ROCK FRACTURE MECHANICS FOR DESIGN AND CONTROL OF GEOTHERMAL RESERVOIR

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1. INTRODUCTION

It has become evident that the productivity of natural geothermal systems is highly dependent upon the existence of fractures and high temperatures in deeper rocks (1). Fracture mechanics studies of the subsurface fracture behavior of rock masses (2)(3) have revealed a decrease in fracture toughness in high-temperature pressurized hot water environments. The results obtained indicate that subsurface cracks are always active and an abrupt change of well bore pressure including hydraulic fracturing and build-up tests in hot water dominated reservoirs causes fracture extensions in the vicinity of fractures resluting in the generation of acoustic emissions. The acoustic emission technique is utilized to map subsurface fractures and to evaluate their shape, size and orientation in geothermal reservoirs and other geological structures (4). The technique is also used as a powerful tool for mapping hydraulically induced fractures in hydraulic fracturing as well as for stimulations to improve productivity and the prediction of lost circulation during drilling. Moreover, it is very important to monitor subsurface fracture behavior for the stable and efficient operation of geothermal power plants.

This paper describes first of all some results of the AE measurements in the Kakkonda geothermal field, Iwate Prefecture, Japan. In conclusion, the application of the AE technique in the evaluation of geothermal reservoirs based on rock fracture mechanics, extremely useful in geothermal energy development, is described.

2. AE MEASUREMENTS IN THE KAKKONDA GEOTHERMAL FIELD

2.1 Downhole Acoustic Measurement System

Downhole AE measurement system has been developed at Tohoku University (5). The system consists of a downhole AE sonde, multiconductor cables, a vehicle for instruments, and signal conditioning and analyzing system. Three-component piezo-electric accelerometers, preamplifiers and an electronic compass are installed in the sonde. The sonde, whose size is 90 mm (diameter) x 2820 mm (length), is pressed against the borehole wall by two-arm fixers set into the upper and lower part of sonde. AE events are automatically detected and digitized by the automatic data acquisition system. Data is transfered and stored including event number, time and scale factor on an 8-inch floppy diskette as 6144 bytes of data. The tri-axial hodogram method is used for AE source location. The method consists of the detection of P-wave arrival, S-wave arrival and P-wave direction. The system locates an AE source within four seconds using a conventional 16-bit personal computer and is as accurate as manual analysis.

2.2 Evaluation of Subsurface Fracture During Drilling Based on AE Measurement

When geothermal wells are drilled, drilling fluid is used to constantly remove drilling chips from the bottom of the borehole. Subsurface fractures are found during the drilling of geothermal wells. A phenomenon called lost circulation in which the circulation of drilling fluid is lost occurs. A geothermal well (K7-2) with an underground crack near the 1300 m depth was drilled in the Kakkonda field. A casing was then set at the 1000 m level. Complete lost circulation occurred at 1330 m of drilling depth with a drilling-break where a bit weight was lowered from 10 tons to 3 tons. AE events began to occure starting prior to lost circulation and AE activity abruptly increased when complete lost circulation occurred. More specifically, when the existence of a crack propagation state in the ground under the AE activity was assumed, the main crack producing lost circulation was encountered at a depth of 1330 m and a readily, collapsible microcrack zone existed at the periphery. When drilling was carried out in this layer, the damage started to produce AE activity due to the hydroststic pressure of the drilling fluid. It appears that the drilling fluid started moving through the main crack upon arrival at the weakest section of the ground layer and the crack developed simultaneously due to the hydraulic pressure of the drilling fluid thus abruptly increasing AE energy. The AE sources were located using the hodogram method where the subsurface crack was found to have caused lost circulation. The subsurface crack encountered (lost circulation layer) was propagated at approximately 500 m for one minute in the southerly and easterly directions from -580 m to -180 m above sea level. It was considered that the scale was sufficient to qualify as a geothermal reservoir. Moreover, the production at the periphery was -200 m or more above sea level. The lower limit of the reinjection zone for reinjecting hot water was deeper than 0 m above sea level and it was found that the underground crack was not directly connected to the reinjected hot water.

