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NEW PROJECT FOR HOT WET ROCK GEOTHERMAL RESERVOIR DESIGN CONCEPT

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ABSTRACT

This paper presents the outlines of a new Hot Wet Rock (HWR) geothermal project. The goal of the project is to develop a design methodology for combined artificial and natural crack geothermal reservoir systems with the objective of enhancing the thermal output of existing geothermal power plants. The proposed concept of HWR and the research tasks of the project are described.

INTRODUCTION

It is well known that the productivity of geothermal wells is strongly dependent on the existence of cracks in rock masses. The concept of Hot Dry Rock (HDR) has been proposed in an attempt to create an artificial heat exchanging circulation system by means of well stimulation techniques such as hydraulic fracturing. This idea has attracted considerable interests and resulted in large-scale research projects in the U.S., Europe and Japan. The majority of currently operating geothermal power plants in Japan heavily rely on natural geothermal fluid stored in the existing subsurface crack network. However, the potential thermal energy from the surrounding areas is typically not fully utilized and remains unexploited. The thermal power output is therefore limited, unfortunately. Thus, there is a strong need for enhancing the thermal power of the existing geothermal reservoirs and for extending their operation life.

In response to the need, a new academic research project has been launched at Tohoku University, Japan. This research project is directed towards establishing an engineering design methodology for the further development of existing natural geothermal reservoirs. We have adopted the basic idea of HDR, and combined the existing available geothermal reservoir in the developments. As a result, the new concept of Hot Wet Rock (HWR) is created. The schematic of the concept is illustrated in Fig. 1. The HWR system refers to the combined natural and artificial crack network.

In this paper, the outlines of the new research project for HWR are presented, and the research tasks of working groups formed in the project are briefly described.

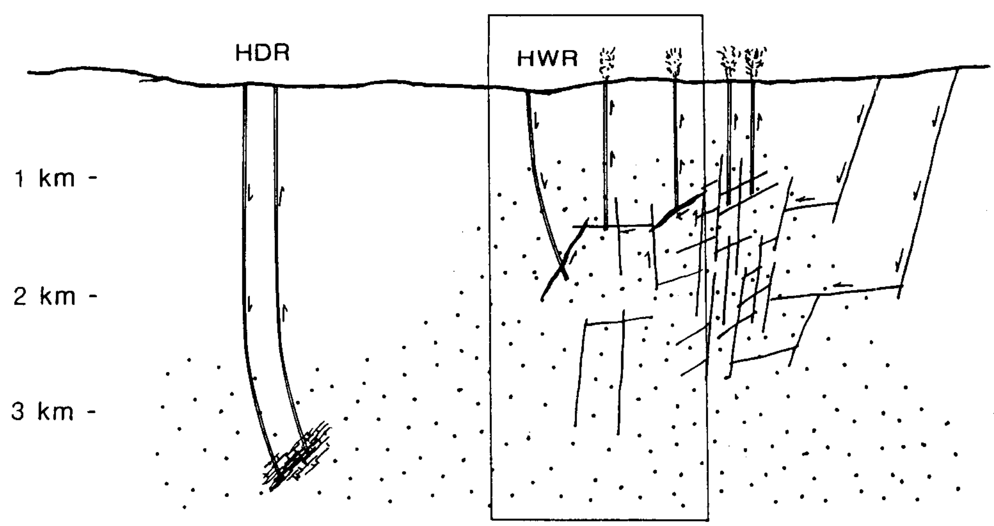


Fig. 1. The concept of Hot Wet Rock (HWR) geothermal reservoir

OUTLINES OF HWR PROJECT

The HWR project is being carried out in close cooperation with the MITI-NEDO geothermal energy development program (1989-1993). Fig. 2 shows the project organization structure. A research group of geothermal energy extraction engineering (GEEE) has been formed at Tohoku University. This research group is composed of several interdisciplinary teams, and plays a technical leading role in the project. As indicated in Fig. 2, a number of private companies and national research laboratories are also participating in the project.

