Enhanced Geothermal Systems (EGS) R&D Program

EGS Report 2000-5

Status Report: Foreign Research on Enhanced Geothermal Systems

Date: September 29, 2000

From: Enhanced Geothermal Systems Research Management Project
Princeton Energy Resources International, LLC, Rockville, Maryland
- Lynn McLarty, Project Director
- Dr. Daniel Entingh, Technology Development Director

For: U.S. Department of Energy, Office of Geothermal & Wind Technologies

Under: DOE Idaho Operations Office Contract DE-AM07-97ID13517
Task DE-AT07-00ID60429

For more information contact Lynn McLarty, at 301-468-8442 or lmclarty@perihq.com

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1.0 Introduction

This report reviews enhanced geothermal systems (EGS) research outside the United States. The term "enhanced geothermal systems" refers to the use of advanced technology to extract heat energy from underground in areas with higher than average heat flow but where the natural permeability or fluid content is limited. EGS covers the spectrum of geothermal resources from low permeability hydrothermal to hot dry rock.

Because this report makes repeated references to enhanced geothermal systems and hot dry rock systems, it is important to note the difference between the two. The term 'hot dry rock' was coined in the early 1970s to describe a geothermal energy extraction concept developed at Los Alamos National Laboratory (LANL). The term 'enhanced geothermal systems' was coined in the U.S. in 1998 by researchers and geothermal industry representatives interested in expanding industry's capabilities beyond the exploitation of high and moderate quality hydrothermal resources.

In developing the HDR concept, researchers at LANL believed that successful exploitation of dry geothermal formations would depend, in part, on their having extremely low natural permeability in order to prevent excessive fluid losses. Indeed, LANL's Fenton Hill project was such a system. Based on this experience, in the U.S., HDR generally connotes a very hot, but very impermeable, basement granitic formation similar to that at Fenton Hill. In *Assessment of Geothermal Resources of the United States – 1978* (1979) the U.S. Geological Survey states "Hot dry rock thus involves three concepts: low porosity (and water content), very low permeability, and high temperature." Similarly, in the *Sourcebook on the Production of Electricity from Geothermal Energy* (1980), William Diment (USGS) describes HDR resources as "environments that are: (1) relatively hot..., and (2) relatively dry in that intrinsic and fracture porosity are low."

However, in Europe and Japan researchers developed similar experimental projects but which differed in that they are in geologic formations with considerably more permeability and fluid content than at Fenton Hill. Although these Japanese and European projects are commonly referred to in the technical literature as "HDR" projects, their differences from Fenton Hill have prompted some researchers to also refer to them as "hot wet rock" projects.

The EGS concept is analogous to that of enhanced oil recovery. In enhanced oil recovery, a medium (typically water, steam, or carbon dioxide) is injected into selected wells, causing the medium to flow through the oil reservoir and 'sweep' the oil toward other wells designated for production. In an enhanced geothermal system, water is injected into selected wells and flows through the reservoir gathering heat energy from the rock before it is brought to the surface via designated production wells. Although injection has been a common practice in commercial hydrothermal systems for years, its primary purpose has been more to support reservoir pressure than to mine additional heat from the surrounding rock.

In EGS systems with low permeability, stimulation will be necessary to improve permeability before successful injection and production can take place. Thus EGS includes all geothermal resources except high and moderate quality hydrothermal resources: (low quality hydrothermal, marginal hydrothermal, fluid-depleted hydrothermal, hot wet rock, moderate permeability formations with low fluid content, and finally, Fenton Hill-like hot dry rock).

Where HDR falls within EGS can best be described by defining a spectrum of permeability and fluid content for all geothermal resources. This spectrum is illustrated in Figure 1 – 1 below. The left side represents the highest permeability and fluid content, which progressively decrease toward the right side of the spectrum. High and moderate quality hydrothermal resources reside on the left and HDR on the right. EGS includes all of the spectrum except the high and moderate quality hydrothermal resources.

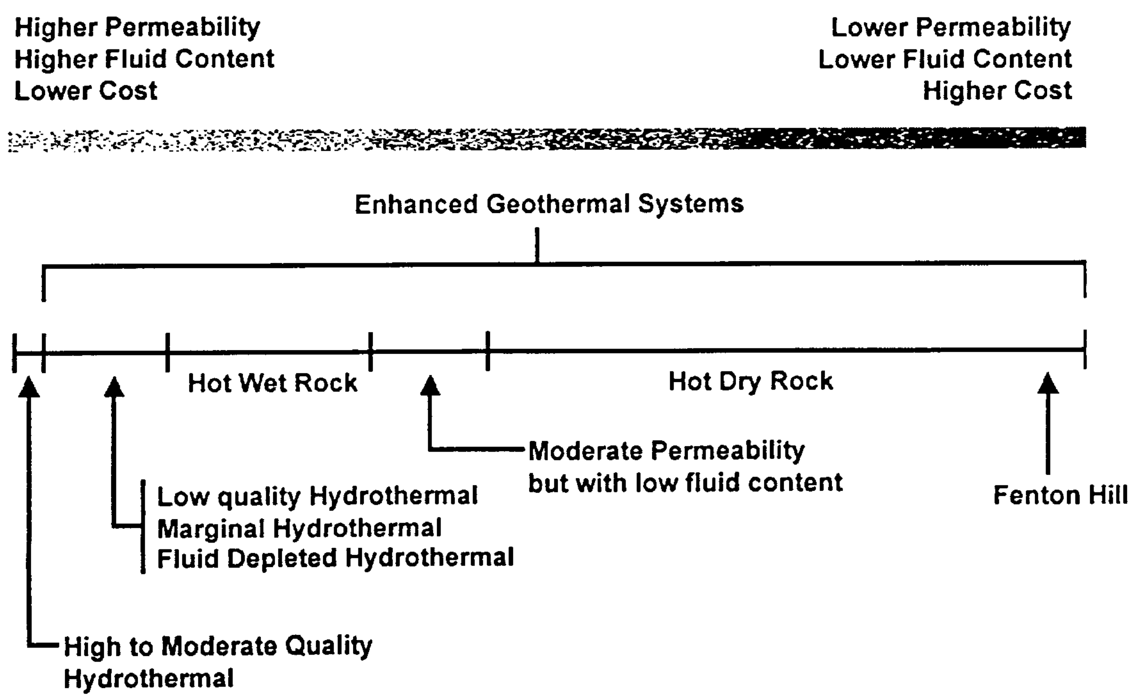

Figure 1 – 1: The geothermal permeability spectrum

Note that Figure 1 - 1 is simplistic for illustrative purposes and does not imply that permeability and fluid content (volume) are directly related. Also, in the diagram, the lengths of the sections devoted to each resource type are meant to be crude approximations of the size of each resource type relative to the others. It illustrates the fact that scientists now believe the hydrothermal resource is rather small on a national scale and that EGS constitutes the greatest potential for geothermal energy.

More important than the semantics of EGS and HDR is the approach to R&D that is embodied in the term "Enhanced Geothermal Systems." The EGS R&D concept adopts an incremental approach to research that is more compatible with the natural evolution of the geothermal industry. Industry will logically develop the highest quality resource sites first and develop sites with progressively lower permeability and/or fluid volume as the necessity and opportunity for such coincide. Thus, it is appropriate to initially focus EGS technology development in and adjacent to hydrothermal reservoirs with incremental expansions of effort to more geologically challenging areas over time. This approach is DOE's response to industry's recommendations.

Having noted the differences between EGS and HDR, nevertheless the term HDR will be used somewhat generically in this report in deference to its use by our foreign colleagues in describing their research.

There is a recent resurgence of interest and activity in this area of research. After several years of limited activity, the three most important active HDR experimental facilities are increasing research operations. These facilities are the European Union's hot dry rock (HDR) project at Soultz-sous-Forets in France, and the Hijiori and Ogachi HDR projects in Japan. In 1999, the Soultz project deepened well GPK2 to 5,000 meters and has been conducting geophysical, geochemical, and stress measurement experiments. During the summer of 2000, the Soultz project engineers conducted a massive hydraulic stimulation of well GPK2. At Ogachi, researchers drilled a new well in 1999 and conducted an injection test in the summer of 2000. At Hijiori, preparations are underway to conduct a two-year circulation test beginning in December of 2000. In addition, scientists in Australia are conducting field investigations as preliminary work to construct an experimental HDR facility.

