HYDRAULIC FRACTURING TESTS TO MAKE GEOTHERMAL RESERVOIR FOR HOT DRY ROCK DEVELOPMENT AT HIJIORI FIELD, JAPAN

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ABSTRACT

Hydraulic fracturing tests were conducted in an existing well to create a fracture near the bottom of the well as one step of hot dry rock development project. The test results showed that a desirable fracture was created by injecting 1,080 m^3 of water and 35 % of injected fluid was vented with the maximum temperature of 105 °C after injection. The well, SKG-2, is located in Hijiori,Yamagata Pref., Japan with the depth of 1,802m and bottomhole temperature of 254°C which was drilled for hydrothermal reservoir exploration by a private company. Through the hydraulic fracturing operation, flow rate, pressure and temperature were recorded as well as micro seimics were monitored both by a triaxial geophone tool and a surface network. Depending on the analysis of data obtained, we have created the fracture large enough for the farther development of hot dry rock research program.

INTRODUCTION

Hot dry rock development program in Japan commenced by Sunshine Project Promotion Headquarters, MITI had been conducted at Yakedake field since 1977 and terminated in 1983. Several logging instruments were developed and short time circulation tests were conducted among four bore holes of 300m in depth. In 1984, Hijiori Project started to develop the technology applicable for hotter and deeper conditions than experienced at Yakedake field. The Hijiori Project have been developed by New Energy Development Organization with surpports of National Research Institute for Pollution and Resources and a private contractor.

In October 1986, a hydraulic fracturing test was carried out in SKG-2. A total 1,080m^3 of water was injected into a 14m open hole interval at the bottom of the well. Injection continued for about 5 hours, with the maximum flow rate of 6 m^3/min and the wellhead pressure reached about 15.6 MPa. After injection hot fluid and steam heated in the fracture was vented and the total venting volume was estimated about 35 % of injected fluid. During the test, flow rate, pressure and fluid temperature were recorded. Before and after injection, we filled the water up to the top of the well and measured the dropping rate of the water level.

Microseismicity was monitored for fracture mapping both by a downhole triaxial geophone tool which was set in SKG-1 well and was apart 1200m from the injection point and by a network of eight surface seismic stations at distances of several km from the injection point.

In addition, geochemical analyses of vented fluid, environmental monitoring on the fluid quality of stream water and hot spring located near the test site and regional micro earthquake monitoring are also conducted.

In this paper, we discuss characteristics of the fracture created by the hydraulic fracturing and briefly summarize microseismic results.

WELL CONFIGURATION AND SURROUNDING ROCKS

SKG-2 well used for an injection test was drilled to the depth of 1,802m with the aim of hydrothermal reservoir exploration by private sector in 1979. Hydrothermal reservoir could not be found even though a bottom hole temperature was very high. We decided to use this well for the hot dry rock project because of the high temperature gradient and the low permeability of basement rock.

Figure 1 shows the downhole configuration of SKG-2. The well is 1,802m and is penetrated into the basement rock, granodiorite, which lay below 1,460m. Initially, 9-5/8" casing was installed to depth of 1,298m and below the depth the well was left open. Natural water level of the well was very stable, about 40m in depth, but fluid was flowed into the formation at the rate of 0.03m^3/min when water was filled up to the surface level. To examine the formation condition around the open hole section, a preliminary injection test with a spinner log followed by temperature log were conducted in 1984. From the tests it became clear that four major leak zones existed along the open hole interval.

Since the hydraulic fracturing was planned to make an artificial fracture in the basement rock for completing a flow path of circulation system, it became necessary to prevent fluid leakage into such leak zones. We decided the full hole pressurization was the most reliable and easy method, as an open hole packer developed at that time could not be convinced to be available to such high temperature. Then a 7" casing(N-80) was installed all along the well down to a depth of 1788 m, remaining 14m open hole section at the bottom.