The HWR concept specifically aims to connect a designed artificial crack with a preexisting geothermal reservoir in order to take full advantage of the surrounding area which is full of potential thermal energy. The establishment of the combined methodology for HWR systems calls for several element technologies. The following investigations form the major research tasks of the project:

(1) Monitoring and modelling of natural crack networks
(2) Design methodology of artificial heat exchange surfaces: optimization of the location and size of artificial cracks
(3) Heat extraction simulation from the combined geothermal reservoir
(4) Methods for predicting long-term reservoir performance

The methods listed above are being developed through working group activities in GEEE as shown in Table 1. The table also shows key personnels and their contributions. The GEEE team has carried out a research project on the design methodology of artificial crack-like reservoir for HDR geothermal energy extraction, which was a grant-in-aid for special distinguished research supported by the Government of Japan, Ministry of Education, Science and Culture (Abé, H. and Takahashi, H., 1983, Takahashi, H. and Abé, H., 1987, Niitsuma, H., 1989). The former project is called Γ-project. A crustal rock fracture mechanics approach has been proposed for HDR systems, and verified through field experiments. In the research task (2) of the HWR project, the fracture mechanics methodology is employed and further extended to the combined geothermal reservoir system.

The methodology is scheduled to be applied in the Yunomori geothermal field of the MITI-NEDO program. The temperature in the field is estimated to be about 200 °C at a depth of 1500 m. The time schedule of well drilling and experimentation is shown in Table 2. The HWR project provides academic supports for designing a geothermal reservoir in the model field along the time schedule.

RESEARCH ACTIVITIES IN GEEE

In this section a brief description of the individual research task is presented together with some results obtained to date. Given the importance of the natural crack characterization on the proposed combined geothermal reservoir performance, various crack monitoring techniques and modeling methods are being developed within the WG research activities. Fig. 3 illustrates a process for the development of design methodology for HWR systems. The WG researches

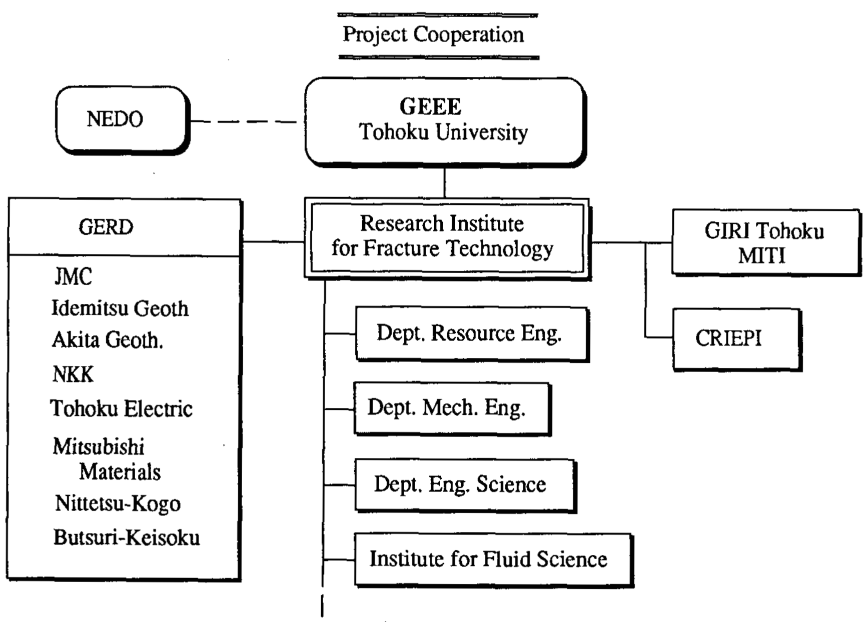


Fig. 2. Research organization structure of HWR project and project cooperation

Table 1. Research group of geothermal energy extraction engineering (GEEE), Tohoku University

Project Chairman	Prof. H. Takahashi (Research Inst. for Fracture Technology)
Project Vice-Chairman	Prof. K. Nakatsuka (Dept. of Resource Eng.)

