PROCEEDINGS, Fourteenth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 24-26, 1989
SGP-TR-122

RESERVOIR PHYSICS AND HOT DRY ROCK IN CURRENT NATIONAL R/D PROJECTS

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ABSTRACT

National geothermal energy development program in Japan began in the early 1970's as one of the Sunshine Project (R/D on new energy technology). The program has been funded by the Sunshine Project Promotion Headquarters, Agency of Industrial Science and Technology, Ministry of International Trade and Industry. The main targets of geothermal energy project are to develop (1)technology for exploration and extraction of hot hydrothermal energy, (2) technology for power generation using geothermal hot water (10MW class binarycycle test plant), (3)technology for hot dry rock power generation systems, (4)technology for multi-phase utilization of geothermal energy and preservation of environment. The FY1988 total budget for all national geothermal R/D programs is about 5386 million Yen (43 million US dollars,1$=125 Yen). NEDO (New Energy and Industrial Technology Development Organization) established in 1980 by the government and private sector plays the main role in promoting national energy development with participation by several national institutes such as GSJ(Geological Survey of Japan), NRIPR(National Research Institute for Pollution & Resources), Tohoku Industrial Research Institute and so on. This paper presents the introduction of main national R/D projects which are going on, and will focus on the reservoir physics and hot dry rock project.

INTRODUCTION

One of the NEDO projects, confirmation study of the effectiveness of prospecting techniques for deep geothermal resources, began in 1980 with the objective of developing geothermal exploration techniques and confirming the results of various geophysical and geological surveys by drilling a deep geothermal wells. Two different geothermal model areas, Sengan and Kurikoma, were chosen for this purpose. FY1988 is a final year for this project and evaluation work is being done for the results of various surface exploration technologies with comparison of deep drilling data. New R&D program will be started following this project, and its emphasis is directed at producing two- and three-dimensional models of geothermal reservoirs, and surveying to locate and to map fractures of hydrothermal systems from the surface and within wells. Sengan and Kurikoma projects are first summarized, and then new future program for the fractured reservoir is discussed.

The hot dry rock project at Hijiori site in Yamagata prefecture has been operated by the New Energy and Industrial Technology Development Organization (NEDO) since 1985. Many experiments of the hot dry rock system are planned from 1989, and NRIPR (National Research Institute for Pollution and Resources) of MITI is in charge of analysis of logging data and circulating data. NEDO and NRIPR will be responsible for the future program of the hot dry rock in Hijiori. Discussion is concentrated on the current HDR research in National Project.

RESERVOIR PHYSICS IN SENGAN PROJECT

The Sengan area is in Akita and Iwate prefectures in northern Japan, and three geothermal power plants in operation, Onuma, Matsukawa and Kakkonda, are located within this area. Sengan area is a high potential area for a large geothermal energy, and it will be of importance to establish the geothermal exploratory techniques for identifying and mapping unknown hydrothermal system at depth in this area. Heat sources are probably the feeding magma of young volcano group as Mt.Yakeyama and Mt.Hachimantai, and its geothermal reservoir layer is assumed to be located in the Neogene Tertiary System underlying each of the volcanic materials.