After installation of casing, a small amount of water was injected in October 1985 to clarify the well conditions such as formation permeability around the open hole interval and to check a fluid leakage through cementing zone. The results showed no leakage was appeared in annulus between 7" casing and 9-5/8" casing during pressurization, and the flow rate into formations when the water was filled up to the wellhead decreased to 1/40 compared with previous test results before installation of the 7" casing. The average permeablility of the rock at the open hole interval was estimated by analysis of the pressure-time curves to be about 10^{-15}-10^{-16} m^2. This fact lead to a conclusion that the 7" casing inserted in SKG-2 would be set sufficiently for a hydraulic fracturing operation scheduled in 1986.

FRACTURING OPERATION

Prior to the main hydrofrac operation scheduled in autumn 1986, series of injection tests with one Halliburton pump, HT 400, were conducted in July, 1986 to get the relationship between the injection pressure and the flow rate. These tests was intended to determine the pump capacity required to create the new fracture for the main hydraulic fracturing test , and to check the vent fluid volume. For the injection tests following procedure was established.

1. Flow rate for the cyclic pressurization are ranging from 100 l/min to 500 l/min.
2. Injection at each flow rate is continued till the wellhead pressure reaches to stable value
3. During veting, the flow rate is measured to get the total volume vented.

In October 1986, the well head of SKG-2 was arranged for $1000m^3$ hydraulic fracturing, and a pond of $1600m^3$ was constructed at the test site. Halliburton equipments and crews were mobilized for fracturing operation. Figure 2 shows the equipment layout for the fracturing operation. Six Halliburton high pressure pumps were manifolded into two 4" injection lines which led to both side of well head. The water supply system consisted of three suction pumps and a $20m^3$ supply tank which allowed overflow the water when suction rate of the pumps was higher than injection rate. Flow meters were installed on the 7" suction line and 3" vent line. Two pressure transducers were installed at the manifold and the wellhead. Fluid temperature was measured by a thermocouple at the well head and by a downhole thermister at the depth of 1,770m in SKG-2.

Pumping began at 10:15 on October 16, 1986 and continued 5 hours with the injection rate from 2 to 6 m^3/min. Just after the termination of pumping, a wellhead master valve was opened and the injected fluid returned to the surface. The temperature of water vented increased with time. Venting continued for about 14 hours and terminated at 4:15 in next morning. Total vented volume was about 35% of injected volume.

Water level in the well and the flow rate into formation when the water was filled up to the top of the well were measured before and after the main hydraulic fracturing to invesigate the effects of fracture created by pumping.

Microseismic signals generated by the hydrofrac operation were monitored to get events for location mapping by two systems. One is a combination instrument of downhole triaxial geophone tool and hydrophone, and the other is a network of eight surface seismic stations. Figure 3 shows the location of wells, SKG-2 for fracturing operation and SKG-1, 600m apart from SKG-2 in the horizontal distance, in which the combination instrument was installed, as well as eight surface stations located at distances of several kilometers from the injection point.

The accuracy of the triaxial geophone tool, in the vertical direction is less than that in the horizontal direction. Therefore a hydrophone was installed at 350m above the triaxial geophone tool to improve the accuracy for the vertical direction. To determine event locations, hodogram method was introduced for triaxial geophone tool and P-wave first arrival times were used for the surface network.

TEST RESULTS AND DISCUSSION

Flow rate, pressure and temperature histories during the operation are shown in Figure 4. When flow rate was kept at 2 m^3/min for 2 hours, the wellhead pressure rose 14.7 MPa, then decreased to 11.6 MPa. But when flow rate was kept at 4 m^3/min and 6 m^3/min, the wellhead pressure decreased very slightly. This rapid pressure drop at the flow rate of 2 m^3/min corresponds to the fluid temperature decrease in the well. In early stage of pumping, the temperature of water in the well dropped very fast, which results in the increase of the density of water column in the injection well. From the temperature profile given by Wellbore Heat Transfer Cord developed at Los Alamos National Laboratory and measured temperature in the well and at the surface, the weight of water column in the well was calculated. Friction loss during pumping in the 7" casing is also estimated to examine the pressure at the bottom of the well. Through these analysis, it became clear that the pressure at the depth where water flowed into the fracture was almost kept constant during the pumping at constant injection rate even if the wellhead pressure was decreased.

