, and then creating within the rock a very large surface area for heat transfer by use of large-scale hydraulic-fracturing techniques developed by the oil industry. After a circulation loop is formed by drilling a second hole into the fractured region, the heat contained in this reservoir would be brought to the surface by the buoyant circulation of water, with no need for pumping. The water in the loop would be kept liquid by pressurization at the surface, thereby increasing the rate of heat transport up the withdrawal hole compared to that possible with steam. Figure 1 is a conceptual diagram of a man-made geothermal system.

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

III. 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 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 volcanism, a large amount of heat is still retained in rocks underlying the entire area within a few kilometers of the surface.

Scientists at the Los Alamos Scientific Laboratory, located on the eastern side of the Valles Caldera, have been interested for some years in tapping the residual heat of this old volcano.

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 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,[4] including heat-flow measurements in holes drilled 200-300 m, which confirmed heat flow values of about 5 heat flow units (HFU)* on the west side of the caldera.

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 785 m (2576 ft). It penetrated about 150 m (500 ft) into the basement granitic rock and reached a temperature of 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 to create such a system.

On the basis of these studies and field experiments, a site on the Jemez Plateau about 32 km (20 air miles) 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

*HFU = 10^{-6} cal/cm^2/s. The worldwide average heat flow is 1.5 HFU.

"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 1.5 km west of the outermost ring fault of the Valles Caldera and about 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 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 limestones (Magdalena Group) of Permian and Pennsylvanian age.

IV. 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 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.

A. 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 35-cm-diam (13-3/8-in.) casing be set to a depth of 488 m (1600 ft). The Precambrian granitic surface was reached at 733 m (2404 ft), and a second string of 27.3-cm-diam (19-3/4-in.) casing was set from the surface to 773 m (2535 ft). Drilling continued to 2042 m (6700 ft) using 24.4-cm-diam (9-5/8-in.) 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 2932 m (9619 ft), and a 185-m-long (608-ft) liner was cemented into the bottom section of the hole to facilitate seating of packers for future fracturing experiments. An 11.6-m (38-ft) section of hole was left uncased at the bottom. The equilibrium bottom-hole rock temperature was 197°C (386.6°F).

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

B. Hole EE-1

The second hole was located 77 m (252 ft) northeast of GT-2 (Fig. 3). Drilling began in May 1975 and was completed in October at a depth of 3064 m (10 053 ft) and a bottomhole temperature of 205.5°C (402°F). EE-1 was cased to 1957 m (6420 ft) with three strings of casing, the deepest being 27.3 cm (19-3/4 in.) in diameter.

Directional drilling techniques were used below this casing to angle EE-1 toward the pressumed fracture at the bottom of GT-2. The hole was drilled through a 205° spiral, turning counterclockwise from an initial northwest heading to a northeast heading (Fig. 4). On October 14, 1975, the intersection was accomplished, creating for the first time a man-made connection between two drill holes in hot, nearly impermeable basement rock. After the intersection was completed and circulation was established, EE-1 was cased to 2926 m (9600 ft) with a 19.4-cm-diam (7-5/8-in.) 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 0.9 m/h (2.8 ft/h) to a maximum of 11.6 m/h (38 ft/h). The maximum standard drilling interval for a single bit was 205 m (672 ft) in 75 h; the maximum directional drilling interval was 34.4 m (115 ft) in 5 h. These two holes constitute the bulk of existing drilling experience in hot granitic rocks using conventional oil-field equipment.

C. Work-Over Operations; GT-2

During the drilling operations in EE-1, a work-over drilling rig (Fig. 3) was moved over GT-2 to continue the experiments to increase understanding of the hydraulic-fracturing and fracture-extension behavior, *in situ* stress condition at depth, and the interactions of pressurized pore fluids with this stress field.

