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TITLE: POTENTIAL FOR HOT-DRY-ROCK GEOTHERMAL RESERVOIRS: EXPERIMENTAL RESULTS

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POTENTIAL FOR HOT DRY ROCK GEOTHERMAL RESOURCES; EXPERIMENTAL RESULTS

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ABSTRACT

Development of hydrothermal geothermal resources associated with volcanic fields of the circum-Pacific region is progressing at an accelerating pace (Anon., 1982). This valuable energy resource base can be greatly expanded by forming artificial reservoirs in hot but dry rock (HDR). Such rock contains insufficient permeability and fluid for natural hydrothermal development, but water pumped in a circulation loop through a HDR reservoir (hydraulically fractured between two drill holes) is being tested and evaluated. The formation of such _in situ_ heat transfer systems, and subsequent testing of the man-made geothermal reservoirs in the Jemez volcanic field, New Mexico have already indicated the technical feasibility of the hot dry rock (HDR) geothermal concept. Documented production history and heat-extraction data obtained during the period from 1978 to 1980 have confirmed heat transfer, low water loss, and predictable thermal drawdown models for the HDR systems. During a nine month test of closed-loop heat extraction operations, 15×10^6 kWh of thermal energy were produced. The effective heat-transfer area and volume of the reservoir increased due to secondary fracturing caused by thermal contraction of the reservoir rock, and sustained pressurization. Drilling, fracturing, and testing of a larger, hotter reservoir system is now underway on a HDR geothermal reservoir of commercial size.

The natural hydrothermal resource is only a small part of the thermal potential associated with young volcanic fields; the large number of hot but "dry" wells drilled each year in the search for hot water or steam

dramatically support this observation. With the introduction of technically controlled man-made geothermal reservoirs, the high-grade geothermal areas being developed today could be greatly expanded in production, and the number of abandoned hot but dry wells reduced.

INTRODUCTION

The U.S. Government supports a significant number of research and development programs to further geothermal energy development. Many of the projects, initiated during the 1973 post oil-embargo period, have been directed at providing improved assessments of the national geothermal resource (White and Williams, 1975; HDRAP, 1977; Muffler, 1979; Rowley, 1982). Both natural (hydrothermal) resources and the much more extensive HDR resources are being evaluated. The majority of U.S. projects concentrated on expanding the resource by supporting exploration, drilling, and development of hydrothermal reservoirs. The Hawaian Geothermal Project (Shupe, 1982) expanded our knowledge of basaltic reservoirs associated with active volcano heat sources. The Raft River, Utah, project (Russell, 1982) demonstrated the feasibility and technology to produce electricity from extensively known hydrothermal reservoirs with fluid temperatures in the 150°C range. At Baca, New Mexico there is a demonstration of the first high-grade (>180°C) hot water (non-steam) reservoir system (Dondanville, 1979) associated with a volcanic heat source. Support was also provided to commercial firms attempting to exploit the highly chemically-charged fluids of the sand-shale reservoirs in Imperial Valley, CA. All the above research and development projects have provided demonstrations of energy production from a spectrum of different hydrothermal reservoirs, and therefore serve to expand our experience and knowledge to a much wider variety of thermal resources.

The Los Alamos project logically projects the use of man-made reservoirs to extract energy from geothermal areas where natural fluids are insufficient for the development of a hydrothermal resource. The geothermal resources available through the use of HDR technology are enormously larger than the total available from all of the many types of natural hydrothermal reservoirs (Muffler, 1979; Heiken et al., 1982). The

HDR resource is enormous and can be used to expand the output of electricity and of hot water from hydrothermal developments. In addition to the high grade geothermal areas, HDR may even be able to supply industrial and direct heat energy from deep wells drilled in regions with "normal" geothermal gradients. Therefore the achievement of HDR technical feasibility can open vastly expanded thermal resources for future development.

The objective of the Los Alamos Hot Dry Rock (HDR) geothermal program is to investigate and develop the technical feasibility, and to provide a commercial-scale demonstration of an artificial geothermal reservoir. This research is focused on a field site in north central New Mexico, (Fig. 1), where a large mass of hot, crystalline rock with extremely low permeability exists below the flanks of a young silicic volcanic system, the Valles Caldera.