Depending on injection and venting records, fracture characteristics were evaluated.

1) Analysis on the vented fluid volume

If the fluid permeation or leakage from the fracture into the formation are very little, the fluid volumes vented after each injection must be the same with that of pumped. Table 1 shows that the rate of the vented volume to the injection volume is dependent with amount of injected volume. In case that fluid volume injected was less than $30m^3$, recovered fluid ratios ranged from 38 to 47 %, but when fluid volume was incresed to 126 m^3, as shown in the test of July 3,1986, the ratio decreased to 22 %. From data obtained by July 1986, we worried about that the very small amount of water might be recovered when we injected a large amount of water. Fortunately, fluid volume recovered after 1,080 m^3 injection test increased to 35% of injected volume. At the Fenton Hill Project in the USA, the ratio was more than 50 %, while at the Cornwall Project in the UK, it was less than 30 %. In these projects, they have created the hot dry rock development system with two or three wells and artificial fractures connected with these wells.

2) The earth stress normal to the fracture plane

An attempt has been made to determine fracture opening pressure using the relation between P and Q^n, where P is the downhole injection pressure minus the fracture opening pressure, P_f-P_o, and Q is the flow rate (LANL,1983). Figure 5 shows both the relations between P and $Q^{1/4}$, and the surface pressure P and the estimated downhole injection pressure P_f are presented. The downhole injection pressure is calculated by considering the friction loss of the fluid along the 7" casing, the pore pressure and the temperature profile of the well. The downhole injection pressure is linearly related to the flow rate bigger than 1 m^3/min. The earth stress normal to the fracture plane is given by extrapolating the straight line back to zero flow rate axis, and the value estimated by this method is about 26.6 MPa.

3) Estimation of fracture radius

Fracture radius created by injecting water of 1,080 m^3 was estimated by assuming a penny-shaped fracture. Murphy(1983) gave one empirical equation which relates the fracture size to the injection volume depending on microseismic location data obtained from numbers of pumping operations conducted for hot dry rock development works throughout the world. According to Murphy's equation, the flow rate must be constant, so that the average flow rate during hydraulic operation, 3.6 m^3/min is used. The radius obtained is about 250m.

4) Estimation of average fracture aperture

Figure 6 shows the change of the water level when the water was filled to the surface level. The water level after the main hydraulic operation dropped faster compared to the that before the tests. If the fracture created was a penny-shape type and fracture aperture was assumed to be constant, the average aperture of fracture could be estimated by the following equation (Yung, 1986).

$$T = (Q_{in}\ln(r_e/r_o))/2\pi\Delta P$$

$$T = W^3/C$$

where T is the transimissivility of the fracture, Q_{in} is the injection flow rate, r_e and r_o are the borehole and fracture radius respectively, ΔP is the pressure drop through the fracture and W is the fracture aperture. Assuming the fracture surface is smooth which correspond to C=12, the average fracture aperture is esitimated to be about 0.3mm from the velocity of water level drop. From this estimation and Figure 5, it is clarified that the fracture created dose not close completely even when no pressure is applied to the wellhead.

FRACTURE MAPPING BY MICROSEISMIC DATA

A hydrophone used for improving the precision in the vertical direction for fracture mapping by triaxial geophone tool could not detect microseimic events because of poor matching of frequency between the hydrophone and predominant frequency of microseismic waves at the hydrophone. So data of ST-5 were used to determine the event locations by hodogram method. And data from one component of triaxial geophone tool were used to that of the surface network for improvement of vertical direction on location mapping.

The locations of microseismic events are shown in Figure 7. Although the number of event from which location could be determined was not sufficient to confirm whole image of the fracture, it might be evident that the fracture extended upward mainly from the injection point in the open hole section and the direcion was nearly SWS-NEN.