2.3 Hydraulic Fracturing of a Geothermal Well Controlled by the AE Technique (6)

Hydraulic fracturing of a production well (KD-3) was effected in the Kakkonda field. The drilling depth of the well was 1269 m, and casing of 13 3/8" (0-360 m) and 9 5/8" (360-965 m) diameter was set into the upper part of the well. The section below 965 m was an open hole of 8 1/2" diameter. The well intersects two fracture zones at 1060 m and 1205-1269 m which were detected from lost circulation of drilling fluid during drilling operations.

A total volume of 1720 kl of cold water was injected using three high-pressure pump -- two 8P-80S (National Supply) and one HT-400 (Halliburton) pump -- which were directly connected to the well-head valve without packersystem. The acoustic emission technique was introduced to evaluate and control the stimulation. Itwas assumued that the distribution of a created reservoir could be mapped by AE source location and the efficiency of the stimulation could be determined from AE activity. The downhole AE system mentioned above was used for the AE measurement.

In the first treatment, total of 900 kl of cold water was injected. Several small breakdowns togather with the acoustic emission and drops in flow impedance were observed. About 160 events were detected during and after the injection. The AEsources are disributed in the area oriented east-west. The vertical distribution of the AE sources is mainly in the area between -250 m and -500 m below sea lavel which corresponds to the steam produced in the lower reservoir. From these AE analyses it was determined that the creation and distribution of an artificial crack was successful and a decision was made to carry out an additional stimulation the following day.

In the second treatment, only 20 AE events were observed while the flow impedance decreased considerably. This fact suggested that the artificial crack was connected to a highly permeable reservoir. The treatment was terminated after the injection of 820 kl.

After treatments, temperature loggings and production tests were conducted in the KD-3 well. The temperature logging effected 62 hours after the treatment revealed that the cold water had been injected mainly into the section between 1205 m and 1269 m of the drilling depth. Steam production was increased 1.65 times after the stimulation. These post-analyses reveal the success of this AE controlled hydraulic stimulation.

2.4 Control of Geothermal Reservoir Stability using the AE Tbchnique

A fracture mechanics model of a crack extension in a geothermal reservoir during in-service operation and during a build-up test is schematically represented by Niitsuma et al (5). The fracture toughness of rock masses under study during in-service operations decreased under chemical attack. The reservoir was then extended by subcritical crack growth under the constant pressure of earth stress such that the stress intensity factor increases during operations. Crack extension occurred when the stress intensity factor exceeded the fracture toughness of the rock mass. Crack extension can also be expected during build-up tests where downhole pressure increases with the closure of the well-head valve. Since crack length increased and fracture toughness decreased during in service operation, a sudden crack extension could possibly occur consequent to an increase in pressure during testing even when pressure is lower than in the test previously conducted. Moreover, Niitsuma et al (7) have demonstrated that the stability of crack reservoirs is a function of the stopped flow-rate in a reservoir system, the closing rate of the well-head valve and the test interval.

Long-distance AE activity during build-up test in the Kakkonda area was measured using a downhole AE sonde installed in a 50 m well in 1982, 1984, 1985, 1986, 1987 and 1988. The AE activity concentrated along and near fault planes and preexisting fracture zones of Neogene formations. This suggests that AE sources reveal the shape of geothermal reservoir. The AE activity depends on the total stoppage of the in the reservoir (7). Itis assumed that AE events correspond to crack formation and propagation which are induced by increases in downhole pressure in deeper reservoir rock. These results suggests that crack extensions due to an increase of downhole pressure can be controlled by changing the stopped flow-rate and test interval. AE activity also depends on the closing rate of the well-head valve (8). Based on these experiments, it appears that AE activity is dependent upon the closing rate of the well-head valve. The more slowly the well-head valve closes, the lower the AE activity. Reservoir stability control has been successfully accomplished through valve operation based on the results of AE analyses.