A major effort continued toward developing fracture-mapping and borehole-ranging techniques. Problems associated with poor acoustic coupling of geophones to the borehole wall, failure of geophones under high-temperature conditions, and the necessity of downhole amplification of geophone signals were attacked. A successful clamping device was developed to couple the geophone instrument package to the borehole, high-temperature downhole electronic amplifiers were tested and installed and geophone components were modified to withstand higher temperatures. Partially successful calibrations of downhole seismometer (geophone) sensitivity were made using surface dynamite shots and an explosive thumping device with signal averaging capability (Dinoseis) to generate acoustic signals. Results of these tests showed an attenuation in the signal amplitude in various directions, which suggests the presence of acoustic-absorbing regions, including the upper sedimentary and volcanic layers at the site.

Other techniques for determining fracture orientation and geometry were also examined. Among these were electrical, magnetic, seismic reflection, seismic refraction, seismic transmission, characteristic vibration, and tiltmeter methods, and--in cooperation with other organizations--development of improved high-temperature impression packers and borehole televiewers.

D. GT-2 Fracturing Experiments

In preparation for fracturing experiments in GT-2, the cemented-in liner was perforated at depths of 2790, 2820, 2850, 2880, and 2910 m (9150, 9250, 9350, 9450, and 9550 ft). Attempts to hydraulically fracture through perforations were hindered by packer leakage problems; eventually, however, fractures were produced and useful data collected in all but the 2790-m zone. Fracture initiation pressures* in these experiments varied from 121 to 305 bars (1750 to 4420 psi) as compared with 121 bars required in the open-hole section at 2930 m (9600 ft). Fracture extension and reopening pressures were also erratic but generally higher than expected. For example, at 2880 and 2910 m (9450 and 9550 ft), fracture reopening pressures were 210 and 350 bars (3000 and 5000 psi), respectively, which suggest a geochemical healing process or a particle plugging process at the

*Hydraulic pressures are measured at the wellhead level. The true hydraulic pressure at the location of a hydraulic fracture is approximately this given pressure plus normal hydrostatic pressure of a column of water extending from the wellhead to that depth.

fluid-injection path into the fracture. Pore-pressure effects, wellbore stress concentrations, and possible tectonic stress variations may also contribute to these observed results, but further investigation is necessary.

In this experimental series, attempts were made to create a circulation path between two points of the same borehole by trying to unite two hydraulic fractures in GT-2. Theoretical calculations indicated that the local stress field around an inflated or growing fracture might induce another fracture to intersect it. The procedure followed was to use a straddle packer across both sets of perforations at 2880 and 2910 m. About 1900 liters (500 gal) of water were injected, a volume equivalent to a single, 30-m (100-ft) radius fracture, and therefore, presumably large enough to create communication between 2880 and 2910 m. However, no communication was observed. Subsequent similar experiments involving other fractures in this region also did not indicate positively that any interfracture connection existed.

Following completion of the fracture experiments through perforations in the liner, the open-hole section at about 2930 m (9600 ft) was pressurized and the fracture at the bottom was presumably extended to a 120-m (400-ft) radius. Whether the fracture actually extended from the bottomhole section of GT-2 during this pump-up is now uncertain. Although, undoubtedly, a fracture was initiated at about 117 bars (1700 psi) from the open-hole bottom section during previous pressure testing of the liner assembly, fracture extension may have occurred from other sections of perforated casing liner, particularly in the 2830-m (9250-ft) zone where fracture breakdown and extension pressures were lowest. Furthermore, the casing might have been ruptured at 2805 m (9200 ft) during previous cleanout operations, possibly creating another point for fracture formation and extention.

V. ENVIRONMENTAL MONITORING

An environmental monitoring study of the project has been initiated and a report issued.[5] 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.

VI. SUMMARY AND HIGHLIGHTS

The planned procedure was to drill EE-1 in such a direction as to intersect the hydraulically-produced target fracture formed near the bottom of GT-2. The connected system was then to be used in a fluid circulation loop that would extract 10-20 MW of thermal energy using an air-cooled heat exchanger at the surface (Fig. 5). The heat exchanger is designed for a flow rate of 556 gpm at 2500 psi; inlet temperature is 204°C (400°F), outlet temperature is 66°C (150°F).