Signals recorded at the 8 surface stations and at the triaxial geophone tool, of which first motions were clear, were used to determine fault plane solutions. Figure 8 shows the fault plane solution from which P axis, the direction of the maximum compressive stress, is nearly vertical and T axis, the direction of the minimum tensile stress, is about horizontal and orientates about SW-NE. From the figure 8 it might be clear that the fracture was made by shear stress, and the fracture extended along the plane of which strike and dip were roughly N135° and 45°S. The plane expected by this solution is almost parallel to the orientaion of the seimic cloud shown in Figure 6.

CONCLUSION

Hydraulic fractureing was conducted with the SKG-2 to make an artificial reservoir for hot dry rock development at Hijiori, Japan. Water of 1,080m^3 was injected and about 35% of injected volume was recoverd to the surface with the temperature of over 100°C. Several findings for the reservoir by injection and venting data and microseismic data during series of injectin tests were:

a) The fracture created is considered to be adequate for hot dry rock development even if some extent of injected fluid leaks to natural fractures.

b) If a penny-shaped fracture is assumed, the radius estimated by Murphy's equation is about 250m which is equivalent to that of microseismic cloud.

c) The fracture is rather steep and it extends mainly to SW or SWS direction from the injection point and weak extension to NE or NEN is ovserved by the event locations of the micro seismic and the fault plane solution.

ACKNOWLEDGMENTS

This project was conducted by New Energy Development Organization under the Sunshine Project, MITI. Authors acknowledge the efforts of contractors member, Masayuki Kosugi, Isao Matsunaga and Tsutomu Yamaguchi of National

Research Institute for Pollution and Resources who joined the experiments.

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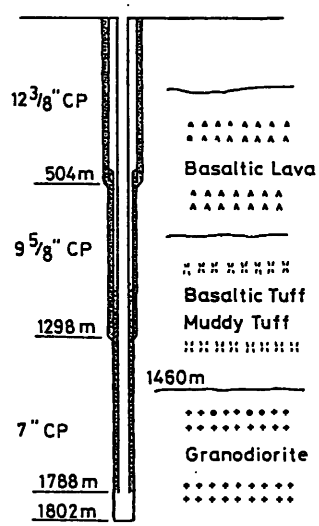

Figure 1. Well configuration of SKG-2.

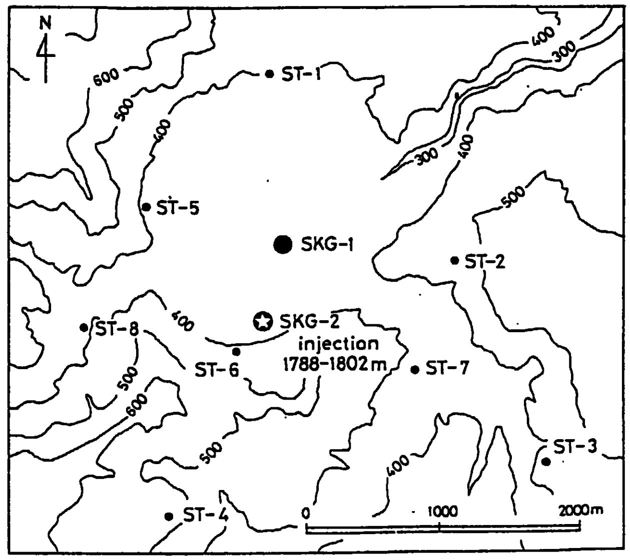

Figure 2. Equipments layout for the hydraulic fracturing operation of SKG-2 well.