Of the three most important active HDR facilities, Soultz seems to be the one that has the most momentum at the present time. In circulation tests, it has achieved greater production rates with less fluid losses than the other two. And although its temperature is lower than at Hijiori and Ogachi, a recent deepening of one of the wells there has encountered a temperature considered by researchers as adequate for power generation.

In the United States, the U.S. Department of Energy has moved beyond the Fenton Hill HDR experimental project to focus on EGS field projects that will seek to enable operators to extract heat energy from impermeable, but hot, areas within or adjacent to commercial geothermal operations. During 2000, the EGS research program, which is conducted by DOE's Office of Geothermal and Wind Technologies, awarded funding for feasibility studies for nine EGS field projects. Of the nine projects, one or two will be selected for implementation beginning in fiscal year 2001.

This report has been prepared in support of DOE's EGS research program and is intended to inform the U.S. industry, research community and policy makers of foreign EGS research in order to

- Encourage cooperation and communication between international researchers pursuing similar objectives
- Avoid duplication of efforts
- Take advantage of new technology as it becomes available.

The information in this report was gathered from recently published technical literature and interviews and conversations with foreign colleagues involved in the research.

This report is organized into sections, the first of which covers the three most important active experimental HDR facilities and briefly summarizes other planned and ongoing HDR facilities. Other sections cover fracture characterization, geochemistry, and supercritical reservoirs.

2.0 Experimental Hot Dry Rock Projects

A number of experimental hot dry rock projects are underway in several different countries. The three most active ones are in France (Soultz) and Japan (Hijiori and Ogachi). These are described below. Other existing and planned projects are mentioned briefly.

2.1 Soultz HDR Project

This section on the Soultz HDR project is mostly based on two recent papers (Baria et al, 2000 and Baumgartner et al, 2000). The material below is paraphrased from these two papers. Other papers are drawn from as indicated.

2.1.1 Background

The Europeans' experimental HDR project is located at Soultz-sous-Forets, France, approximately 50 km north of Strasbourg in southeastern France. The site is located in a former oil field on the western edge of the Rhine Graben. A graben is a portion of the earth's crust that is bounded on at least two sides by faults and which has sunk in elevation. Begun in 1987, the project is sponsored by France, Germany and the European Commission and is associated with an industrial consortium.

The project succeeded in creating a reservoir system in the granitic basement formation and circulating water through it to collect heat. Figure 2 – 1 provides a schematic representation of the system. Scientists began constructing the system in 1987 and by 1989 had completed drilling and testing the initial well, GPK1. The well penetrated the crystalline basement rock at a depth of 2000 meters. Temperature measurements revealed a fairly normal geothermal gradient in the granitic basement rock and a moderately high gradient in the overlying sedimentary rock. The bottom hole temperature was measured at 140°C.

During 1992-1993, GPK1 was deepened to a depth of 3,590 meters, and scientists conducted injection tests. Associated measurements included microseismic monitoring, production logging, and fluid sampling. In 1994, GPK1 was switched to production to measure productivity and injection properties. The information gathered during the injection and production tests and other measurements were then used to target a second well (GPK2) to a depth of 3890 meters about 450 meters south of GPK1.

Hydraulic stimulations of GPK2 were conducted during 1995 and 1996. In 1997 scientists conducted a 4-month test circulating water between the two wells. The flow rate was approximately 25 liters per second. Although this rate is not enough to support commercial power production, the test demonstrated brine could be circulated through the enhanced geothermal system between wells separated by more than 450 meters with low power consumption for circulation, no geochemical problems, and no water losses.

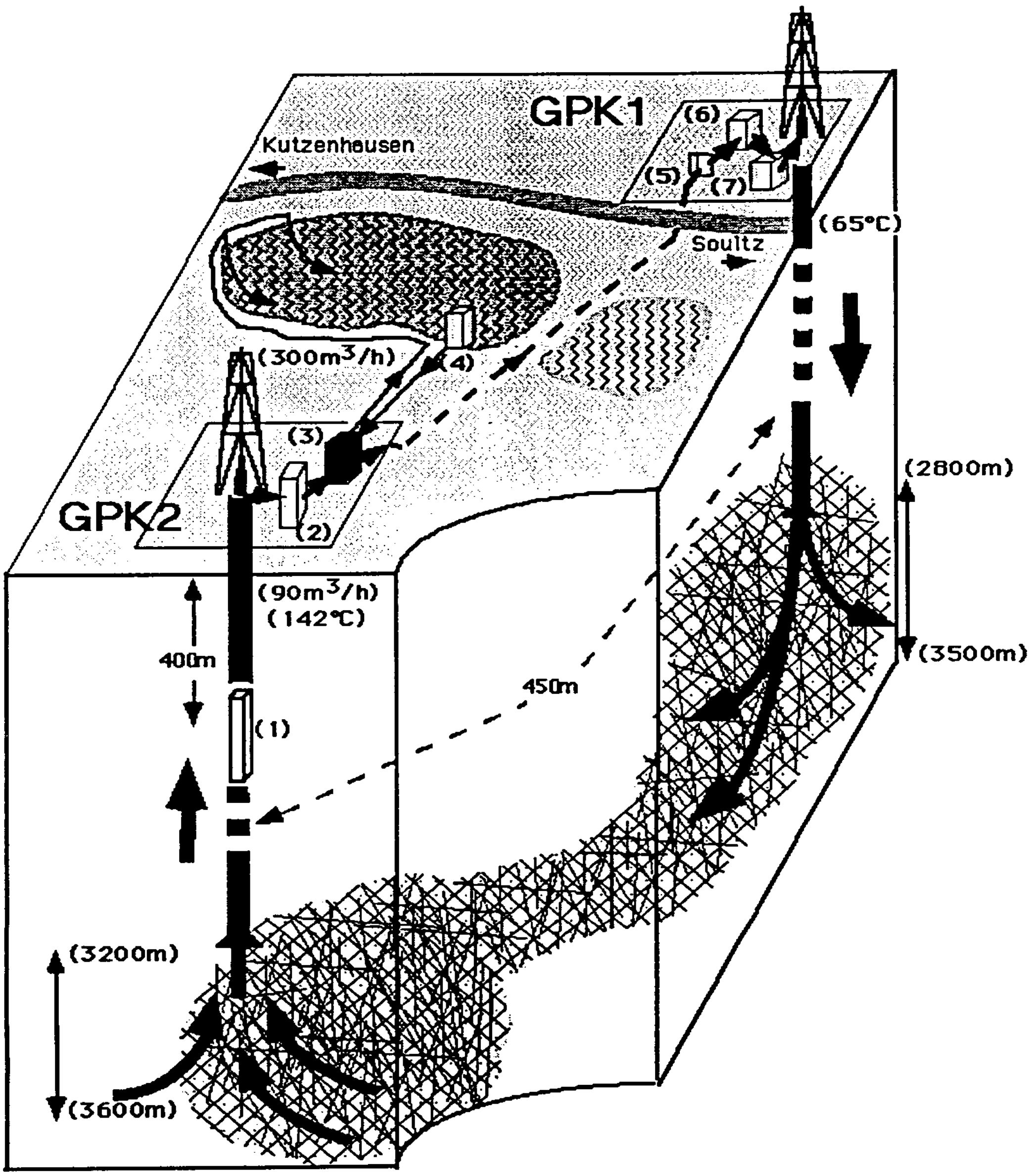

Figure 2 – 1: Schematic of the Soultz HDR System (Baria et al, 2000).