The desired intersection was not made, but a connection between EE-1 and GT-2 by a hydraulically-produced fracture zone system was established. At the present time, the impedance to fluid flow in this downhole fracture zone results in a pressure drop that is too high to permit fluid flow rates that would support a 10- to 20-MW(t) heat extraction experiment. Although the exact reasons for the failure to achieve the desired simple intersection have not been established, two primary contributing factors are clear. First, there was considerable uncertainty concerning the relative locations of the two boreholes near full depth, because conventional borehole surveys provided ambiguous results and borehole ranging techniques had not yet been sufficiently developed. Second, the orientation, linear extent, and general shape of the target fracture were poorly known when EE-1 was being drilled. Present plans call for attempts to reduce the flow impedance of this fracture system to permit the 10- to 20-MW (thermal) heat extraction experiment to be carried out.

In the course of the work outlined above, many diagnostic and analytic techniques have been developed. Instrumentation and equipment capable of performing necessary measurements at downhole temperatures up to 200°C (390°F) and pressures up to 400 bars (6000 psi) have been developed. A list of major technical achievements follows. For a detailed description of the work involved, see Ref. 6.

1. Successful drilling into hard crystalline rock was accomplished to depths of about 3 km (10 000 ft) and bottomhole temperatures of about 200°C (390°F).

2. Hydraulic fractures in the crystalline rock with radii as large as 150 m (500 ft) were successfully produced in open-hole sections and through casing perforations, at temperatures up to 200°C.

3. Values of <u>in situ</u> permeability of the Fenton Hill granite were measured, and are in the low microdarcy range. The permeability shows a strong dependence on pore fluid pressure, in agreement with laboratory permeability measurements on core specimens.

4. Directional drilling at depths of up to 3 km was successfully accomplished.

5. At least 90-95% of water injected into fractured regions was recovered.

6. A connection was established between two deep boreholes through a fractured region of hot granite for the first time. The flow impedance of this connection had an initial value of about 1320 bars/liter/s (1200 psi/gpm), and has now decreased to about 30 bars/liter/s (27 psi/gpm).

7. Instruments were developed to operate for several hours under the high-temperature (200°C) and high-pressure (400 bars) downhole conditions. Included were acoustic detectors, a mechanical acoustic source, temperature probes, self-potential (SP) and induced-potential (IP) probes, and water samplers.

8. The compressional and shear (P and S) components of seismic signals produced by fracture extension and inflation were detected downhole. Analyses of particle motion at the P-wave arrival provide a map of what is believed to be the main fracture originating near the bottom of GT-2, as well as a preliminary map of the bottomhole EE-1 fracture.

9. Acoustic ranging has quantitatively identified the relative positions of GT-2 and EE-1 at several depths.

10. SP and IP techniques have determined vertical fracture lengths at the borehole, as well as fluid-injection points and precise casing location.

11. Pressure-flow and fluid residence time distribution studies have measured certain properties of the downhole system, such as the product of the effective fracture surface area and the square root of the permeability, and the effective fracture volume for circulating fluid.

12. Core sample studies have provided physical and chemical data that will aid in predicting and analyzing fracture initiation and growth, in predicting downhole heat transfer rates, in altering reservoir rock permeability, and in predicting and controlling scaling and corrosion problems.

13. Techniques were developed to examine reservoir performance by modeling fluid flow and heat transfer in hydraulic fractures and wellbores of specified geometries.

14. A geothermal power-production system model was formulated that bases the total capital investment for a power plant on the costs of production and reinjection wells and major equipment.

To accomplish these results, industrial participation was obtained in many areas. Private firms were engaged under contract for the drilling of GT-2 and EE-1, for workover operations in GT-2, and for activities closely associated with the drilling. In addition, subcontracts were arranged for downhole instrumentation development, including acoustic sources and detectors, borehole logging equipment, and acoustic data analysis.