Many geophysical and geological surveys in addition to gravity, geochemical and

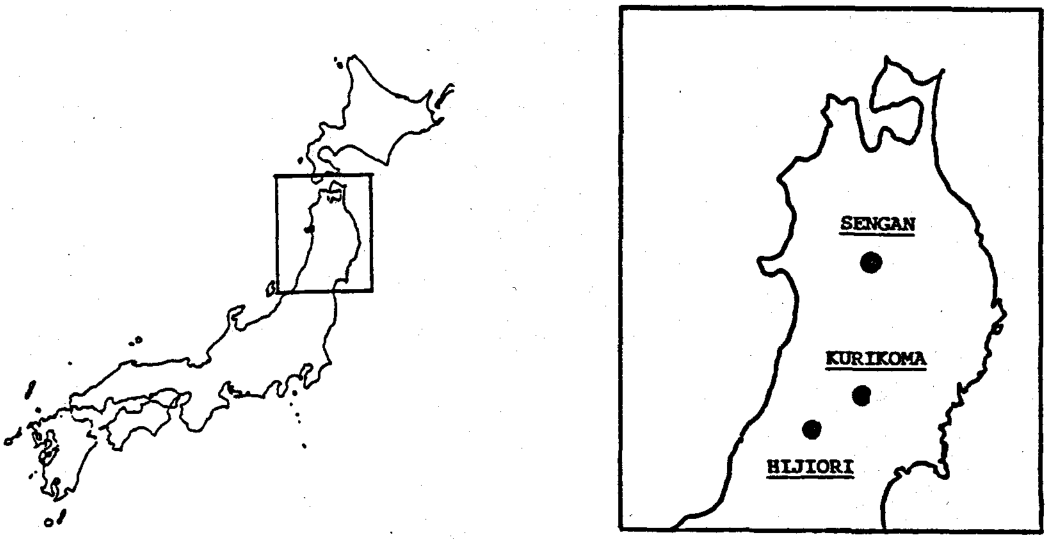

Figure 1: Location Map

aeromagnetic surveys, were applied in Sengan to make a geothermal subsurface model,such as refraction method, magnetotelluric exploration, Schlumberger electrical surveys, heat flow surveys by 200-800m wells, core dating by ESR (Electron Spin Resonance), Tubel method and so on. Geological Survey of Japan joins this Sengan project in the analysis of geologic structure, geochronological study, borehole geochemistry, thermophysical modeling, DC resistivity and magnetotelluric method. Geological study of the basement rocks around the central part of the Sengan geothermal area revealed that Mesozoic and Paleozoic siltstone, shale and chert are distributed in the Yuze and Ryugamori districts, and sedimentary rocks underwent the contact metamorphism by intrusive rocks. But no evidence for Pre-Tertiary igneous rocks was found out in the studied area. The isotopic compositions of surface water in Sengan area correlate inversely to the altitude of the sampling sites (-0.25‰ /100m for $\delta^{18}O$). In some wells, it shows abnormally low $\delta^{18}O$ values with respect to the altitude of the well. Temperature logging data of deep wells and physical properties of core samples were extensively collected for the thermophysical modeling of the Sengan field. A forward modeling of the temperature structure has been continued to find out the subsurface temperature distribution at depth consistent with well logging data of surface temperature. Geothermal model of Sumikawa area, north part of Sengan area, is considered as follows.

Heat sources are assumed to be the deep of Mt.Yakeyama and Mt.Hachimantai. The individual heat source situates in the center of a up-flow zone and several hydrothermal convection systems are formed. Steam cap has been formed at the top of the reservoir, and lake deposite and Quaternary andesitic volcanics are considered to be this cap rocks. Fracture System of Sumikawa area was formed in relation closely to the volcanic activities, and geothermal fluids predominantly flows through these fractures.

In Nov. 1987, a deep confirmative well (N61-SN-7D) was drilled to depth of 2486m (8287 ft). The drilling location of this well was based upon the subsurface prediction of probable existence of geothermal reservoir at depth. Mud-logging was started from a depth of 1111m (3703ft), and aerated drilling operations were started from a depth of 1924m (6413ft). Drill cuttings were collected at every 5 meter and core was also collected at 1505m, 1921m, 2292m and 2484m. Several geophysical well loggings were conducted for the N61-SN-7D such as temperature logging, electrical logging, dual latero logging, neutron logging, density logging and spectro gamma logging. After a 7 inch slotted and uncemmented liner was installed, injection test and warm-up test were conducted. The permeability-thickness product (kh) of the N61-SN-7D is 3.11-9.38 darcy-m by multi-flow injection-test and kh calcuated by fall-off curve is 7.73 darcy-m. From the results of the hydrostatic-pressure balance and geophysical well logs, the major lost circulation zone is inferred to be at 2325m (7750ft) depth. The highest calculated static temperature is 304°c at 1800m (6000ft). This temperature, however, is not considered to correspond with the static formation temperature because of large circulation losses during a drilling operation. In 1988, a production test for this well N61-SN-7D was conducted, and its data are as follows.