2.1.2 Objectives

The current objective of the Soultz project is to investigate whether the favorable conditions encountered during circulation tests at 3000 – 3500 meters depth will also be found at a depth where the formation temperature is 200°C. This temperature, targeted as necessary for commercial power production, was estimated to occur at 5000 meters depth. An industrial consortium, GEIE (Exploitation Miniere de la Chaleur) was formed to pursue this objective. The consortium consists of Electricite de France, Electricite de France International, Electricite de Strasbourg, Pfalzwerke, REW, ENEL (Italian electric utility), and SHELL International. Plans include deepening one of the existing wells to achieve the target temperature and conducting measurements and evaluations of temperature, the natural fracture system, the stress field, hydraulic characteristics and results of stimulation, and geochemical behavior.

The strategic objectives of the Soultz project are to first construct a small (3 – 5 MW) scientific pilot project to generate electricity, followed by the construction of a larger (10-15 MW) commercial pilot project.

2.1.3 Recent Operations

During the spring of 1999, well GPK2 was deepened to 5048 meters. A pilot hole for stress measurements was extended from the bottom of the well to 5084 meters. The well is completed with 7 inch casing down to 4431 meters. The test zone is an 8.5-inch open hole completion extending 617 meters below the casing shoe. Figure 2 – 2 presents the well design. The bottom hole temperature was measured to be very close to 200°C.

During drilling and just afterward, various geological investigations were conducted, including coring, drill cuttings analysis, and geophysical logging. Previous coring experience using a positive displacement motor and diamond coring assembly in GPK1 was problematic because of the high temperature. Therefore in the deepened section of GPK2 scientists used a conventional roller cone coring bit without a downhole motor. They ran the coring bit from 5048 to 5051 meters, but were able to recover only 1.2 meters of the core. The initial analysis of the core indicated the granite was very similar to that found in wells GPK1 and EPS1. Some well developed fractures (approximately 1 mm width) sealed with hydrothermal deposits were evident in parts of the core sample.

Drill cuttings were sampled continuously throughout the deepening of the well. The analysis of the cuttings was used to produce a lithological log. Numerous alterations and fracture zones exist below 4000 meters, and the hydrothermalization appears to be more prominent below 4500 meters. The test zone includes fractured zones between 4550 and 4600 meters and 4750 and 4850 meters. The granite in the test zone varied from white-gray porphyritic granite with 2 micas to gray-dark biotite rich granite to white-gray k-feldspar depleted granite. A preliminary geological cross section of GPK2 after extension is presented in Figure 2 – 3.

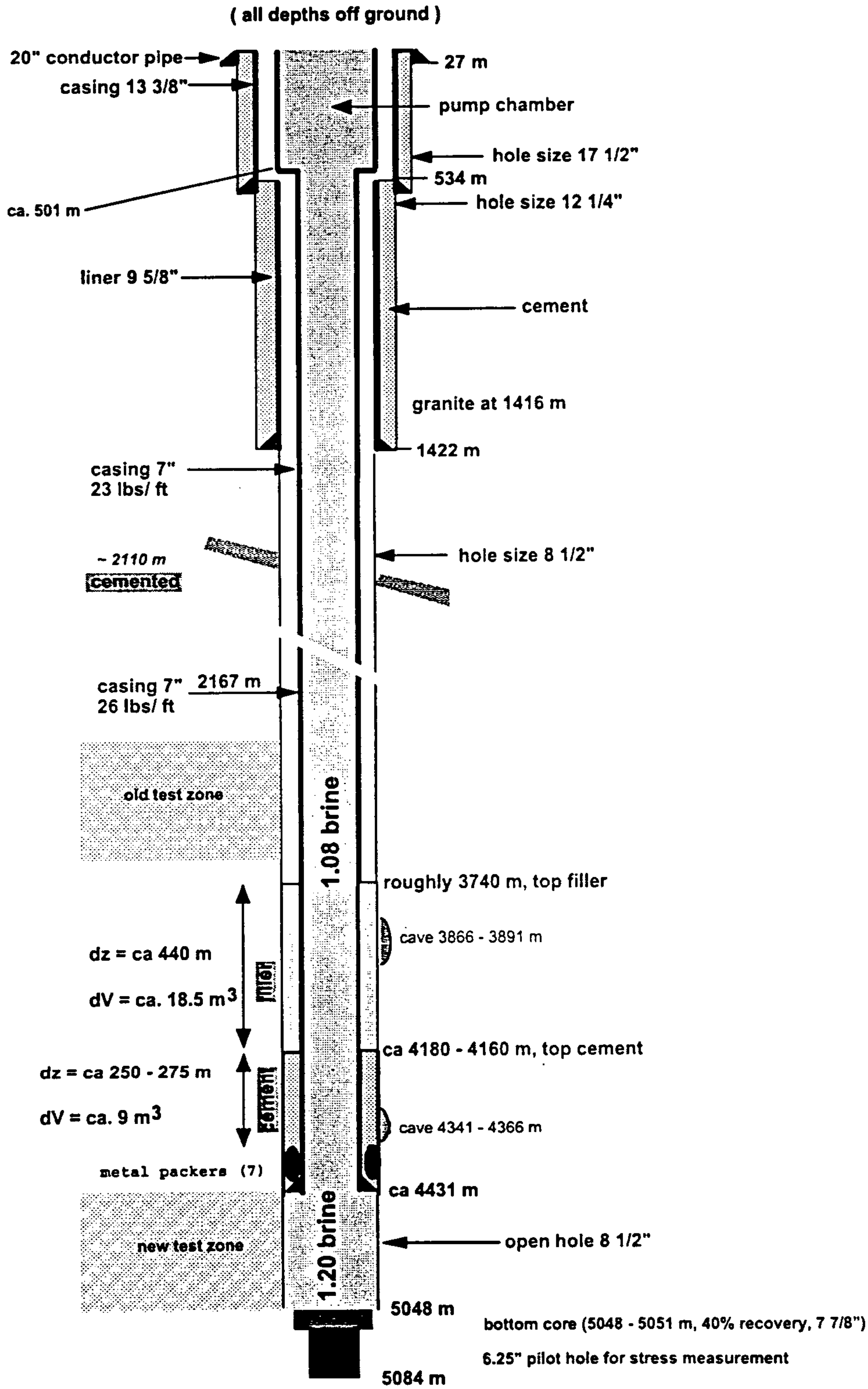

Figure 2 – 2: Present situation of the well GPK2 after re-entry and deepening to 5084 meters (Baria et al 2000).