The first test well, completed in 1972, confirmed the existence of a HDR resource. Permeability within the Precambrian crystalline rocks was determined to be low enough for the experiments. Four deeper boreholes subsequently were drilled through the 800 m thick, insulating young volcanic and sedimentary sequence into the underlying hot Precambrian complex. For one wellbore pair, the wells were connected at 2.7 to 3.0 km depth by hydraulic fracturing. Heat was extracted by circulating water down one well into the fractured rock, and recovering it in the second well to provide a closed-loop heat transfer system with reservoir rock temperatures of 185°C. This system afforded the first technical feasibility demonstration of a HDR geothermal reservoir.

Reservoir tests of this first HDR system were completed in December, 1980. The work conclusively demonstrated that a geothermal reservoir can be artificially produced where rock has low permeability and no naturally circulating fluids are present. Heat stored in the rock is recovered by creating an artificial fracture path that will transmit injected water through the hot rock mass.

Drilling of a second pair of deeper wells began in May of 1979, and was finished in August of 1981. This system is currently undergoing fracturing and reservoir evaluation tests. The wells are inclined at 35° from the vertical in the reservoir section; a bottom hole temperature of 320°C was attained. The production wellbore is 380 m above the injection wellbore in the inclined parts, thus providing a configuration that allows development of a parallel vertical fracture system that is a factor of ten larger than that of the first reservoir. A heat extraction system of commercial scale will therefore be possible. The potential of such HDR reservoir systems for both electricity production and direct heat applications has proven attractive to several other countries. The Los Alamos HDR Project is supported by the U.S. Department of Energy and by significant contributions from the Federal Republic of Germany and Government of Japan. Scientists and engineers from both countries are in residence at Los Alamos and participate actively in the project. Projects based upon Los Alamos concepts are underway in West Germany, Scandinavia, Japan, France, the United Kingdom, and Italy.

HDR RESERVOIR CONCEPT

Forming a HDR reservoir involves drilling a pair of wells with one injection well and one production well. A vertical hydraulic fracture system is then formed between the two wells (Fig. 1). The fracture serves as the heat transfer surface for heat extraction by water pumped down the injection well. The original HDR reservoir formed at Fenton Hill approximates this simple form. The two wells were nearly vertical and therefore only a limited rock volume was available to fracture between the two wells. Nevertheless, two different heat transfer systems were created, and extensive reservoir performance data were collected. Initial tests were conducted in 1977 and 1978; additional hydraulic fracturing extended the reservoir area several fold. The larger system was evaluated for periods of up to nine months in 1979-1980. Table 1 summarizes the Fenton Hill reservoir results.

Technical successes of the first experiments led to the decision by the U.S. Department of Energy in 1979 to construct a larger, commercial size system in a hotter reservoir. The extended heat transfer fracture area would be generated by drilling inclined injection and production wells. Figure 1 illustrates the concept. These engineering-system wells were completed in the fall of 1981 and now are undergoing fracturing and reservoir evaluation tests. The bottom-hole temperature is 327°C. Inclined wellbores may permit the spacing of multiple, vertical fractures about 50 m apart horizontally to open up a significant heat transfer area; ten to twenty fractures are possible. Such a system can produce 35 to 50 MW(t) of thermal power. Drawdown of the reservoir temperature is predicted to be less than 10% within ten years. A study of the economics of a power station based upon this reservoir configuration (Murphy, 1982) indicates that the break-even cost of electricity is 4.4 cents per kWh.

