DEVELOPMENT OF DRILLING AND PRODUCTION TECHNOLOGY FOR DEEP GEOTHERMAL RESOURCES

Shinichi ISAKA, Terumichi IKAWA, Tsukashi AKAZAWA
New Energy and Industrial Technology Development Organization (NEDO)

ABSTRACT

Deep geothermal resources are believed to exist below already-developed shallow geothermal reservoirs. These currently unutilized resources are expected to contribute to the expansion of geothermal power generation capacity in the near future. To ensure that deep geothermal resources can be exploited safely, efficiently, and economically, NEDO is developing appropriate technologies. The content of the technological development in this project consists of the "development of drilling technology for deep geothermal resources" and the "development of production technology for deep geothermal resources". This paper outlines the progress of NEDO's technological development for exploiting deep geothermal resources.

INTRODUCTION

The total power generating capacity of the 15 geothermal power plants in Japan is approximately 500,000 kW. However, it would be difficult to increase geothermal power generation capacity by tapping only shallow reservoirs. Therefore, to increase the geothermal power generating capacity further, deep geothermal resources should be developed. The deep geothermal resources supposedly exist under high pressure conditions at a depth of 3000-4000 m and a temperature of approximately 350 deg.C.

With regard to safe and efficient drilling and production of deep geothermal resources using conventional technology, there are several problems in terms of technological limitation and profitability. It is important to develop technology which enables safer and more efficient drilling and production according to each situation as well as technology which can determine the characteristics of the resources. Under these circumstance, NEDO started in fiscal 1992 the "Development of Drilling and Production Technology for Deep-seated Geothermal Resources" project as a part of the New Sunshine Project of the Ministry of International Trade and Industry (MITI).

This project consists of two categories: drilling technology and production technology, as shown in Fig.1.