Steam	161 t/hr
Hot water	318 t/hr
Reservoir temperature	272 °c
Well head pressure	12.5 kg/cm^2
Liquid chemistry	neutral Nacl type

It was found that the geothermal energy of this N61-SN-7D well corresponds to 16 MW power generation, and this is the biggest productivity for a single geothermal well in Japan. This success encourages the continuing effort to develop geothermal resources deeper than conventional 1000-1500m depth.

RESERVOIR PHYSICS IN KURIKOMA PROJECT

The Kurikoma area is centered on the Onikobe caldera in Miyagi prefecture, and a geothermal reservoir layer is thought to exist in fissures extending from the upper portion of the Pre-Tertiary granitic basement to lake deposits at the base of the caldera. Kurikoma project began in 1980, and airborne infrared thermal image surveys were conducted in this year over an area about 200 km^2 including the Onikobe caldera. Magentotelluric (MT) exploration and the electrical (Schlumberger) method were also conducted for the subsurface resistivity structure of Kurikoma field. GSJ revealed that the basement beneath the caldera was 1-2 km depth from the surface with two-dimensional inverse modeling technique of the MT data. It was also found that there exists a horst structure in Katayama area which is the most active geothermal manifestation area. This horst may be playing the important role for the conduit of hydrothermal up-flow system by providing the vertical faults. Other geophysical data such as gravity and aeromagnetic data were already surveyed and collected in this area. A total of six 1500 m class well were drilled for geological surveys, subsurface temperature distribution and core analyses.

The result of two-dimensional multi-layer analysis shows that gravity anomalies are consistent with the features of the granitic basement or the upper green-tuff layers, and short wavelength Bouguer anomalies seems to correspond to the distribution of lake deposits and/or andesitic lava. The three dimensional structure in the Kurikoma area was also obtained on the assumption of three homogeneous layer model under the control information of basement outcrop. 3D hydrothermal numerical modeling in the Onikobe area is being conducted with IFDM codes of geothermal simulation program.

HDR IN HIJIORI PROJECT

After the field studies of hydraulic fracturing at Yakedake which is the first test site for hot dry program in Japan, Hijiori in Yamagata prefecture was selected as another substantial test field to extract geothermal energy from a hot dry rock. Two wells, SKG-1 and SKG-2, had been drilled for geothermal survey at Hijiori. The depth of SKG-2 is 1802m, and the temperature at its bottom is about 250°c. The basement rock (granodiorite) lies below a depth of 1460m and the artificial reservoir was intended to be made in this basement rock by drilling and hydraulic fracturing.

In 1984, logging and pumping tests were conducted to get information for hydraulic fracturing. The natural inflow was 1.0 m^3/h, and a well head pumping pressure at flow rate of 0.4 m^3/min was 6 MPa. Lost circulations were detected at depth of 1530m to 1540m, 1570m to 1580m, and 1620m to 1640m. As a result of these tests, a full hole pressurization was selected as a hydraulic fracturing method. In 1985, 7" casing was installed from the surface to a depth of 1788m in SKG-2. Permeabilities of the basement rock at depth of 1788m to 1802m were estimated from 1 to 10 microdarcy.