RESERVOIR TESTING RESULTS

The first deep borehole of the Fenton Hill research system, Geothermal Test-2 (GT-2) was drilled in 1974 to a depth of 2.9 km where the temperature was 197°C. A series of hydraulic fracturing experiments was then performed in GT-2. The energy extraction well (EE-1) was drilled toward the largest of the GT-2 fractures in an effort to form a heat-extraction loop. The intent was to produce a large vertical spacing between the inlet and outlet locations in order to maximize the effective heat-transfer area while still achieving a reasonably low impedance to flow. Low flow impedance is required for high rates of heat extraction. Higher pressures will normally result in greater in-situ permeation water losses. After trying several methods of improving communication between the two boreholes, an acceptable connection was achieved by side-tracking the GT-2 wellbore at a depth of 2.5 km and redrilling it towards the top of a large fracture centered at a depth of about 2.75 km in EE-1. The well-bore penetrated several major opened natural fractures (joints), but probably did not intersect the major vertical fracture. This path had low enough flow resistance to proceed with heat-extraction tests. The combination of the original GT-2 wellbore with the redrilled path is referred to as the GT-2B wellbore. In subsequent testing of the reservoir, EE-1 was used as the injection well and GT-2 as the production or extraction well.

The biotite granodiorite, like the other Precambrian rocks at Fenton Hill, contains many joints or natural fractures which are seen at 0.01 to 0.1 m intervals in cores, and are recognized on certain geophysical logs. These joints are almost invariably sealed by a variety of minerals including calcite, alkali feldspar, epidote, and quartz. The sealing processes have been so effective that intrinsic permeability and water losses during flow tests have been extremely low. Apparently, recurrent seismic activity, which commonly keeps joints open in many natural hydrothermal systems, has been too low in the Fenton Hill area to reopen the sealed fractures.

Reservoir performance was first evaluated during a 75-day period of closed-loop operation from January 28 to April 13, 1978 (Fig. 2). Hot water from GT-2B was piped to a water-to-air heat-exchanger where the water was cooled to 25°C before reinjection. Makeup water, required to replace downhole permeability losses to the rock surrounding the fracture, was added to the cooled water and pumped down EE-1, and then through the fracture system. Heat was transferred to the circulating water by thermal conduction through the nearly impervious rock to the fracture surfaces. The average thermal power extracted during this test was 3.1 MW, evaluated at the surface. The flow impedance, a measure of the pressure loss through the reservoir per unit flow rate, initially 1.7 GPa s/m^3 (15 psi/gpm), decreased by a factor of five as thermal contraction and continued pressurization resulted in the opening of natural joints that provided additional communication with the producing well. Water losses to the rock surrounding the fracture steadily diminished and eventually this loss rate was about 1% of the injected rate. The geochemistry of the produced fluid was benign and the seismic effects associated with heat extraction were immeasurably small. However, the relatively rapid thermal drawdown of the produced water from 175 to 85°C (345 to 185°F), indicated that the effective heat-transfer area was small, about 8000 m^2 (86,000 ft^2), and essentially confined to a fractured region between the main injection and production zones in the EE-1 and GT-2B wells (Murphy et al., 1977; Tester and Albright, 1979; Murphy and Tester, 1979).

A high back-pressure flow experiment (Brown, 1982) was run for 28 days during September and October 1978. The purpose of this experiment was to evaluate reservoir flow characteristics at high mean pressure levels induced by throttling the production well. As a consequence of these higher operating pressures, the flow impedance was reduced several fold, but as discussed later, the effective heat transfer area remained nearly the same. It was discovered during this experiment that, as a result of deteriorated casing cement, the water injected into EE-1 was flowing up the wellbore/casing annulus to depths as shallow as 700 m (2500 ft). This posed a potential danger to the shallow aquifers, as well as creating high water losses. To lessen these problems, and also to investigate the feasibility of creating a larger fracture from the same wellbores, the EE-1 casing was recemented (Pettitt, 1980) near the casing bottom at 2.93 km (9600 ft). An enlarged reservoir was then formed by extending a hydraulic fracture from an initiation depth of 2.93 km (9620 ft) in EE-1, about 200 meters deeper than the first fracture in EE-1. The resulting large fracture propagated vertically upward to at least a depth of 2.6 km (8600 ft) in GT-2B. Thus, the new fracture appeared to have a minimum inlet-to-outlet spacing of 300 m (1050 ft), more than three times that of the reservoir prior to re-fracturing, which suggested that the effective heat-transfer area might be significantly greater than in the first reservoir. Preliminary evaluation of the new reservoir was accomplished during a 23-day heat-extraction and reservoir-assessment experiment (Murphy, 1980).