Many of the techniques, equipment, and instruments required for creating and characterizing a hot dry rock reservoir at a depth of 3 km and a temperature of 200°C were not available at the start of this project. Although considerable progress has since been made in developing these tools, the task continues to be formidable. Theoretical and laboratory studies, while valuable aids, cannot by themselves produce methods and equipment that are certain to work satisfactorily in the field. Only after deep boreholes became available could capabilities be developed through field experiments. For example, in the development of fracture-mapping methods, several field techniques, such as monitoring of surface seismic signals during downhole fracturing, the use of surface and near-surface active sources combined with downhole acoustic detectors, and use of a borehole televiewer, were tried before it was determined that downhole acoustic detection was required. At that time, suitable equipment had to be designed and built and appropriate data analysis methods had to be developed. These methods and equipment will have to be upgraded and new tools developed, as reservoirs are created at greater depths and higher temperatures.

During the next few months, additional field experiments and modeling studies will be conducted to better characterize the downhole reservoir system. It is anticipated that an attempt will be made to reduce the flow impedance by chemical leaching, fracture propping with particles, or fracture extension. If the impedance can be sufficiently reduced, the 10- to 20-MW(t) circulation loop experiment will then be conducted. If it cannot, present plans call for redrilling the bottom portion of either EE-1 or GT-2 to intersect a known fracture in GT-2 or EE-1, to create a connection of the kind initially attempted. Provided this new connection has sufficiently low impedance, the 10- to 20-MW(t) circulation loop experiment will then be conducted.