3.APPLICATION OF THE AE TECHNIQUE TO THE EVALUATION OF GEOTHERMAL RESERVOIR BASED ON ROCK FRACTURE MECHANICS

It is very important to control subsurface crack extension in geothermal energy development since productivity is highly dependent upon the distribution and dynamics of reservoir cracks. Using conventional methods, it has not been possible to collect geothermal fluids if large-scale subsurface cracks have not been found during the drilling of geothermal wells. As previously explained, it is believed that subsurface cracks are always active during in-service operations and an abrupt change of well-bore pressure causes subsurface crack extension. Figure 1 demonstrates a conceptual geothermal reservoir in the Kakkonda area. This illustration suggests that hydraulically induced crack propagation without control brings about breakthroughs which create a connection with the production zone and re-injection zone or shallow cold water (Figure 1 (a). In this case, the re-injected water moves downward and cools the production zone rendering it impossible to stably produce a predetermined amount of geothermal steam. In such case, a method for obtaining a predetermined quantity of steam through the excavation of a new geothermal well has heretofore been employed. However, high drilling costs result in increases in power generation costs which have prevented the acceleration of geothermal energy development.

In order to circumvent these problems, the rock fracture mechanics approch is being employed to provide new insights into the fracture of rocks, especially in the design of crack-like reservoirs. A combined technique of rock fracture mechanics and the AE technique has been developed by the authors. Figure 2 illustrates a geothermal reservoir evaluation system based on rock fracture mechanics. In the application of this method two basic measurements are

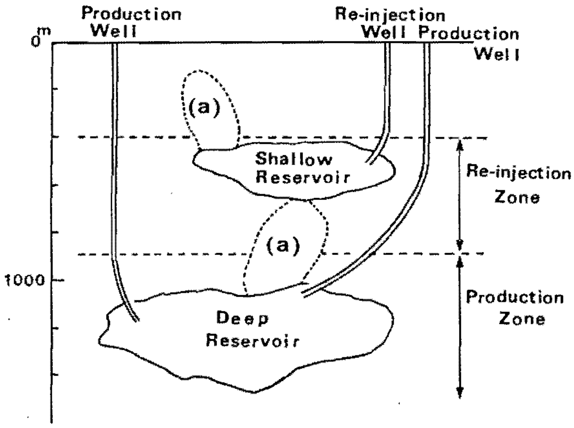

Fig. 1 Conceptional geothermal reservoir in Kakkonda area.

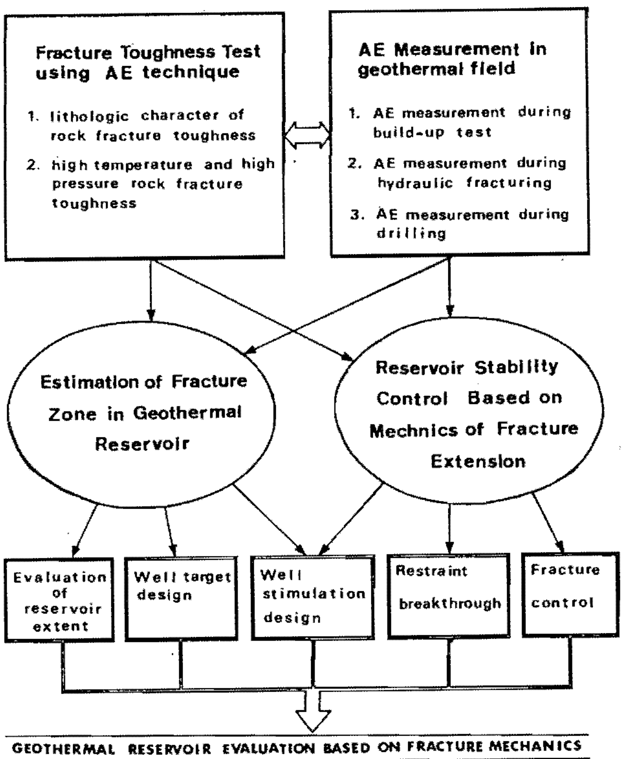

Fig. 2 Geothermal reservoir evaluation system based on rock fracture mechanics.