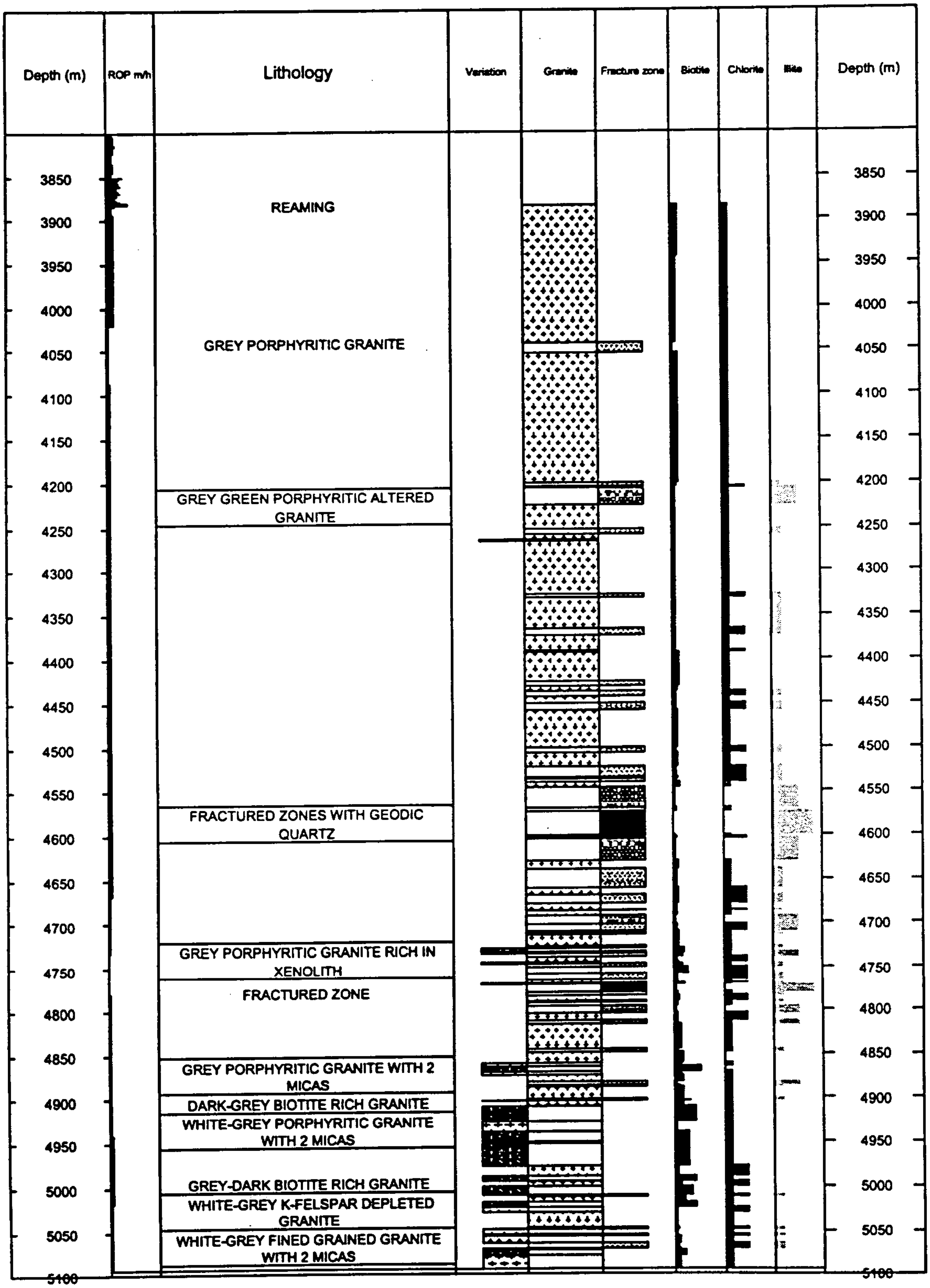

Figure 2 – 3 Preliminary geological cross section of GPK2 after extension (Baria et al 2000).

Geophysical logging during the drilling operation included Natural Gamma Spectrometry (2000 – 4500 m), 6-arm caliper (3200 – 4625 m), Azimuthal Resistivity Imager (3500 – 4500 m), and Ultrasonic Borehole Imager (3200 – 3875 m). Initial analysis indicates the joint network and pattern of alteration appears to be similar to that found higher up in the well (3500 m). Continuous coring and borehole imaging in the other wells on site have provided information of the joint network. There are two principal joint sets striking N10E and N170E and dipping 65°W and 70°E respectively. The formations are pervasively fractured with about 3.2 joints per meter on average.

Hydrofracture stress measurements in the test zone were conducted in late 1999 but have not been reported on. The measurements were conducted using metal packers. During the summer of 2000, scientists conducted a massive hydraulic stimulation of GPK2. The data gathered during the stimulation have not been fully analyzed. Project engineers reported that the stimulation required lower pressures than expected to achieve targeted injection rates (personal communication with Harris, 2000).

For the deepening of GPK2, Soultz project engineers developed new cementing strategies that may be of interest for application in hydrothermal wells. Due to their effects on chemical reactions and cement set-times, high temperatures and brine chemistry create challenges for cementing wells. For deepening the GPK2 well, investigators decided to use fly ash to seal the annulus of the floating internal casing string. They also decided to avoid all uses of Portland cement because of its tendency to harden very rapidly once the retardation period has elapsed and because magnesium chlorides found in the brines at Soultz tend to destabilize the cement reaction. The researchers developed High Magnesium Resistant (HMR) cements based on blast furnace cements and fly ash. The HMR cement is insensitive to chlorides and remains stable in the presence of chloridic acids. The HMR cement sets gradually and achieves compressive strengths comparable to API type class G cements, although it does take longer to harden. In order to avoid salinity problems, all cement slurries were mixed using brine with an NACL concentration of 200 g/l. This avoided contamination of the slurry with the much more complex, but lower NACL concentration, natural brine.

The casing packers developed for the Soultz project are also of interest for possible applications in hydrothermal wells. At temperatures above about 140°C conventional rubber based packer elements tend to fail. So the Soultz project developed all new packers that eliminate all rubber elements except for static O-rings. Researchers developed inflatable soft metal packer shells that can be inflated with cement. The packer used for deepening GPK2 included a mandrill of 7" 26 lb./ft C 95 casing and a sleeve constructed of salt water resistant Cu alloy. In laboratory tests the anchoring force of a single element packer increased from a minimum of 30 tons inside a totally smooth steel pipe to over 100 tons inside a pipe that was grooved to simulate a rough borehole wall. A single long (12 meters) packer unit was assembled using seven inflatable packers connected with 7" BTC casing couplings. Patents for the metal casing-packer technology are pending.

It is interesting to note that recent scientific work suggests a new heat and fluid flow model for the heat flow anomaly at Soultz. Previous models were based on regional fluid circulation from east to west through a sandstone aquifer across the Rhine Graben. However, recent geochemical analyses of pore fluids indicate deep flow through the granitic basement. A model based on this analysis shows that fluids in vicinity of Soultz generally move upwards. The implication of this is that the Soultz HDR project will benefit not only from extraction of heat in the rock mass between injection and production wells but also from its connection to the regional fault system that acts as a large heat and fluid reservoir (Pribnow and Clauser, 2000).

2.1.4 Planned Operations

Planned operations include analysis of the data gathered during the hydraulic stimulation of GPK2, possible deepening of an additional existing well or drilling a new one, and conducting a long-term circulation test. A schedule for the planned operations was not available.

2.2 Hijiori Experimental HDR Project

Development of the Hijiori HDR project began in the mid 1980s. The high temperatures (> 250°C) encountered at relatively shallow depths (1800 meters) coupled with the identification of two faults controlling natural permeability seem to indicate that the system is basically a hydrothermal reservoir with limited permeability.

The general description and historical account of the Hijiori HDR project below is from Yamaguchi et al, 2000. The information on planned operations is from personal communications with Isao Matsunaga (June 2000).

2.2.1 Background

The Hijiori experimental HDR project is located in Yamagata Prefecture, Japan, north of Tokyo. The New Energy and Industrial Organization funds the project. The site is on the southern edge of the Hijiori caldera. The caldera, which is about 2 km across, was formed about 10,000 years ago. The underground system consists of a shallow reservoir at 1800 meters depth and a deep reservoir at 2200 meters depth. The shallow reservoir was developed during the first phase of the project between 1985 through 1991. The deeper reservoir was developed during the second phase between 1992 and 1994. The reservoirs intersect two natural fractures, which account for the majority of the flow in the system.

In 1985 researchers adopted an existing geothermal exploration well, SKG-2, for use as an HDR test well. The well was 1802 meters deep and had a bottom hole temperature of 253°C. Researchers hydraulically stimulated the well to create the shallow reservoir and then drilled three wells to intersect the reservoir. HDR-1 was drilled to 1805 meters in 1987 and deepened to 2205 meters; HDR-2 was drilled to 1910 meters in 1989; and

HDR-3 was drilled to 1907 meters in 1990. Well tests indicated good connectivity between these three wells.

In 1991 the project conducted a 90-day circulation test of the upper reservoir, injecting into SKG-2 and producing from HDR-1, HDR-2, and HDR-3. All three production wells produced hot water and steam at temperatures from 150 to 180°C. Recovery of the injected fluid was estimated to be about 80% and the thermal recovery was estimated to be about 8.5 MW.

During the second phase, scientists created the deep reservoir by hydraulic stimulation in HDR-1 between 2150 and 2200 meters. In 1993 they deepened HDR-3 to 2300 meters and in 1994 they plugged back HDR-2 at 1600 meters and redrilled it to a depth of 2300 meters. Afterward, HDR-2 was renamed HDR-2a. This completed the construction of the dual reservoir system. The system, depicted in Figure 2 – 4, is essentially comprised of two steeply dipping fractures, one of which constitutes the upper reservoir and the other the lower reservoir.