Working Group	Personnels and Organization	
	WG Leader	WG Subleader
Subsurface Structure Evaluation WG	Prof. H. Niitsuma (Dept. of Resource Eng.)	Ass. Prof. M. Sato (Dept. of Resource Eng.)
Subsurface Crack Design WG	Prof. K. Hayashi (Inst. for Fluid Science)	Ass. Prof. T. Hashida (RIFT*)
Rock Mass Property Evaluation WG	Ass. Prof. K. Matsuki (Dept. of Resource Eng.)	Ass. Prof. T. Hashida (RIFT)
Thermal Design and Evaluation WG	Prof. T. Shoji (RIFT*)	Prof. K. Hayashi (Inst. for Fluid Science)

* RIFT: Research Institute for Fracture Technology

Table 2. Time schedule of MITI-NEDO project: Yunomori field experiments

Year	Schedule
1989	Selection of model field: Yunomori field
1990	Test drilling
1991	Drilling of production well
1992	Hydraulic fracturing (#1) Drilling of reinjection well
1993	Hydraulic fracturing (#2)
1994	Circulation test

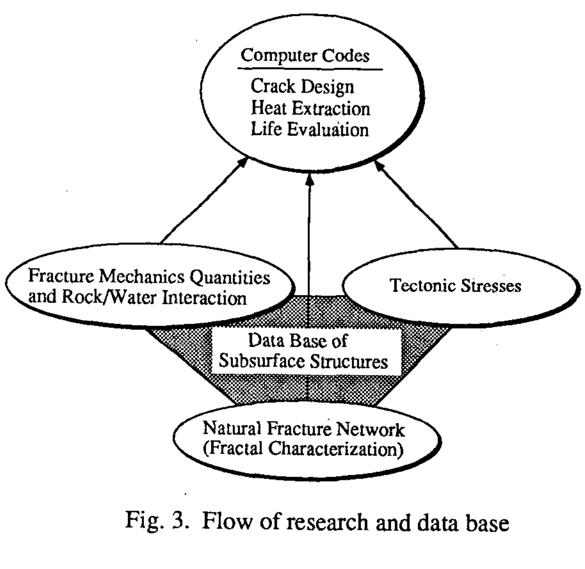


Fig. 3. Flow of research and data base

are also designed to establish a data base of subsurface structures.

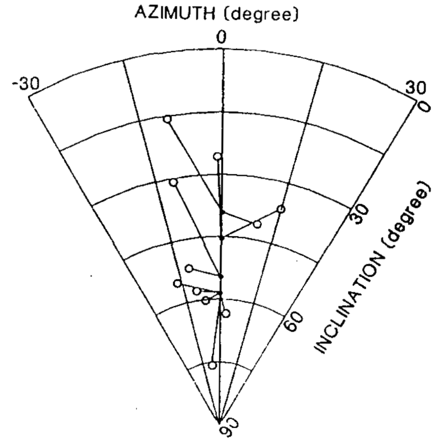
(1) Subsurface Structure Evaluation WG

Development of methods for monitoring subsurface cracks is a key issue for the design and performance evaluation of HWR systems. In this project extensive experimental and theoretical investigations are programmed in order to develop reliable methods for evaluating preexisting fracture networks and for detecting artificial cracks induced by hydraulic fracturing technique. The methods being developed are listed in the following:

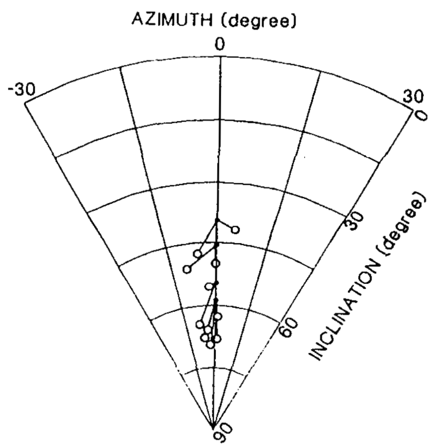
(a) Monitoring of Preexisting Fractures
- ○ Triaxial shear shadow
- ○ Shear wave splitting
- ○ Acoustic emission monitoring of drilling
- ○ Borehole radar
- ○ Magnetic tracer test.