Long-term reservoir characteristics were investigated in a second evaluation, beginning March 3, 1980 (Fig. 2). Because of large reservoir size and resulting slow thermal drawdown, a lengthy flow test of 286 days was necessary to evaluate the reservoir. Because of the low power levels produced with these research size reservoirs, no attempt was made during the reservoir tests to use the heat for generating electrical energy or for some other useful purpose. Instead the heat was simply dissipated to the atmosphere with an air cooled heat-exchanger. However, during the long-term test a small electrical generating unit, designed and assembled by Barber-Nichols Engineering, Denver, Colorado (Olander, 1979), was incorporated into the circulation loop. This generator extracts energy from the super-heated water produced from the reservoir and heats the generator working fluid, refrigerant 114, which is then expanded through a single stage turbine. It produced a peak power of 60 KW(e).

Reservoir geometry can be inferred from several different experiments and a variety of other data. The most common data used are those obtained from tracer, spinner, and temperature logs, and from heat-extraction experiments. An early conceptual model of the system indicated a small fracture exploited in the early experiments, and an enlarged fracture system during the long-term experiments. Fractures induced are vertical and they connect with sloping natural joints, which dip at about 60°. The hydraulic fractures are shown as circular in (Fig. 1), but this is speculative. However, unlike oil and gas reservoirs where distinct changes in the lithology, such as upper and lower confining shale layers, result in roughly rectangular fractures, it is thought that the fractures in this HDR system are roughly circular because of the homogeneity of the biotite granodiorite.

Almost all of the heat-transfer area in this model of the system probably comes from the hydraulic fractures. The heat-transfer area of the inclined joints is expected to be small, and so is combined for computational convenience with the main hydraulic fractures. The first two reservoirs of the HDR energy system at Fenton Hill showed growth in heat-transfer area through all segments of operation. This growth has resulted from pressurization, cooling (thermal contraction), and fracture face displacement or movement. During the early experiments thermal drawdown was significant because of the small size of the reservoir involved. In later experiments drawdown was much less in the larger reservoir. No drawdown was observed during early experiments in the larger reservoir and, during the 286 day test, the reservoir sustained only an 8°C thermal drawdown (Fig. 2). Modeling of these early reservoirs led to an estimated initial heat-transfer area of 8000 m^2, but by the end of the testing the heat-transfer area increased to about 45,000 m^2 or 50,000 m^2, about six times larger. As measured by tracer chemicals, the volume of the reservoir had grown from 11 m^3 to 266 m^3 through the course of the research experiments.

Water losses were low; for comparable operating pressure conditions, only a 30% increase in water loss was observed for a six-fold increase in heat-transfer area. The impedance remained constant throughout the longer drawdown test at about 1.6 GPa s/m^3. This is in contrast with the first reservoir that exhibited a sharp decline in impedance, presumably due to the large thermal drawdown that the smaller first system experienced. If an impedance similar to that experienced during the final tests occurs in the deeper, hotter reservoir currently under development, the system could essentially be self-pumping due to the density difference of the water in the cold injection well and hot production well.

Geochemical monitoring of the system provided valuable insight concerning pore fluid displacement and flow connections in the reservoir. The concentrations of dissolved chemicals in the produced water were low and the pH was near neutral, so the produced water was of good quality. The produced water is potable and problems with corrosion or scaling of surface equipment have been minimal. Seismic activity in the research reservoirs has been insignificant. Seismic events associated with heat extraction have measured less than -1 on the extrapolated Richter scale.

HDR FIELD TEST IN JAPAN

In Japan, HDR field tests have been carried out 4 km west of Yakedake volcano, Gifu Prefecture. Boreholes penetrate a sequence of Paleozoic sedimentary rocks from depths of 43 m to 1000 m. Borehole HSV-1 was drilled to survey a potential hydrothermal reservoir to a depth of 1000 m, where the borehole was found to be dry. The bottom-hole temperature was high; 180°C at 1000 m. Casing was placed to a depth of 600 m.