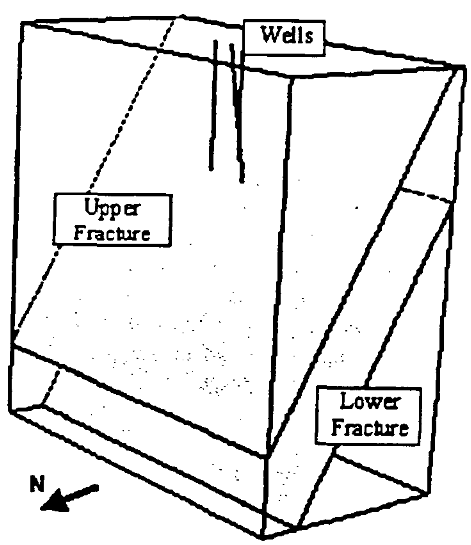

Figure 2 - 4: Schematic of the Hijiori HDR System. (Swenson et al, 2000)

In 1995 scientists conducted a preliminary flow test for 25 days using HDR-1 for injection and HDR-2a and HDR-3 for production. Water was injected at a rate of 60-120 t/h and hot water and steam were produced at a rate of 14-15 t/h with a temperature of 180°C. Good permeability was observed between HDR-1 and HDR-3, but the permeability between HDR-1 and HDR-2a was not good. Scientists then attempted to improve the permeability between HDR-1 and HDR-3 by injecting additional water into HDR-1 and producing it in HDR-3. However, no improvement occurred.

2.2.2 Objectives

The primary objective of the Hijiori project is to develop technology that will lead to commercial application of hot dry rock technology. The project is not intended to become a commercial operation.

2.2.3 Recent Operations

Other than analyses of data collected during earlier operations, there has been little activity since the last flow test in 1996. Recently, the project scientists have been preparing for a long-term circulation test (LTCT), which is scheduled to begin in December 2000 and continue for two years. Preparations have included some improvements to the surface facilities and some analyses to evaluate different operating strategies for the LTCT. One analysis included simulation of the LTCT under five separate cases: (1) a nominal case with injection flow of 16 kg/s, (2) a case with half the nominal flow, (3) a case with double the nominal flow, (4) a case where HDR-2a was blocked at the lower fracture in order to block the flow of cold water observed in earlier flow tests, and (5) a case with enhanced connectivity between the lower and upper fracture. The analysis employed two computer codes. WELF98 was used to convert pressure-temperature-spinner (PTS) data to individual fracture data including pressure, temperature, and flow rate for each fracture intersecting the wellbore. Geocrack2D was used to simulate the reservoir. Geocrack2D is a finite element model developed to solve coupled structure/fluid/thermal problems where the flow is within fractures. The simulation was based on data from the 1991 and 1995 flow tests (Swenson et al, 1999).

Five separate cases were simulated:

1. Nominal case – injection rate of 16 kg/sec into HDR-1 with production from HDR-2a and HDR-3.
2. Same as 1, except injection flow rate of 8 kg/sec, in order to evaluate the effect of reduced flow on production temperatures.
3. Same as 1, except injection flow rate of 32 kg/sec, in order to evaluate the effect of increased flow on temperature.
4. Same as 1, except lower fracture production HDR-2a is blocked, in order to block flow of cooler water experienced in earlier tests.
5. Same as 1, except high permeability path added that connects the lower and upper fractures.

The results showed considerable cooling on the fractures, especially the lower one, in well HDR-2a. However, the temperature in HDR-3 stays relatively constant. Predicted production temperature in HDR-2a, with mixing of fluids from both fractures, declines from about 240°C to about 180°C during the simulated two year flow test. The predicted production temperature for HDR-3 remains constant at 240°C. In Case 4, where the flow in HDR-2a from the lower fracture is blocked, the predicted production temperature in HDR-2a only declined to about 210°C during the simulated test (Swenson et al, 1999).

2.2.4 Planned Operations

Project funding for FY 2000 (fiscal year is April through March) is 200 million Yen (about US$1.9 million). Project scientists plan to commence the Long Term Circulation Test in December of 2000. The test is scheduled to continue for two years. The circulation test will include the injection of about 16.7 kg/s into HDR-1 during the first year (into the lower reservoir). Then in the second year, injection will be into both HDR-1 and SKG2 (into both the shallow and deep reservoirs).

During the LTCT, project engineers expect a 50% fluid recovery rate at first and that this will improve with time, reaching 70 – 80%. Engineers will conduct microseismic monitoring during the flow test with one sensor at a depth of 700 meters in SKG1 and the remaining sensors on the surface. CRIEPI (Central Research Institute of the Electric Power Industry) scientists will be in charge of collecting and analyzing the microseismic data.

The project engineers will also conduct pressure-temperature-spinner (PTS) tests several times during the flow test and one tracer test at the beginning of the flow test and then additional tracer tests every 3 or 4 months. Fluid chemistry will be monitored throughout the flow test. An automated system will be set to gather water samples at defined time intervals.

Geothermal Research and Development Co. (GERD), out of Tokyo, will conduct environmental monitoring. It will collect and test water samples from the river and nearby hot springs every month.

2.3 Ogachi Experimental HDR Project

The following background information on the Ogachi HDR project is mostly from Kitano et al, 2000. The information of recent and planned operations is largely from personal communications with project engineers Hideshi Kaieda and Yoshinao Hori (June 2000).

2.3.1 Background

The Central Research Institute of Electric Power Industry (CRIEPI) sponsors the Ogachi HDR test site, located in the southern Akita Prefecture, Japan. CRIEPI is an organization similar to the Electric Power Research Institute in the United States. The project was begun in 1989 when CRIEPI began exploration at the Ogachi site. The site is situated in the mountains at about 600 m elevation. The geology consists of Cretaceous granodiorite covered with Tertiary lapilli tuff to a depth of 300 m. The granodiorite contains a number of natural joints with an average spacing of about 8 cm. The joints have relatively low permeability. Investigations indicate the presence of two faults 500 m and 900 m to the west of the site. It is suspected these faults are connected to the Ogachi reservoirs.

In 1990 scientists at the site drilled an injection well, OGC-1, to a depth of 1000 meters where the rock temperature was measured at 228°C. The well was completed with casing leaving the bottom 10 meters as open hole. Then in 1991, engineers stimulated the well by injecting over 10,000 cubic meters of water into it. Acoustic emissions data indicated the stimulation created a fractured reservoir about 200 m thick and about 500 m wide, propagating about 1000 m in the NNE direction. This reservoir is the lower of two reservoirs created to date.

Scientists created the second reservoir in 1992. They began by milling out the casing in OGC-1 between 711 m and 719 m depth. The hole below this section was then filled with sand in order to isolate this new open-hole section from the lower reservoir. Then a second stimulation was conducted, pumping about 5,500 cubic meters of water into the well creating a reservoir approximately 200 m thick and estimated to extend over a 400 x 800 m area in a ESE direction. A schematic of the two reservoirs and surface facilities is presented in Figure 2 - 5.

The production well OGC-2 was drilled to a depth of 1100 m in January of 1993 and a 22-day circulation test was conducted. Then in 1994 a 5-month circulation test was conducted.

Well OGC-1 was extended to 1027 m in 1995. After extending the depth of OGC-1, scientists stimulated the lower reservoir by injecting 3400 cubic meters of water at a rate of 105 cubic meters per hour at a wellhead pressure of 18 MPa. They followed this with a stimulation of OGC-2 with 4300 cubic meters of water at a rate of 135 cubic meters per hour also at 18 MPa.

To judge the effects of the stimulation, the scientists conducted a one-month circulation test between the two wells in 1995. During the test the circulation pressure decreased to about 7 MPa, about half that of an earlier test, and the recovery rate was 25%, about double of that in the earlier test. The temperature of the produced fluid was 165°C.