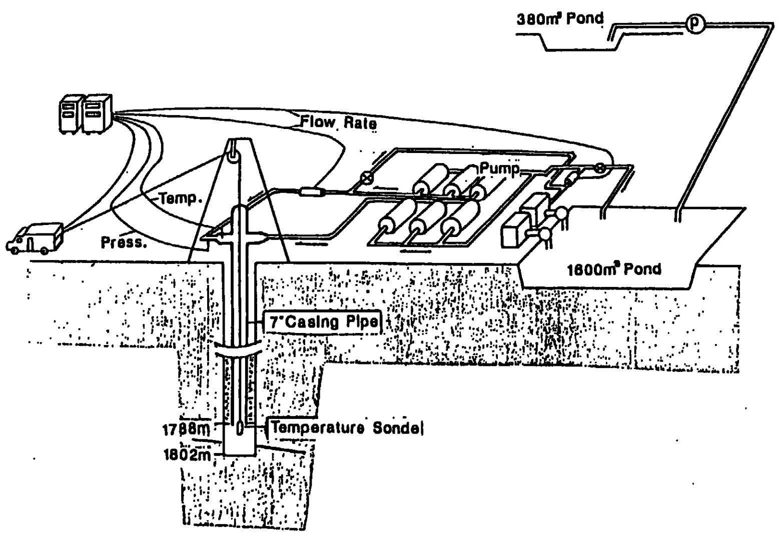

Figure 3. Location of wells and seismic stations of surface network.

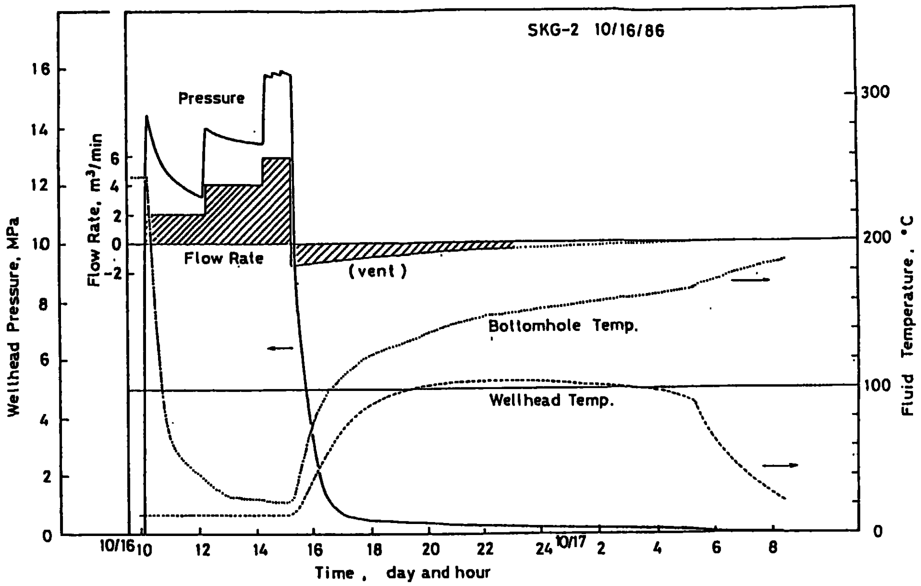

Figure 4. Pressure, flow rate and temperature recorded during the hydrofrac operation operation conducted at the depth of SKG-2.

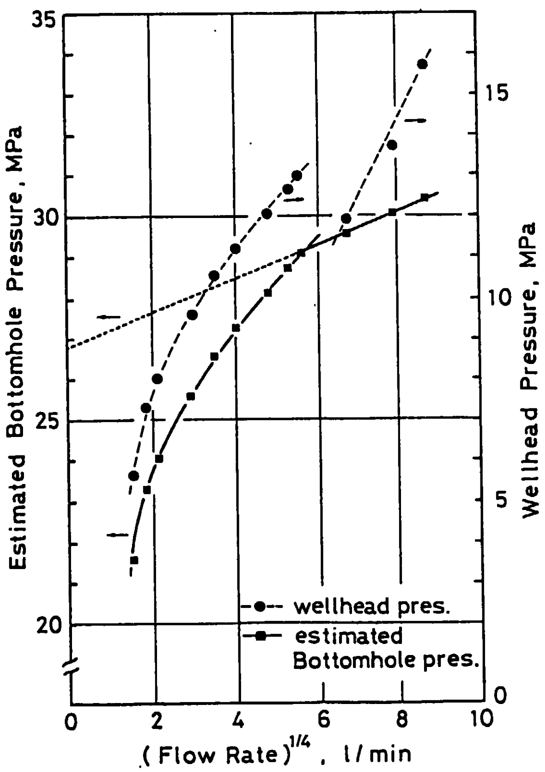

Figure 5. Relations between (flow rate)$^{1/4}$ and pressures at wellhead and bottomhole.