In 1977, a HDR research project was started in HSV-1 at Yakedake. Pressure was applied along the entire wellbore, with a flow rate of 75 ℓ/min. There was no indication of breakdown and the maximum wellhead pressure was 100 kg/cm^2. Several fractures may have been initiated at depths between 605 and 740 m, according to a temperature log. Casing was placed down to 995 m to leave an open-hole section of 5 m at the bottom of hole and pressure was applied again in 1979. A fracture was created at the bottom of the hole. The diameter of HSV-1 is only 5.6 cm so that packers and commercial logging tools, except for the temperature tool, cannot be used.

To provide more data on fracture initiation and extension, three boreholes were drilled beside HSV-1 in 1980. The depth of these holes is 300 m and bottomhole temperature is 60°C. One of them, HY, with a diameter of 16 cm, was used for fracturing and the other two wells, S1 and S2, 6 cm in diameter were used for observation. Acoustic emission package tools, which consist of accelerometer, geophone, and hydrophone sondes, were placed in the S1, S2 and HSV-1 boreholes. Hydraulic fracturing tests were repeated along the HY hole, using an open hole packer. Several fractures were initiated during the experiments but acoustic tools which were located in the HSV-1 hole received reduced amplitude signals because of the uncemented casing pipe installed in this hole. In 1981, two more observation holes, S3 and S4, were drilled. The distance between the HY hole and these four observation holes is about 50 m. An open hole packer was used in fracturing tests for zone isolation. Several fractures were created and connected to the S3 hole. Short term loop flow tests were conducted. During the 5th test, water was circulated at flow rates of 50 to 140 ℓ/min for 70 minutes and the maximum temperature of water recovered was 40.2°C. High quality micro-seismic signals were detected during fracturing and circulation tests and are now being analyzed.

This experimental project will terminate in 1983. It is planned that a new test site will be selected and surveyed during 1984-1985 and then experimental studies will be started to establish a several-megawatt HDR pilot plant by introducing technology developed at the Yakedake and Fenton Hill projects.

RESOURCE POTENTIAL

There are ample geothermal resources in the circum-Pacific region; in fact there are few countries within this region without them. Associated with subduction zones around the Pacific are hundreds of young volcanic fields, and also areas of crustal extension showing high thermal gradients and obvious surface manifestations of heat, such as hot springs, geysers, and volcanic eruptions (for a general review see Healy, 1975). Of the thousands of pages written about the geothermal resources of the Pacific margins, nearly all of it concerns only natural hydrothermal systems. What most of the discussions of high-temperature resources don't point out is the fact that hydrothermal systems make up only a small part of the total geothermal resource present in each area. The many hot but "dry" wells (i.e., wells without enough fluid for production) drilled each year by geothermal developers is an indicator of the elusive nature of hydrothermal systems. In order to take full advantage of geothermal energy in the Pacific region it is necessary to develop man-made (hot dry rock) geothermal systems.

The largest natural, high-grade, geothermal resources are associated with large calderas. It is generally assumed that a caldera-forming eruption has left a large magma body at shallow depth, which will require several million years (Myr) to cool to ambient temperature (Smith and Shaw, 1975). Young, large calderas are common along plate margins around the

Pacific. Because of the visible indicators of hydrothermal activity it has always been assumed that these large features are occupied almost exclusively by hydrothermal systems. Although every caldera is a little different, many of them contain very thick (1 to 2 km) deposits of densely welded tuff. Tuffs deposited during caldera collapse form an initially hot deposit of great volume. Caldera fill is kept hot by shallow magma bodies and dike-sill systems which invade and congeal beneath the caldera for several hundreds of thousands to several Myr (Smith and Shaw, 1975). Within densely welded tuffs that fill a caldera, the only permeability is fracture permeability. Indeed, in most calderas, hydrothermal systems are associated with fairly active faults crossing the crater and along caldera margins (summarized in Heiken and Goff, 1982). Most of the geothermal resource lies within the caldera, locked up in tuff units with low matrix permeabilities. Surrounding a caldera is also an extensive thermal aureole, which could also be developed using man-made geothermal reservoir systems.