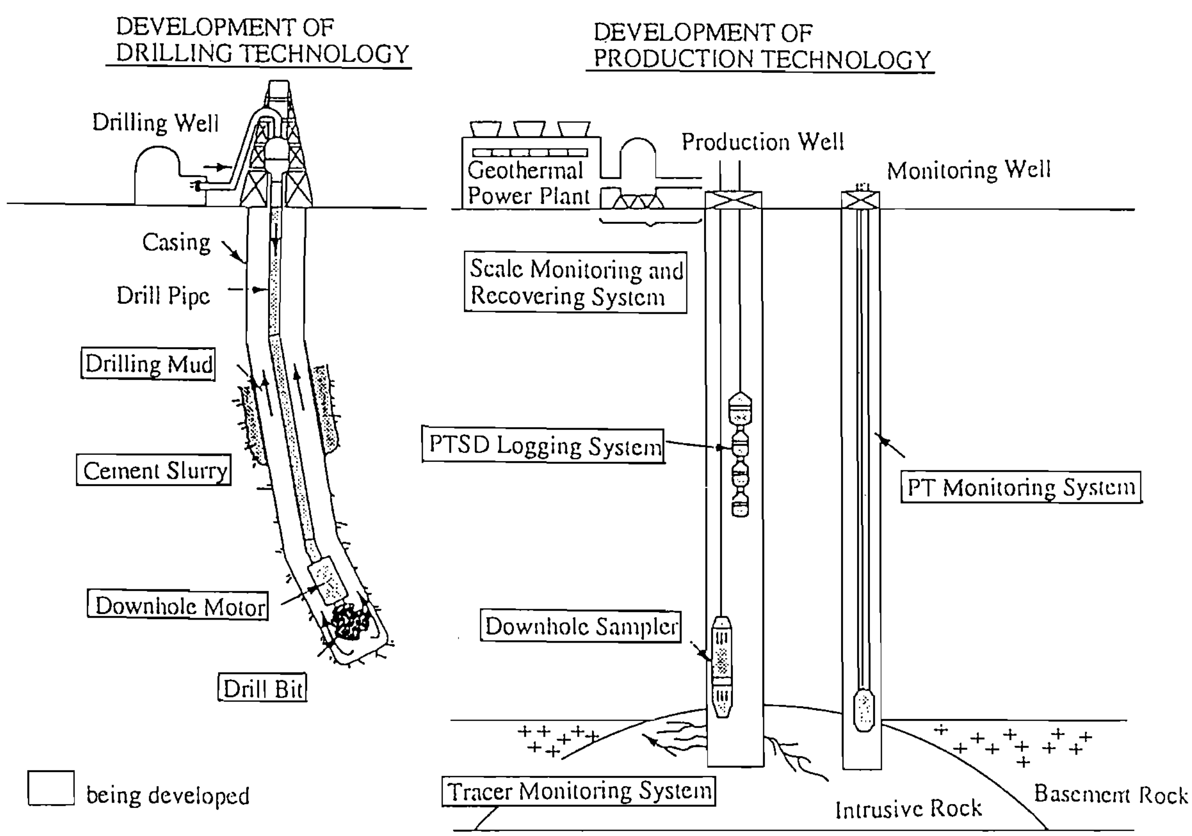

Fig.1. Development of drilling and production technology for deep geothermal resources.

DEVELOPMENT OF DRILLING TECHNOLOGY

(1) Heat-Resistant, Durable Bits

The average life of a bit used for drilling geothermal wells below a depth of 2000 m is 30 hours or less. The main targeted areas for deep drilling are harder and hotter than the areas for shallow drilling. Consequently, more bits are used for deep drilling. Bits with higher heat-resistance and durability should therefore be developed for longer bit life and shorter drilling time, thus reducing the cost of drilling.

Main specifications for the development of bits are as follows:

- Bit size : 8-1/2 inch
- Tooth type : IADC classification 537X
- Weight on bit : 10 - 18 ton
- Rotary speed : 40 - 100 rpm
- Drilling fluids : Drilling mud
- Acceptable maximum temperature (operating): 250 deg.C (over 30 Hr)
- Acceptable maximum temperature (survival): 350 deg.C (6Hr)

Main objectives of the development are as follows:

- Heat-resistant, durable bearings and sealing
- Heat-resistant, durable cutter mechanism.

Fig.2 illustrates the difficulties of using bits to drill in high temperature, hard rock. This fiscal year those bits were used in actual drilling for the purpose of checking their performance and confirming whether other problems remain.

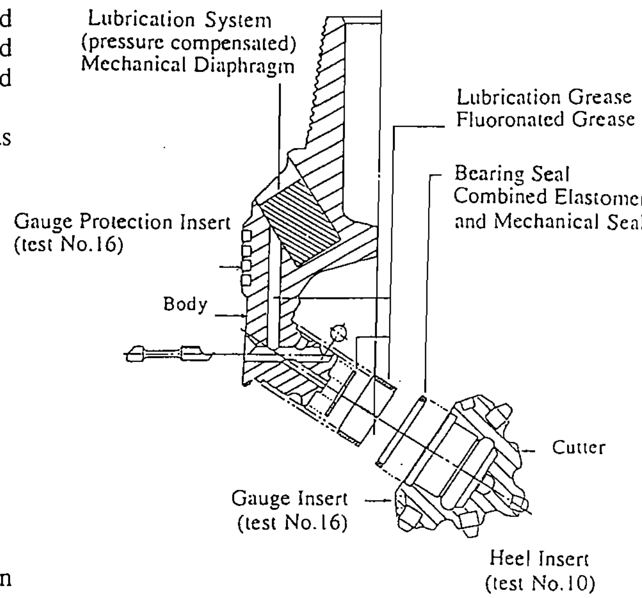

Fig. 2. Components of preliminary test bits.

(2) Drilling Mud

As the temperature rises, due to degradation of the cohesion of the mad, mud fluidity and viscosity decreases. This leads to a deterioration of the mud's ability to convey and suspend cuttings. The mud cake formation and lubrication abilities also deteriorates. Such deterioration can cause problems in drilling, including increases in the torque, sloughing of the hole, and sticking of the drill pipe; and can thus lead to longer drilling periods and higher drilling costs. The maximum temperature range for the special heat-resistant mud used at present is from 220 to 230 deg.C. Development of mud for stable use even at high temperatures can reduce drilling costs by reducing the amount of mud used and preventing accidents in the hole.