Table 1. The rate of the vent fluid volume to the injection volume.

	Flow Rate, L/min	Injected, Q_1, L	Vented, Q_2, L	Q_2/Q_1 %	Comments
86/ 7/ 2	83	1,000	350	35	after 10min. shut-in
〃	162	1,850	350	19	after 10min. shut-in
〃	162	1,590	750	47	
〃	273	2,650	630	24	after 10min. shut-in
〃	553	5,260	1,320	25	after 10min. shut-in
〃	537	5,260	2,430	46	
86/ 7/ 3	511	126,200	27,000	22	after 5min. shut-in
86/10/15	266	2,650	1,100	42	
〃	504	10,800	4,800	44	
〃	486	29,220	11,160	38	
86/10/16	2,000 ~ 6,000	1,080,000	380,000	35	105℃ recovered

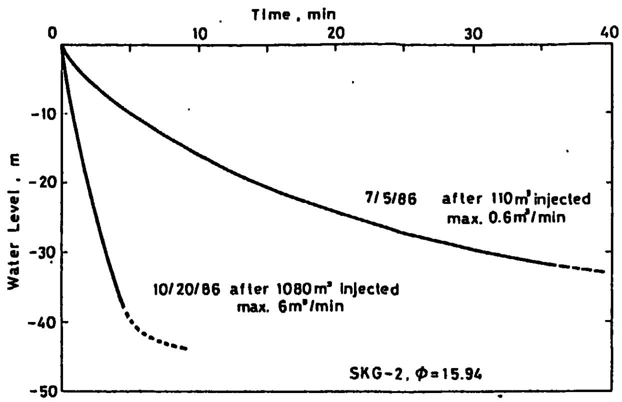

Figure 6. The water level change in SKG-2 when the water was filled up to the wellhead.

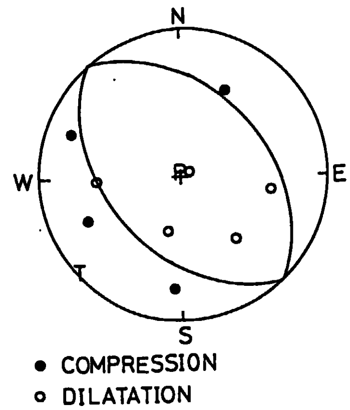

Figure 8. Fault-plane solution obtained from the first motions of signals recorded at surface stations and the 3-axis geophone.

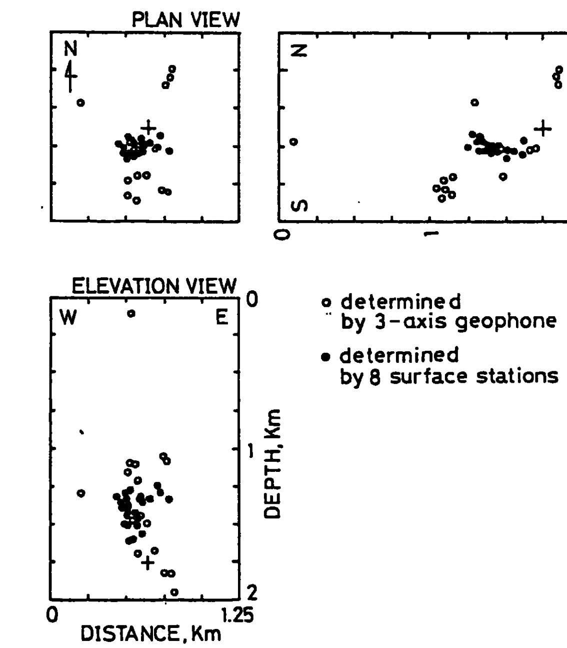

Figure 7. The locations of micro seismic events obtained by 3-axis geophone tool and by the network of eight seismic stations.