In 1997 the scientists decided to test each of the reservoirs separately. The reservoirs were isolated from each other by the use of packers in the wellbores. The scientists injected about 13,000 cubic meters into the upper reservoir through OGC-1 at a rate of 15 cubic meters per hour and pressure of 18 MPa. A subsequent failure of the packer precluded a similar test of the lower reservoir, so they conducted a circulation test through both reservoirs. Compared to the 1995 test, the injection pressure doubled for the same flow rate and the recovery rate was only half.

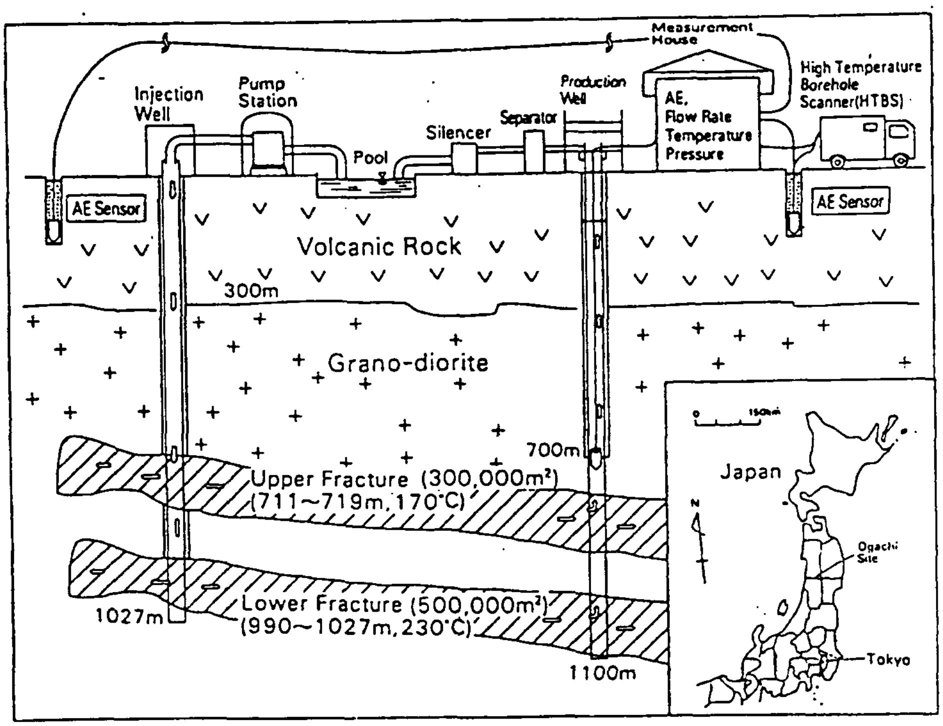

Figure 2 - 5: Schematic of the Ogachi HDR Reservoir (Kitano et al, 2000)

The low rates of return in the various circulation tests suggest a reservoir system that is surrounded by naturally fractured rock with considerable permeability. Investigations of core samples and borehole televiewer logs indicate this to be the case. Natural fractures are highly developed in the system especially in the upper reservoir. Fractures with high dip angles are dominant throughout the reservoir. The upper reservoir revealed no dominant fracture orientation. In the lower reservoir, the fractures around the injection well trended N-S with moderately high W dips. Around the production well, the fractures trended NE-SW with a high SE dip (Ito and Kitano, 2000).

The well stimulations and circulation tests are summarized in Figure 2-6.

FY	Experiment	Injection			Production			Reservoir	
		Flow rate (l/min)	Wellhead Pressure (MPa)	Total Water Volume (×10³)	Flow Rate (l/min)	Temperature (Max:°C)	Recovery (%)	Area of AE Distribution (×10³)	Modal Volume of Tracer Test (m³)
91	Lower Fracturing	640	18-18.5	10	-			500	
		710	18-18.5						
92	Upper Fracturing	500	22-22.5	5	-			300	
		700	23.5						
93	22 days Circulation	750	17	21	12	109	2	-	
		1200	19		30				
94	Production Well Fracturing	750	13	3	-			80	
	5 months Circulation	500	13	140	50	160	10	-	10-15(Upper)
		750	16		65				230-250(Lower)
95	Injection Well Fracturing	1500	16	4	-			20	
	Production Well Fracturing	2200	18	4	-			80	
	1 month Circulation	500	7	24	125	170	25	-	135
		750	9		150				
97	Upper Reser.Circulation	150	19	3	-			-	
	Injection from Production Well	750	10	10	-			-	
		500	7.5						
	Upper Reser.Circulation	220	19	3	-			-	
	10 days Circulation	500	13	6	75	116	15	-	138

Figure 2 - 6: Summary of Well Stimulations and Circulation Tests at Ogachi (Kitano et al, 2000).

2.3.1 Objectives

The objectives of recent operations at Ogachi are to develop the following methods:

- Exploration methods for deep underground geologic structures, in particular permeable faults
- Evaluation methods to determine the size and direction of growth of the reservoir as well as the fracturing mechanisms in the reservoir
- Evaluation methods for the nature, permeability, distribution, and structure of fractures developed in the reservoirs
- Hydraulic evaluation methods for permeability, modal volume and water flow paths
- Computer simulation methods for estimating the production and behavior of the reservoir.

The long-term objectives at Ogachi are to demonstrate the viability of geothermal heat extraction through multiple HDR reservoirs with multiple wells and develop a 100 MW commercial project.

2.3.2 Recent Operations

The project completed a new injection well in the spring of 2000. Project scientists conducted an injection test on June 20, 2000. The test consisted of injecting increasing volumes, in four steps, up to 750 liters/min. Each step lasted approximately 24 hours. The production wells were shut in during the test. Using data from the test, the project engineers will estimate the permeability distribution and then compare that with seismic data. Interpretation of the data from the test is not yet completed.

The pressure distribution in the well is being measured at one-meter intervals (entire length of the well) using a fiber optic cable.

The project budget for FY 2000 is 80 million Yen (US$750k). Fifty million will be spent on logging and other measurements and 30 million will be spent on operations. Last year the budget was 180 million Yen (US$1.7 million), of which 100 million (US$940k) was spent on drilling the new well.

2.3.3 Planned Operations

In the next phase, Phase V, of the project, engineers intend to conduct more hydraulic fracturing in all 3 wells and then conduct a long-term flow test for 1 to 2 years. Phase V is scheduled to run from 2002 through 2004.

Phase V will require industrial partners for funding.

2.4 Other Experimental HDR Projects

There has been considerable interest in HDR projects in other countries as well. The Swiss and Germans have been exploring the feasibility of HDR. In Germany, scientists have been conducting HDR investigations in Urach Spa beginning in 1977 with the drilling of the Urach 3 well. This well was deepened to 3348 m in 1982 and a temperature of 147°C was measured. In 1992, this well was extended to a depth of 4444 m where the temperature was measured at 170°C. The project has included considerable analyses of the stress field and natural fracture system employing an array of well logs, core analysis, and hydrofac packer tests (Tenzer et al, 2000).

The Swiss are investigating HDR in the town of Basel in northwestern Switzerland. Two separate sites near the Basel geothermal district heating system have been identified for further investigation. Scientists plan to drill a deep (2300 m) well there but it is unclear when this may take place (Brunner, 1999).

Also, there has been interest in HDR in Australia, where it is believed there may be a considerable HDR resource. Scientists believe that high-heat producing basement rocks overlain by insulating sedimentary formations create ideal heat traps in large areas of the country. The estimated subsurface temperature at 5 km depth is estimated to be greater than 250°C in significant parts of Australia (Swenson et al, 2000).

Also, the crustal-shortening environment creates a stress regime with a vertically oriented minimum principal stress, which is favorable for creating horizontal or sub-horizontal reservoirs. This type of geologic environment may allow the creation of multi-cell reservoirs where the cells are "stacked" one above the other and are intersected by common wells. However, the crustal-shortening regime does have negative consequences as well. Because the minimum principal stress is vertical and is roughly equivalent in magnitude to the lithostatic pressure, high injection pressures will probably be required to stimulate wells in this environment (Swenson et al, 2000).