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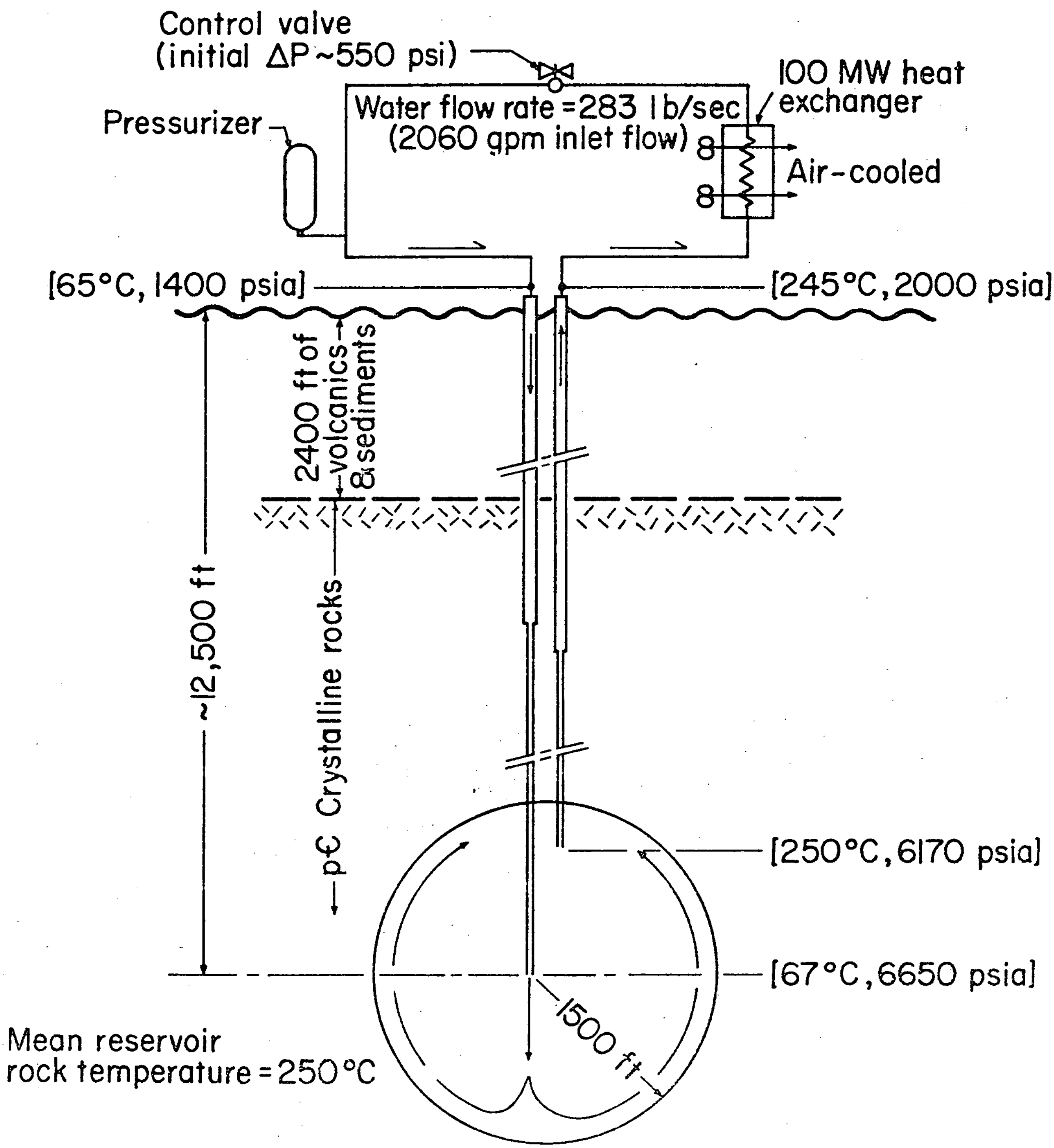
LIST OF FIGURES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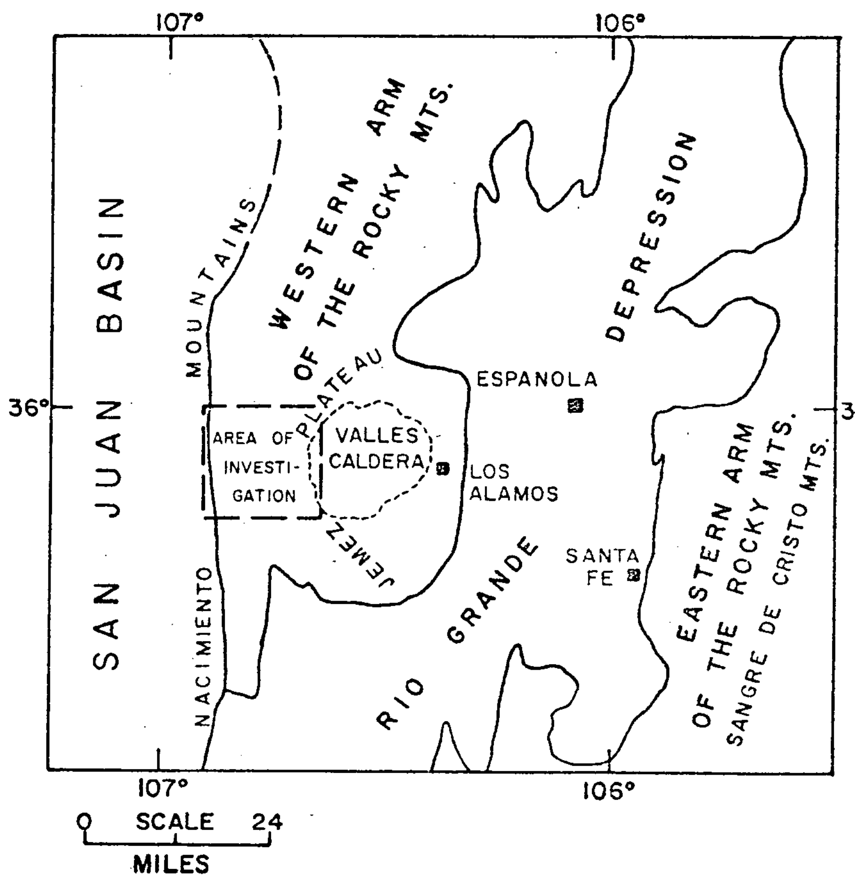