(b) Monitoring of Artificial Fractures
- ○ Downhole acoustic imaging (triaxial hodogram AE source location); Theoretical study on AE source mechanism is also supporting the development of the method.

For each method, suitable signal detectors and signal processing techniques are being developed. For example, a wideband and high sensitive triaxial seismic detector has been developed for downhole AE source location. In conjunction with the sensor development a new calibration technique for detectors has been devised, which utilizes the spectral matrix analysis to improve the accuracy of the detection of P-wave direction in the triaxial hodogram analysis. The usefulness of the new detector and analyzing technique has been verified through experiments in the GEEE Higashihachimantai model field (Moriya et al., 1990, Niitsuma et al., 1991). In the tests seismic sources were simulated using an air gun in a borehole, and signals from the artificial source were monitored by the triaxial AE sensor set in an another borehole. Fig. 4 compares the results of source location evaluated by the spectral matrix analysis with those obtained by the conventional method in time



(a) conventional method,



(b) spectral matrix method

Fig. 4. Results of AE source location in calibration tests

domain. The points along the vertical axis indicates the actual location of the artificial seismic sources. It is seen that the new signal processing technique reduces significantly the error in the source location. Furthermore, a triaxial shear shadow technique has been applied to delineate the single crack created by hydraulic fracturing in the Higashihachimantai model field in the course of Γ-project (Niitsuma, H. and Saito, H., 1991). It has been demonstrated that the crack orientation determined by this technique was consistent with that predicted by tectonic stress measurements and core sample observation. The technique is currently being extended to cover more complex fracture networks.

(2) Subsurface Crack Design WG

The research items are outlined below.

(a) Tectonic stress determination; There has been no analyzing method applicable to determine in-situ stresses under the influence of thermal stresses in hydraulic fracturing method. Such a method is now under investigation.

(b) Subsurface crack evaluation based on pressure-flow rate-time records; Computer codes are under development to simulate the crack growth induced by hydraulic fracturing in HWR systems on the basis of the fracture mechanics approach. In order to support the development experimentally, a downhole devise for measuring the crack opening displacement has been fabricated.

(c) Percolation modeling for prèdicting reservoir performances; Percolation theory is employed to characterize fracture type reservoir and to predict reservoir performance (Usui, T. et al., 1991). Fig. 5 shows a model to examine the effect of an artificial crack on the reservoir permeability. The rectangular inspection area around the injection well is divided into 60×60 grids and the artificial crack is envisioned to extend horizontally towards existing reservoir from the injection well. Natural cracks within the inspection area were generated by using the percolation theory. Namely, the existence or absence of natural crack at the grid point was determined on the basis of the probability density, p. The value of p corresponds to the natural crack density. One segment of grid line whose both ends are

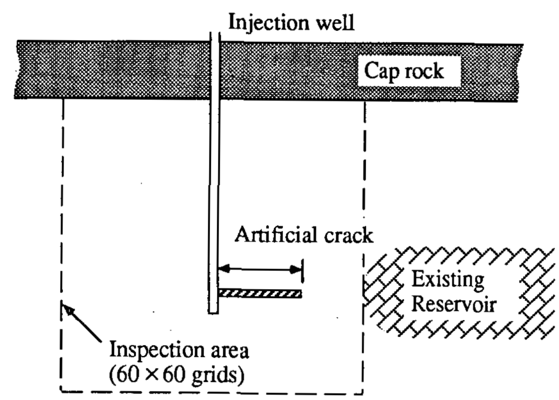


Fig. 5. Reservoir model for examining the effect of an artificial crack on the flow impedance