Currently, Pacific Power Corporation is conducting exploration at the Hunter geothermal anomaly in the Hunter Valley in eastern New South Wales near the towns of Muswellbrook, Denman and Jerry's Plains. In 1999, the company began a pilot program drilling shallow exploratory wells in order to gather data to delimit the geothermal anomaly. Depending on the results of the pilot program, the company plans to drill intermediate-depth holes to measure geophysical parameters and conduct geo-mechanical testing (Burns, 2000).

3.0 Reservoir Characterization

Knowledge of the reservoir, especially of the fractures and faults, is essential for developing the reservoir, operating it, and predicting its performance. Fractures and faults form the pathways through which the circulating fluid passes and absorbs heat from the rock. This is true not only of EGS systems but also of most hydrothermal systems. Considerable research has been focused on locating, mapping, and delineating these features. This report looks at some of this research that is focused on EGS applications.

3.1 More-Than-Cloud Project

The More-Than-Cloud project, and its successor projects, Post-More-Than-Cloud and the Murphy Project, are collaborative efforts among international researchers to develop new methods to characterize the cracks that form a subsurface fracture network. The research takes advantage of interdisciplinary work among geophysicists, reservoir engineers, and rock mechanics experts. The research, which is funded by Japan's New Energy and Industrial Development Organization, includes researchers from France, Germany, Japan, Switzerland, United Kingdom and the United States. U.S. researchers involved in the MTC include Mike Fehler, Jim Albright, Scott Phillips, and Lee House (all of LANL) and Rick Aster (earthquake seismologist from NM Tech). Subsequently, the Murphy project also included Dan Swenson (Kansas State University) and Hugh Murphy (Colorado School of Mines).

This research has focused on methods of analyzing data generated from Acoustic Emission (AE) and Microseismic (MS) methods. AE/MS methods have been used to map HDR reservoirs for years. However, event locations in such methods are not very accurate, resulting in a blurred "cloud-like" image of the reservoir. Thus the name "More-Than-Cloud" was adopted for this project.

The project has devised four new methods for analyzing AE/MS data to image the reservoir. Two of the methods are designed to measure induced fractures. These are the Collapsing Method and Doublet Analysis. The other two, designed to measure natural fractures, are the AE reflection method and the seismic while drilling (SWD) method (personal communication with Niitsuma, 2000).

3.1.1 <u>Collapsing Method</u>

Uncertainties in the locations of AE/MS events are caused by random noise and by a lack of knowledge of the velocity structure of the environment. R. Jones of CSMA Consultants Ltd. (United Kingdom) developed a concept to relocate seismic sources by statistical methods. In this method, referred to as the "collapsing method," seismic locations are moved inside their uncertainty confidence ellipsoid until a simplified image of the event cloud is generated. Basically, each location is shifted towards the point with the greatest density of locations within the error ellipsoid of the original location. Figure 3 – 1 depicts a demonstration of the method using AE/MS data from Mammoth Lakes, California. In the Figure, fault structures are delineated with the method (Murphy et al, 2000).

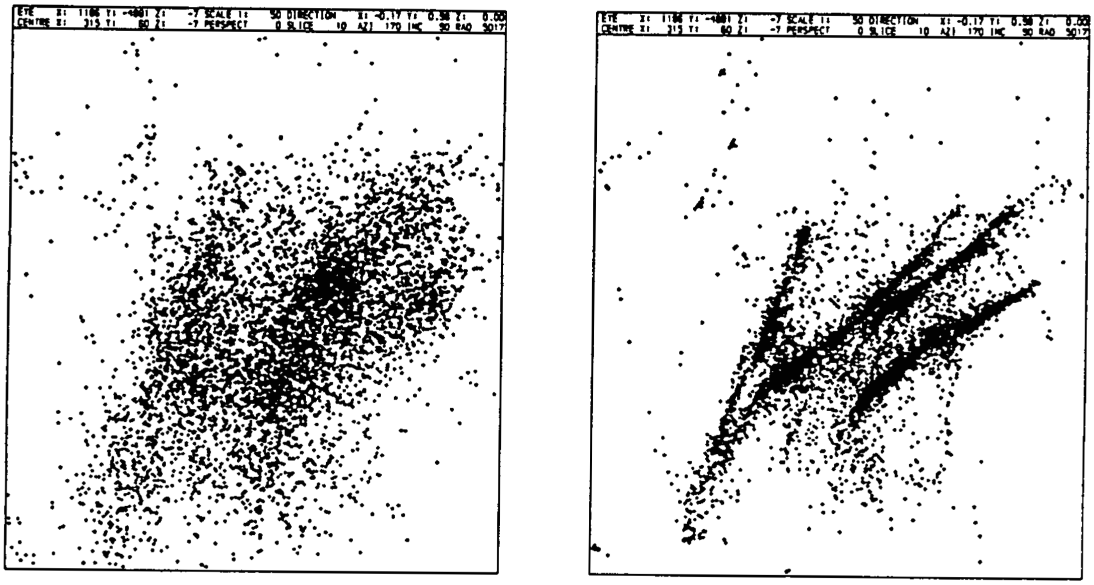

Figure 3 –1: Location of microseismicity at Mammoth Lake, USA. Left: conventional technique (JHD); Right: collapsing method (Murphy et al, 2000).

3.1.2 Doublet/Cluster Analysis

A group of seismic events occurring at different times but having similar waveforms are referred to as a doublet, multiplet, or cluster. Assuming doublets have the same source mechanism, an improved reservoir image can be obtained through the temporal-spatial analysis and source-mechanism analysis of doublets. Figure 3 – 2 compares AE/MS events at Hijiori that were determined by conventional seismic mapping and those determined by doublet analysis. The doublet analysis shows a more precise structure (Murphy et al, 2000).

3.1.3 AE/MS Reflection Method

Soma and Niitsuma developed the AE/MS Reflection method to characterize very deep reservoirs. The method discriminates the reflected phase from the AE/MS signal by analysis of three dimensional hodograms (Soma et al, 1997). This method has been applied to image the deep reservoir at Kakkonda, Japan as well as the reservoir at Soultz.

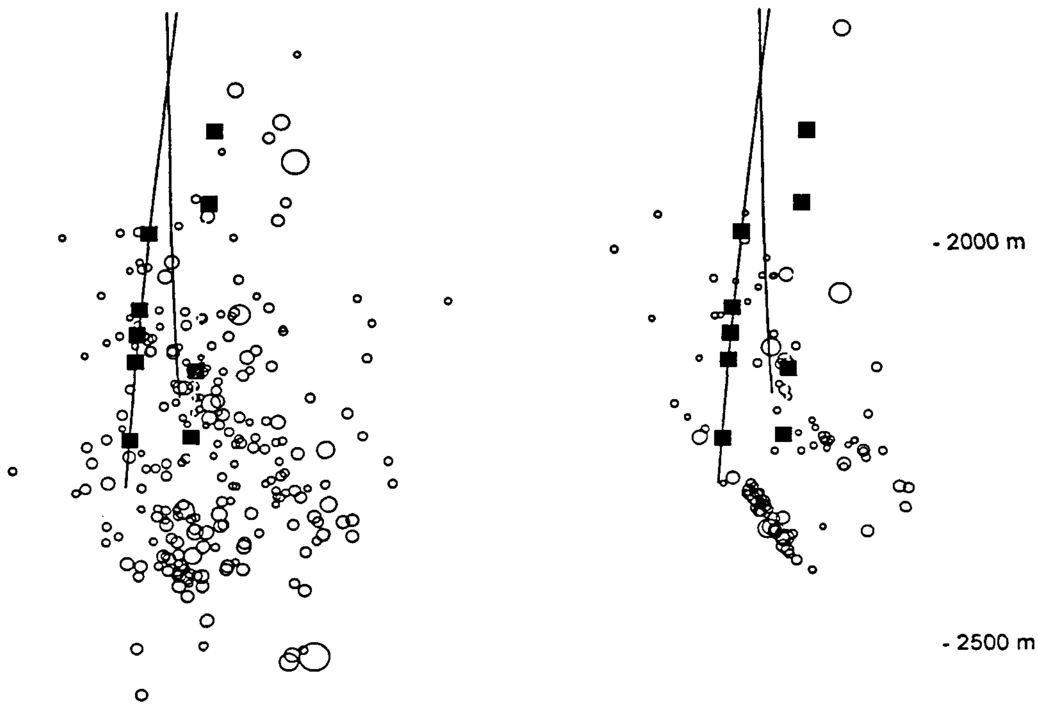

Figure 3 – 2: Location of microseismicity at Hijiori, Japan. Left: conventional technique; Right: doublet analysis (Murphy et al, 2000).