performed. The first is a laboratory fracture toughness test using the AE technique which yields the rock fracture properties of a geothermal environment. The second consists of AE measurements during build-up tests, Hydraulic fracturing and drilling operations in geothermal fields. After these measurements have been analyzed, the results indicate the fracture zone of the geothermal reservoir and the method to control reservoir stability through the application of fracture extension mechanics. In addition, the extension of reservoir, well target design, well stimulation design and restraint breakthrough fracture control design influence the evaluation of these results.

As mentioned above, the evaluation of geothermal reservoirs based on rock fracture mechanics using the AE technique reveals rock fracture properties, fracture shapes and the characteristics of subsurface fractures in geothermal fields. Therefore, a predetermined quantity of steam can be stably obtained by extending or preventing the extension of subsurface cracks. Figure 3 shows illustrative procedure for the stable continued operation of the geothermal power plant based on rock fracture mechanics.

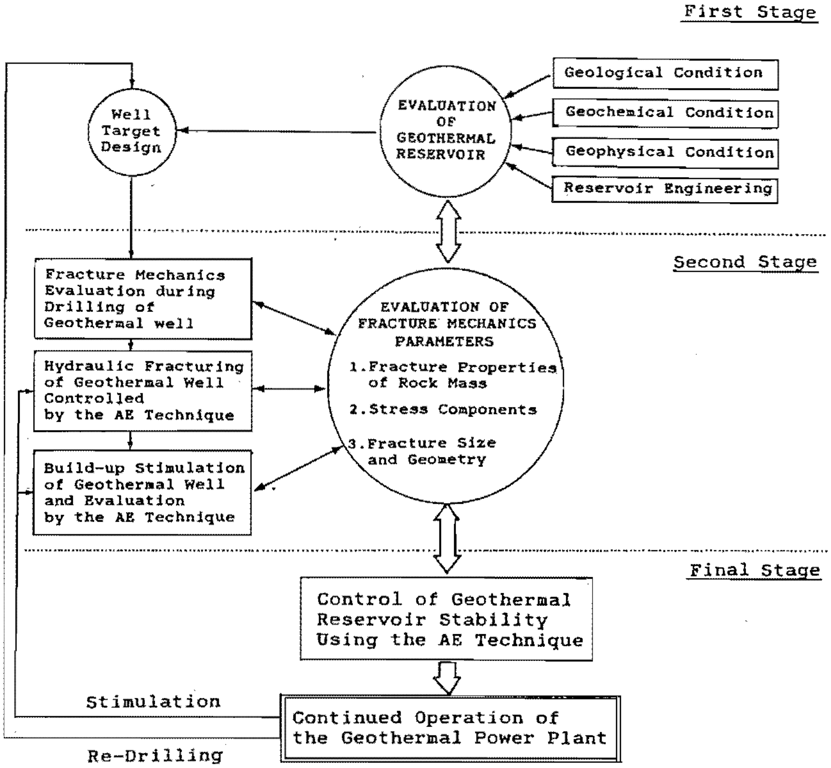

Fig. 3 Illustrative procedure for design and control of geothermal reservoir based on the rock fracture mechanics.

ACKNOWLEDGEMENT

The authors are deeply indebted to Prof. Hiroyuki Abe, Prof. Katsuto Nakatsuka and Prof. Noriyoshi Chubachi of Tohoku University for their kind suggestions. Thanks are also due to Dr. Ko Sato of Japan Metals and Chemicals Co., Ltd.,for his valuable advice.

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