Much less is known of the hot dry rock geothermal resource in and near composite cones. Within the Cascade Range of the western United States, there has been some limited drilling into composite cones. When the shallow, water-filled, permeable carapace of pyroclastic rocks and lava flows has been penetrated, there is a considerable resource available near the base or core of one of these volcanoes. There is, however, in many cases, limited permeability. For information on the HDR resource available in composite cones, see reports by Arney et al. (1981, 1982). If geothermal development is to succeed in the Cascade Range, HDR systems must be developed.

Along the Pacific plate margins within the U.S., the hot dry rock geothermal resource has been evaluated, with some preliminary estimates of its magnitude (Goff and Kron, 1982; Arney, 1982). Preliminary results indicate that it is a much larger resource than that available to us through the development of hydrothermal systems.

CONCLUSIONS

The first HDR reservoir system operated with thermal power of up to 5 million watts (17 million BTU/hr) for nine months. Results from this initial system have demonstrated the technical feasibility of creating and operating a hydraulically fractured HDR geothermal system. It provided the incentive to create the engineering system at Fenton Hill, which is expected to approximate a system of commercial size. As this paper is being prepared (June, 1982) fracturing operations have begun in the new system. Similar experiments at Yakedake have also led to the search for a site to begin a HDR commercial test in Japan.

We hope that, in the future, geothermal wells will be drilled into thermal anomalies without regard to the type of reservoir system. Where the production of natural fluid is adequate, the hydrothermal resource would be developed; where production of water and steam is inadequate, the well would not be abandoned as is currently the practice. Instead, the heat would be extracted with a man-made geothermal system.

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FIGURE CAPTIONS

Figure 1. Hot dry rock geothermal reservoir systems developed at Fenton Hill, New Mexico Test Site.

Figure 2. Thermal performance of research heat extraction reservoirs at Fenton Hill.

Table 1. Summary of HDR Reservoir performance - Fenton Hill (Nominal Values).