3.1.4 Seismic While Drilling Method

While vertical seismic profiling is the most important method for gathering data on subsurface structure, it is expensive and impossible to conduct simultaneously with drilling. Cost considerations preclude its frequent application during drilling. It is for these reasons that scientists are seeking to develop methods that use the drill signal to gather data about the subsurface structures. Although the signal characteristics are highly dependent on the field and drill system, information about the structure can be recovered with appropriate signal processing (Asanuma et al, 2000).

Researchers have developed the triaxial drill-bit VSP (TAD-VSP) method with a downhole multicomponent detector and have successfully resolved subsurface structures in test sites and geothermal fields. At Soultz, the method was used to obtain a reflection image consistent with logging, the distribution of microseismicity, and the A/E reflection method (Asanuma et al, 2000).

4.0 Geochemistry

Geochemistry is important in EGS applications for a number of reasons. Over time, geochemical fluid-rock interactions may impact the performance of an enhanced system. In order to properly simulate such systems and predict their performance accurately, models will need to include these interactions. This will facilitate the evaluation of the risks of scaling and corrosion in the wells, gathering system and power plant as well as the impact on reservoir performance of increases or decreases in permeability caused by mineral deposition or dissolution in the reservoir (Durst and Vuataz, 2000).

Also, monitoring changes in the chemistry of the circulating fluid in an engineered reservoir over time can provide data that is useful to evaluate some characteristics of the reservoir. In some reservoirs, minerals in the rock will dissolve in the circulating fluid. Knowledge of the changes in the mineral content of the of the circulating fluid can be used with knowledge of the reservoir (temperature, pressure, lithology, chemistry of in situ fluids, etc.) and knowledge of dissolution rates of the minerals present to estimate the amount of rock surface area that the fluid comes into contact with. This information can be used with data from tracers to estimate reservoir volume. This information is important for modeling the reservoir and predicting its performance over time (Kiho, 2000).

5.0 Supercritical Reservoirs

Both Japan and Iceland are investigating the potential of supercritical water as a heat extraction fluid from rock with very high temperatures. The information in this section is from Hashida, 2000.

Supercritical water has a significantly higher heat capacity than subcritical water and may be useful for increased extraction of the heat energy stored in rock masses. Lab experiments suggest that supercritical water may permeate pervasively in rock masses with no apparent pressure difference. This enhanced permeability of supercritical systems may make it possible to create a porous type reservoir and to access heat in a larger rock volume than would be possible with a fractured type reservoir at 200-300°C.

HDR experimental projects conducted to date have reservoir temperatures below the critical temperature of water. However, Japan's deep geothermal resource program has encountered temperature of 500°C at the Kakkonda geothermal site in northern Japan. At this site the temperature and pressure conditions exceed the critical point of water (374°C and 22 MPa) at a depth of 3.1 km. Supercritical conditions are not unique to Kakkonda. They have also been encountered in the Tuscany geothermal areas and the Phlegrean fields in Italy and in the Nesjavellir geothermal field in Iceland.

The Japanese research on supercritical reservoirs is focused in the following areas:

- Evaluation of fracture criteria of rock masses and formation processes of supercritical reservoirs
- Supercritical water-rock interactions
- Development of methods for monitoring supercritical reservoirs and for determining tectonic stresses
- Development of a predictive model for the performance of thermal extraction from supercritical reservoirs

Laboratory experiments suggest the feasibility of creating artificial cracks in supercritical rock mass by hydraulic injection. The tests indicate that the presence of supercritical water reduces the shear strength of granite samples by 25-30% over that in the dry condition. Fracture criteria are being identified to incorporate into a numerical simulation code to predict the fracture growth induced by hydraulic injections under a given tectonic stress state.

Scientists are also investigating supercritical fluid-rock interactions, including dissolution and precipitation in multi-component systems. Dissolution experiments indicate that the solubility of Iidate granite in water at supercritical conditions was significantly lower than that in the subcritical region. The reduced water-rock chemical interaction suggests supercritical reservoirs may not be subject to plugging of fluid flow paths due to precipitation.

6.0 Conclusions

Foreign colleagues are continuing their efforts to develop EGS technology. It is important for U.S. industry, researchers and policy makers to keep apprised of these efforts in order to encourage cooperation and communication between international researchers pursuing similar objectives, avoid duplication of efforts, and take advantage of new technology as it becomes available. The European and Japanese efforts are currently the most significant. Although the funding for foreign EGS research programs has been greater than recent funding for EGS research in the U.S., it is still rather limited considering the technical barriers being addressed. Therefore, progress from one year to the next is limited.

In recent years, there has been a resurgence of interest and activity in EGS research. After several years of limited activity, the three most important active HDR experimental facilities are increasing research operations. These facilities are the European Union's hot dry rock (HDR) project at Soultz-sous-Forets in France, and the Hijiori and Ogachi HDR projects in Japan. In 1999, the Soultz project deepened a well to 5,000 meters and has been conducting geophysical, geochemical, and well stimulation experiments including a massive hydrofracture operation during the summer of 2000. Scientists are still analyzing data from these experiments. At Ogachi, researchers drilled a new well in 1999 and conducted an injection test in the summer of 2000. The analyses of the injection test data are not complete. At Hijiori, preparations are underway to conduct a two-year circulation test beginning in December of 2000. In addition, scientists in Australia are conducting field investigations as preliminary work to construct an experimental HDR facility.

Of the three most important active HDR facilities, Soultz seems to be the one that has the most momentum at the present time. In circulation tests, it has achieved greater production rates with less fluid losses than at Hijiori and Ogachi. And although the temperature is lower at Soultz than at Hijiori and Ogachi, the deepening of well GPK2 at Soultz resulted in a bottom-hole temperature (approximately 200°C) considered by researchers as adequate for power generation.

Additional research in reservoir characterization warrants continued attention, including four new methods for analyzing AE/MS data to image the reservoir. Two of the methods are designed to measure induced fractures. These are the Collapsing Method and Doublet Analysis. The other two, designed to measure natural fractures, are the AE reflection method and the seismic while drilling (SWD) method. The most important of these are the Collapsing Method and the Doublet Analysis (personal communication with Niitsuma, 2000). The triaxial drill-bit VSP method (seismic while drilling) also shows some promise for identifying subsurface structures. With continued development it may become an important method for characterizing both hydrothermal and EGS reservoirs.

Recent EGS research on geochemistry has been somewhat limited. The Japanese and Europeans have done most of this research. Continuing efforts to understand rock-water interactions may prove important for characterizing and operating EGS reservoirs.

Both Japan and Iceland are investigating the potential for extracting energy from rock masses that contain water at supercritical conditions. It is somewhat early in this research to properly judge how important it may become. Supercritical conditions have been encountered in only four geothermal fields, Kakkonda (Japan), Tuscany and Phlegrean (Italy), and Nesjavellir (Iceland). However, undiscovered supercritical reservoirs may exist at accessible depths in volcanic areas. The importance of this research is inherent in the high temperature of these systems and the potential they offer to create a porous type reservoir and to access heat in a larger rock volume than would be possible with a fractured type reservoir at 200-300°C.

It is recommended that U.S. industry, researchers, and policy makers continue to be informed about foreign EGS research and that U.S. researchers collaborate with their foreign colleagues to the extent possible.

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