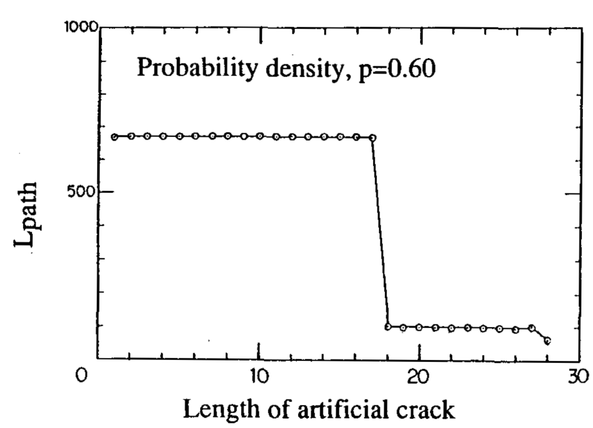


Fig. 6. Example of numerical results based on percolation theory

assigned under a given value of p is taken as an unit of natural crack. Fig. 6 gives an example of result predicted by the model, where L_{path} represents the minimum length of connected paths between injection well and existing reservoir in terms of grid numbers. Higher value of L_{path} can be taken as reflecting higher flow impedance. It is seen that the L_{path} drops rapidly as the artificial crack length reaches 18 grid length. As exemplified in the above example, the percolation model enables an quantitative prediction of an improvement of reservoir permeability by artificial cracks.

(3) Rock Mass Property WG

In order to provide rock mass property and rock/interaction data necessary for the subsurface crack design and thermal extraction analysis, the following investigations are being carried out:

(a) Development of fracture toughness testing method; Core-based test methods are being developed to determine the fracture toughness K_{Ic} under confining pressures. In addition to ISRM suggested core specimens, i.e. short rod and chevron bend, round compact tension specimens are used to evaluate the K_{Ic} in the mutually orthogonal orientations from one piece of core sample.

(b) Determination of tectonic stresses by use of rock core; Various methods including ASR, AE, DSA and DRA will be utilized to finally develop an integrated technique for determining accurate tectonic stresses in addition to the hydraulic fracturing method mentioned above.

(c) Water-rock interaction; Autoclave experiments are performed to determine the kinetics of dissolution and scaling. Investigation of the effect of dissolution on the permeability and the slip resistance along preexisting fractures is also included.

(d) Fractal geometry characterization of geothermal reservoir fracture network: Recent geophysical investigations have revealed that subsurface fracture network could be described by a fractal geometry. In the following a fractal geometry based approach is briefly presented (Watanabe, K. and Takahashi, H., 1991). The fractal relation between fracture length r and the number of fractures N whose length is equal to or larger than r may be expressed by

$$N = Cr^{-D} \qquad (1)$$

where D is fractal dimension and C is a constant which depends on the fracture density of rock mass. Fig. 7 shows an example of fracture network generated by the developed method on the basis of the fractal relation. Based on the recent observation (Meredith, P.G., 1990), the D is assumed to be 1.0 in the computation. The parameter C may be related to the number of fractures measured along a scan-line (as illustrated in Fig. 7) by the following equation

$$C = m / \left\{ \overline{\cos\theta_i} (1 - \ln r_{min}) \right\} \qquad (2)$$

where m is the number of fracture per unit length of the scan-line and $\overline{\cos\theta_i}$ represents an average of $\cos\theta_i$ with θ_i being fracture angle. r_{min} is the smallest observable length of fracture and depends on the resolution of measurement. The equation allows the parameter C to be determined from the observation of core samples. The above method for characterizing the fracture network has been applied to Kakkonda geothermal field in Japan. The result is shown in Fig. 8 in terms of a comparison between the computed fracture density parameter and the fluid loss observed during well drilling in the field. The general correspondence suggests that the modeling procedure provides a reasonable means for characterizing geothermal subsurface fracture networks.