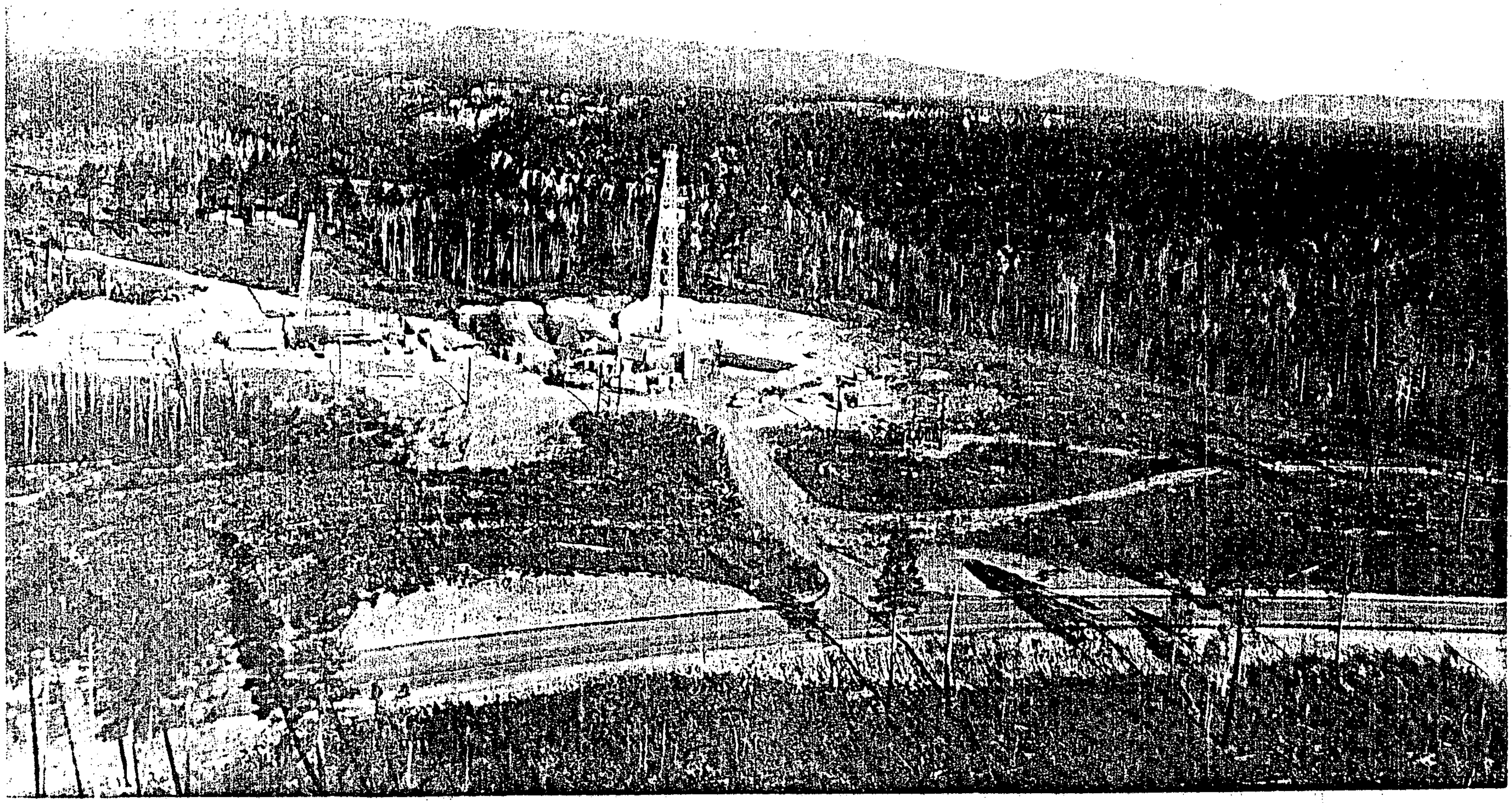
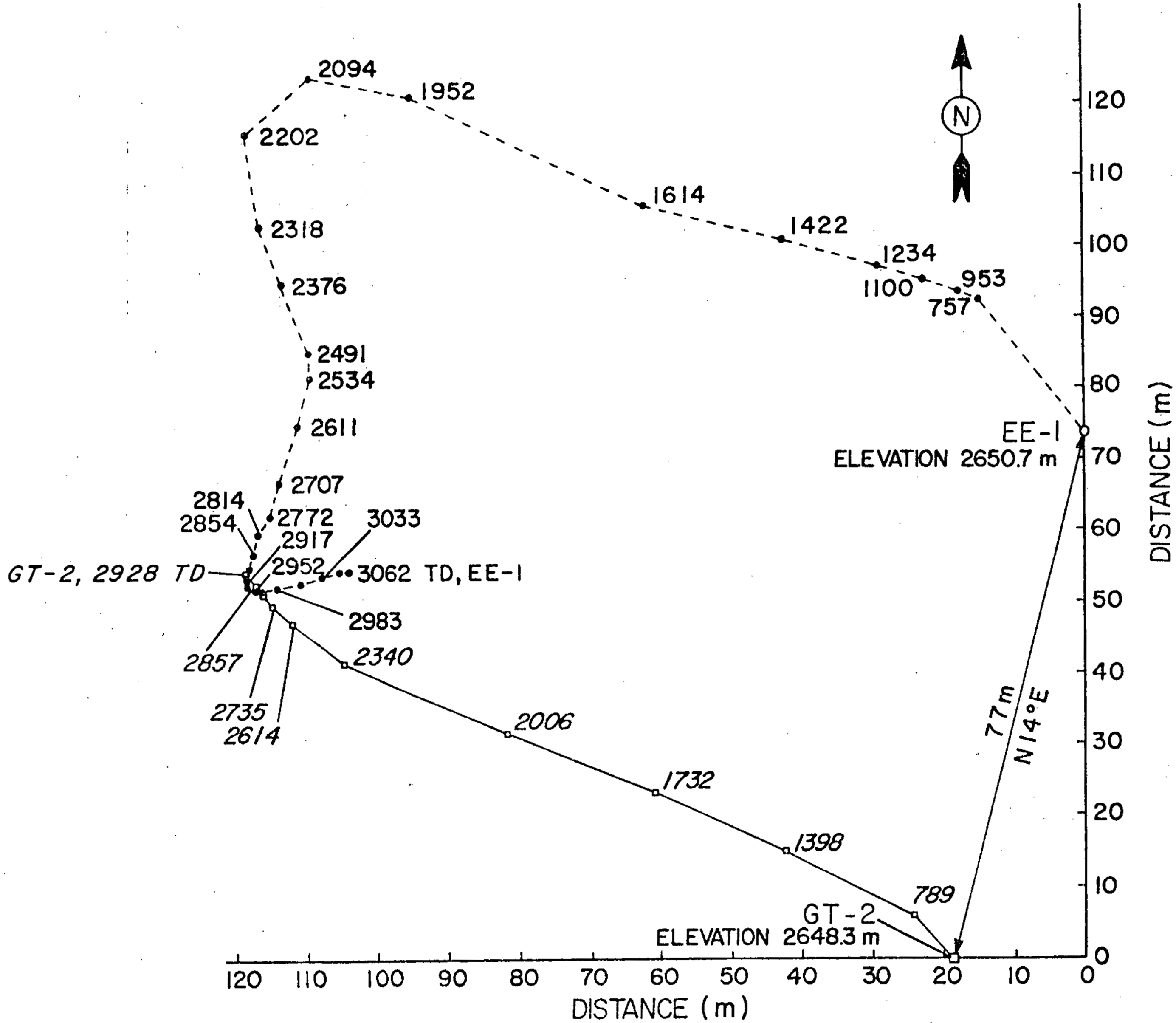
100 MW heat exchanger
Water flow rate =283 lb/sec
(2060 gpm inlet flow)
Pressurizer
Air-cooled
[65°C, 1400 psia]
[245°C, 2000 psia]
2400 ft of volcanics & sediments
~12,500 ft
p€ Crystalline rocks
[250°C, 6170 psia]
[67°C, 6650 psia]
1500 ft
Mean reservoir
rock temperature = 250°C