In October 1986, a hydraulic fracturing was conducted by injecting about 1000 m^3 of water at depth of 1788m to 1802m in SKG-2 well. Flow rates were 2 to 6 m^3/min and well head pressures were 11 to 16 MPa. 380 m^3 of hot water were vented from SKG-2 well after this injection. Microseismics were observed by 8 seismic sensors at 100m depth and a downhole triaxial geophone in SKG-1. Hypocentral locations of about 30 high-quality events indicated that microseismics occurred at 200m to 400m south of SKG-2 and at depth of 1500m to 1800m. The number of microseismic events, however, was insufficient for finding out the location of the hydraulically fractured zone.

In 1987, a new well, HDR-1, was drilled in the south of SKG-2 to confirm the artificial fractured reservoir created by 1986 hydraulic fracturing operation. The bottom of HDR-1 & SKG-2 well was 30m apart at depth. 9 5/8" casing was installed in HDR-1 from the surface to a depth of 1500m, and 8 1/2" borehole was left open below 1500m. In Nov. 1987, 380 m^3 of water were injected into SKG-2 in order to confirm that HDR-1 was bored through the hydraulically fractured zone. Flow rates were 0.7 to 1.5 m^3/min and well head pressures were 8 to 11 MPa. The maximum production flow rate was 0.01 m^3/min which was only 1 % of the injection flow rate. Weak temperature anomalies were found at depth of 1743m and 1786m in HDR-1 well.

In July 1988, an additional stimulation was conducted to improve the hydraulic communication between SKG-2 and HDR-1. An injection of water into SKG-2 was for 11 hours, and a total 2000m³ of water was injected. Flow rates were 2 to 6 m^3/min and well head pressures were 4 to 15 MPa. After the injection, the well head of SKG-2 was opened, and an estimated amount of vented hot water was approximately 400 m^3.

The well head of HDR-1 was opened before the start of the injection, and water flow from HDR-1 started at about six hours after the start of the injection. The production flow rate from HDR-1 was about 0.1 m^3/min at the beginning, but the temperature of produced water increased gradually. When the water temperature reached 100 °c, hot water and steam were spouted and the flow rate of this hot water, as high as 154 °c, was estimated over 2 m^3/min. The flow rate decreased rapidly after half hour later and it was less than 0.2 m^3/min. Another spout of hot water & steam started after about two days later, and it continued for about 30 minutes. The maximum flow rate of this second spout was estimated at about 2 m^3/min and its temperature was 158 °c. The production flow continued until the well head of HDR-1 was closed. A total amount of the produced water was about 350 m^3 but that of the produced steam was not measured.

The hydraulic communication was improved by this stimulation, but the intermittent spout of hot water and steam had not been expected at all. About a hundred microseismic events were observed during this injection, and most events occurred in the south to SKG-2 at depth of 1400m to 1800m.

In August 1988, a short circulating operation was conducted in order to evaluate characteristics of the fractured reservoir. The injection flow rate was 1 m^3/min and it was changed to 0.5 m^3/min. This flow rate was changed again to 1 m^3/min and maintained at this value until the end of the injection. A total 14000 m^3 of water were injected in SKG-2. A venting of SKG-2 was started immediately after the end of the injection, and about 170 m^3 of hot water was vented.

Water flow from HDR-1 was started immediately after the injection. Hot water was produced from HDR-1 intermittently, and the production flow rate was not constant. The maximum flow rate was about 0.5 m^3/min and the maximum temperature at the well head of HDR-1 was 124 °c. A total 4500 m^3 of hot water was produced until the well head of HDR-1 was closed. The total volume produced from HDR-1 was 32 % of that of the injected water into SKG-2. The amount of the produced steam is not included in this recovery. PTS logging in HDR-1 revealed that hot water flowed into HDR-1 through several fractures across this well. It was also found that flushing of hot water occurred in HDR-1 and the depth of flushing point moved up and down. Although tracer test was operated two times using tracer KI, concentration of tracer was not identified partially because the production flow rate from HDR-1 changed so frequently. Microseismic observation was conducted but few events were observed.