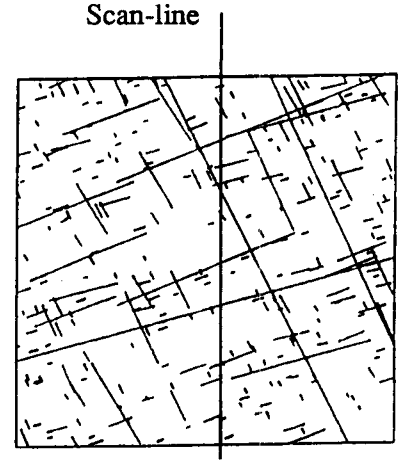


Fig. 7. Fracture network simulated by means of fractal relation

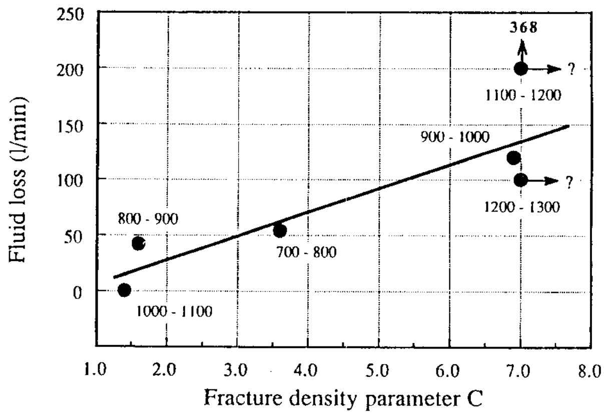


Fig. 8. Comparison between computed fracture density and fluid loss observed during well drilling

(4) Thermal Design and Evaluation WG

It is well accepted that the primary fluid flows occur not through homogeneous rock formation, but through fracture networks in fracture type geothermal reservoirs. Considering the complex geometry of fracture networks, it is essential to develop an efficient numerical method for analyzing the heat and fluid flows in HWR reservoirs. LINK (Line-Source and/or Sink Implanted Networks for Fractured Continua) method based on a double porosity and double permeability model has been developed (Kimura, S. et al, 1991, Masuda, Y.et al, 1991). The concept of the numerical method is shown in Fig. 9. In the method the heat and fluid flows in the fracture, and those in the less permeable rock are calculated separately. As schematically illustrated in Fig. 9, the transport between the rock and fracture network is modelled through one dimensional links. Specifically, the interaction between the fractures and the rock formation is taken into account through sink and source terms in a set of governing equations, describing the transport in the respective system. The present method has been proven to be ten times more efficient than a conventional algorithm by carrying out FEM

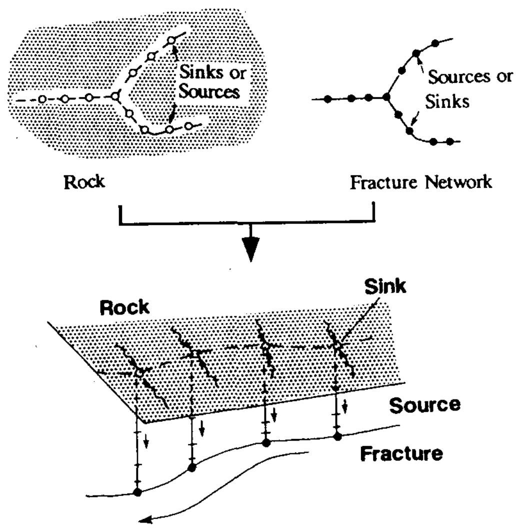


Fig. 9. Concept of proposed LINK method

computations on a simple two-dimensional model. The method is currently being extended to three-dimensional and complex fracture networks. Furthermore, experimental results of dissolution and scaling kinetics are incorporated into the simulator to develop a method for predicting the long-term reservoir behavior based on the rock-water interactions.

Preceding the massive hydraulic fracturing in the Yunomori field, some element technologies above mentioned are being tested in the GEEE Higashihachimantai geothermal model field and Kamaishi test field. Ultimately, the outputs of each individual groups will be integrated to form the foundation of the design methodology for HWR systems.

CONCLUDING REMARKS

The HWR research project outlined in this paper focuses on the development of an engineering methodology for combined fracture type geothermal reservoirs. The technology is expected to enable the further development and enhancement of the thermal power of existing geothermal reservoirs, and then to extend their operation life time. The interdisciplinary approach of the project would facilitate to establish a useful data base of geothermal subsurface structure, which is needed to determine the optimal artificial crack and to design the well stimulation procedure. A comprehensive HWR design methodology, coupled with a subsurface structure data base should be evolved and verified through the field experiment in the course of this project.

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