Index map of major structural features and area of investigation for the Geothermal Test Site in north-central New Mexico. (Modified from Kelley[1])

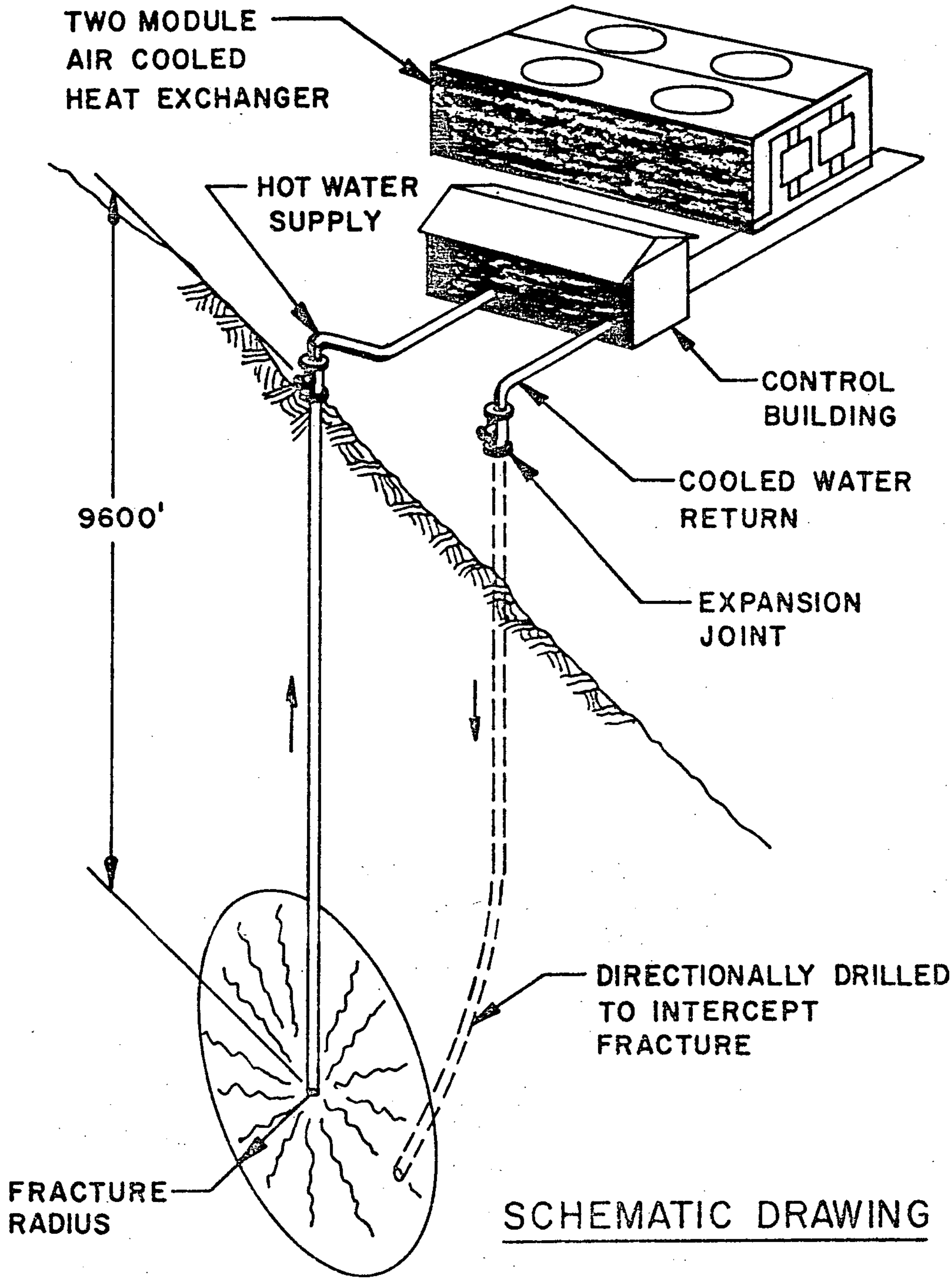




DIRECTIONAL DRILLING IN GT-2 AND EE-1, PLAN VIEW

(DEPTHS, IN m, MEASURED FROM ELEVATION TAKEN AT CASING FLANGE NEAR GROUND LEVEL)

20 MW (THERMAL) DRY HOT ROCK ENERGY SOURCE DEMONSTRATION



SCHEMATIC DRAWING