In addition to the hot dry rock program, a development of instruments has been carried out. A PTS log and a borehole televiewer were made, and they were now in operation. An triaxial geophone will be made which can be operated at temperature up to 250 °c and at a hydraulic pressure down to a depth of 1800m for eight hours. An improved borehole television is also being developed for a high temperature condition.

A TREND IN FUTURE

Geothermal reservoir descriptions including HDR project about a geological structural model and reservoir parameters have been based primarily on the geophysical interpretation. Spatial information about reservoir parameter variations can be inferred from the data of well drilling and reservoir geophysics.

A majority of geothermal reservoir belongs to the fractured media type. The present exploration techniques and assessment for this fractured reservoir is still incomplete and its maturity will be future tasks. In the stage of reservoir survey and evaluation, it is important to understand individual fractures and to estimate the quantity of resources. The final goal of our program for fractured reservoir is to locate and predict subsurface characteristics of fractured reservoir. This means the determination of the location, orientation, extent, porous or sealed, aperture etc of fractures in reservoirs at depth. The following new geophysical methods are planned to be applied for the geothermal reservoir in new program.

Electromagnetic Array Profiling (EMAP)
Cross-hole seismic tomography
Vertical Seismic Profiling (VSP)
High precision seismic reflection

Electromatromagnetic Array Profiling is already being tested in Sumikawa area, and its results will be checked with conventional MT method and with a deep well data.

Two shallow experimental wells S-1 & S-2 (500m) and two deep wells (2000m) are planned to be completed for testing the technical feasibility of these new geophysical methods and to develop the special tools for these methods. In 1988, Tanna area in Shizuoka prefecture was chosen for the shallow experimental field for VSP and seismic tomography, and a first shallow S-1 well will be drilled in this winter. Another shallow S-2 well is planned to be completed in 1989 near S-1 site. The drilling location of deep wells (2000m class) is not decided yet.

The Hijiori HDR reservoir will be evaluated experimentally and theoretically. Before these evaluations, another deeper HDR reservoir will be tested by the hydraulic fracturing and drilling of a new well, HDR-2. The final hot dry rock system at Hijiori site will consist of dual extraction systems by 1989. One is a hydraulic fractured zone at a depth of 1800m between SKG-2 and HDR-1, while another will be a fractured zone at a depth of 2200m between HDR-1 and HDR-2.

CONCLUDING REMARKS

The Sunshine Geothermal Program in Japan is now 14 years long, and many fruitful results were completed. This paper introduced one of the geothermal exploration program in Sengan and Kurikoma area, and hot dry rock project in Hijiori site. It also refered to the new geothermal project specially oriented for the fractured reservoir system. The development and testing of improved geophysical methods for determining fracture characteristics of geothermal reservoir rocks are very important, and will help to improve the characterization and assessment of actual geothermal reservoirs.

ACKNOWLEDGEMENT

The authors express our appreciation to the Sunshine Project Promotion Headquaters, AIST, MITI, especially to Mr. Masanori Yoshikai, senior officer for development program (Geothermal Energy) for publishing this paper in the 14th Workshop Proceedings on Geothermal Reservoir Engineering, Stanford Geothermal Program.

year	million Yen	(Million $)
1980	5,603	(44.8)
1981	7,218	(57.7)
1982	7,040	(56.3)
1983	6,275	(50.2)
1984	6,116	(48.9)
1985	6,217	(49.7)
1986	5,977	(47.8)
1987	5,092	(40.7)
1988	5,386	(43.1)

Table 1: A Trend of Geothermal Program Budget

Geothermal Energy Projects Budget -- FY 1988

	million Yen	(million $)
Geothermal Exploration	1,456	(11.6)
Geothermal Survey	1,380	(11.0)
Drilling Technology	294	(2.4)
Binary Cycle Generation	1,441	(11.5)
Hot Dry Rock Research	758	(6.1)
Others	57	(0.5)
Total	5,386	(43.1)

Table 2: Geothermal Energy Projects Budget -- FY 1988