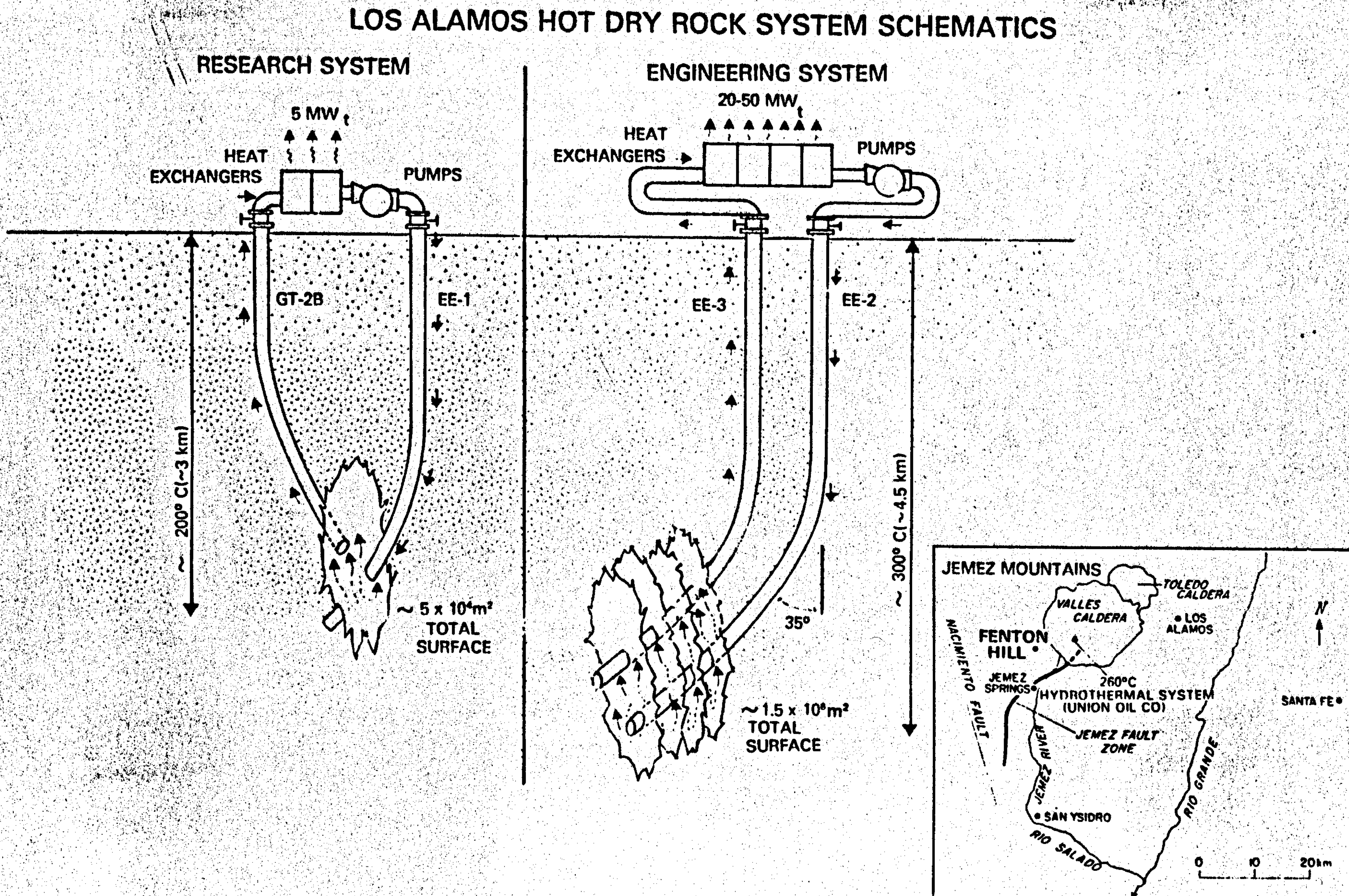

Fig. 1
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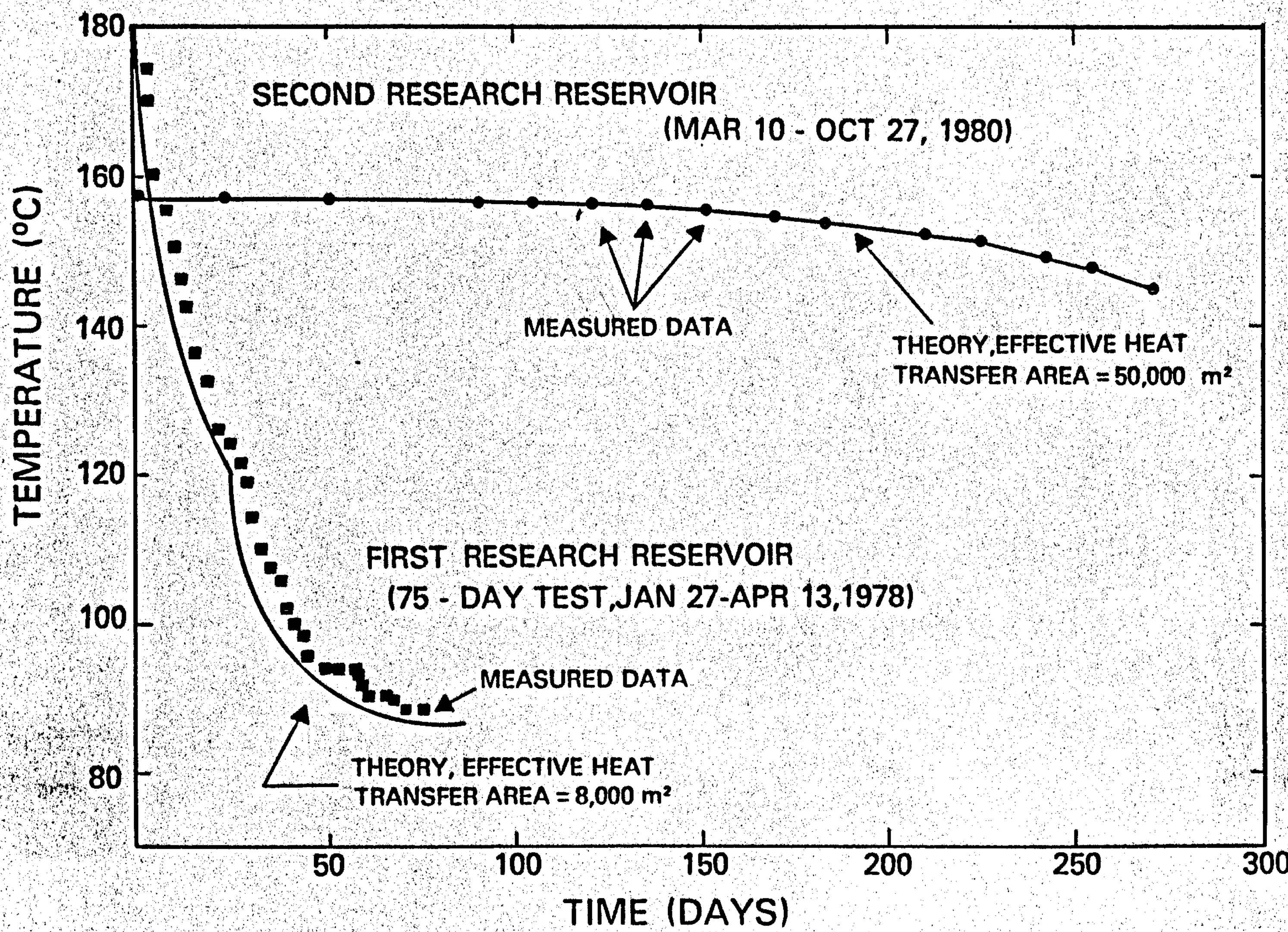

Fig. 2
Rowley et al.

TABLE I

SUMMARY OF HDR GEOTHERMAL RESERVOIR PERFORMANCE - FENTON HILL (NOMINAL VALUES)

Reservoir Designation	Description & Heat Transfer Area (m^2)	Well Pair & Dates	Reservoir Depth ft(km); & Temperature	Water Flow Rate, gpm(m^3/s)	Production Temperature*	Duration of Test(s),Days	Thermal Energy Produced KWh(t) x 10^6 & Power Level MW(t)	Major Results/Goals
RESEARCH/ PROTOTYPE	Initial Fracture System (8000)	GT-2/EE-1 / 1977-1978	8700 (2.7) 185°C	125 (0.008)	170-90°C	76	8.5 / 4	Demonstrated: o Technical feasibility of concept o Drawdown data fit thermal-hydraulic model o High pressure operation lowers impedance.
				200 (0.012)	100°C	45 (High Back Pressure Exp.)	~3.7 / 3.2	
	Refractured System (50,000)	GT-2/EE-1 / 1979-1980	9600 (2.9) 197°C	100 (0.0065)	150°C	268	16.2 / 3 to 5	Demonstrated: o Large fracture size o Low water loss o Fracture growth verified o Large extension of fracture (~1,050 ft (320 m) o Drawdown less than 8°C o 60 KW(e) generator operated.
ENGINEERING/ COMMERCIAL SIZE (DESIGN VALUES)	Ten Parallel Vertical Fractures** 10x(50,000)	EE-2/EE-3 / 1983-1984	11,000-15,000 (3.3 - 4.5) ~320°C (~260°C Avg.)	1500 (0.0225)	240°C	>1 year	>350 / 35 to 50	Design: o Commercial size reservoir o 20 year life with <20% drawdown o Wellbores inclined 35° in reservoir region.

* Injection temperature ~40°C.
** Fracturing operations currently underway (July 1982).