Main specifications for the development of mud are as follows:

- Formation temperature: 350 deg.C.
- Plastic viscosity: 10 - 20 cp
- Yield value: 2 - 15 lbs/100ft2
- API filtration: < 75 ml
- Density (Mud weight): 1.03 - 1.20

(Each property to be measured after 3 days static aging at 350 deg.C.)

Main objectives of the development are as follows:

- Mud system for stable use
- Materials for thickener, dispersing deflocculant and lubricating potential of the mud system

NEDO has carried out this development step by step from 250 to 350 deg.C. To maintain stable theological properties and good filtration properties of the mud for use in geothermal wells, high-temperature mud materials and additives should be developed such as viscosifier, thinner, lubricant and total mud systems.

The main materials are as follows:

- Viscosifier: synthetic inorganic polymer, synthetic organic polymer (high molecular weight)
- Thinner: synthetic organic polymer, thermally stable and water-soluble modified materials (polymer)
- Lubricant: Soluble or dispersible type; metallic soap, modified poly alcohol, etc.
  Suspensibility type lubricant ; very fine inorganic solids
- Other: mud additives to maintain the basic functions of mud.

In the previous fiscal year, a mud system for stable use at 300 deg.C. was nearly perfected in the laboratory.
This fiscal year, one of the mud system was used in actual drilling for the purpose of checking its function and also researching its chemical properties in terms of whether other problems remain.
The test results are shown in Table 1.

TABLE 1. LABORATORY TEST RESULT OF MUD SYSTEM

Sample No.	Condition	Rheological Properties AV (cP)	PV (cP)	YV (lb/100ft2)	Gel (lb/100ft2)	pH	API Filtration WL (ml)	FC (mm)
NBP-10	Base Fluid	9.0	8	2	1 - 2	6.9	9.6	1.2
	+ Salt	8.0	7	2	1 - 2	5.8	11.2	1.1
	+ Cement	11.5	10	3	2 - 3	7.9	10.2	1.1
	+ Solid	18.5	17	3	3- 4	6.0	10.8	1.5
	Stabilization	14.5	13	3	2 - 3	6.3	10.1	1.2
BSP-9	Base Fluid	14.5	13	3	1 - 2	5.8	14.4	1.3
	+ Salt	24.5	19	11	2 - 10	5.9	15.0	1.6
	+ Cement	8.0	7	2	1 - 2	6.8	15.0	1.5
	+ Solid	19.5	17	5	2- 3	5.8	14.6	1.7
	Stabilization	10.5	9	3	1 - 2	6.0	13.0	1.2
BMP-12	Base Fluid	12.0	11	2	1 - 2	5.9	12.0	1.8
	+ Salt	18.0	16	4	1 - 2	5.7	18.6	2.1
	+ Cement	11.5	10	3	1 - 2	6.9	8.5	1.2
	+ Solid	18.0	17	2	1 - 2	5.7	13.5	1.8
	Stabilization	12.0	11	2	1 - 2	5.9	11.7	1.3
Spec. for development		-	*10-20*	*2-15*	-	-	*< 75*	*< 2*

(After 3 days at 300 deg.C.)

AV: Apparent Viscosity, PV: Plastic Viscosity, YV: Yield Value,
Gel: Gel Strength, WL: Water Loss, FC: Filter Cake

(3) Cement Slurry

Cementing is particularly important for the construction of wells and securing long-term, stable production of steam. Conventional cement, due to the deterioration of its performance, can impede production. Geothermal formations include areas with low reservoir pressure such as lost circulation zones. Since these areas cannot hold the weight of the cement slurry, cement cannot be filled to the planned depth in the casing annulus. Consequently, some spots in those areas remain cement-free water pockets. Expansion of those pockets by heat can hinder production by crushing the casing. If conventional materials with a specific gravity less than the cement slurry are used , the performance, including the strength, will be drastically diminished and the material will be damaged. Therefore, heat-resistant cement and cement slurry possessing enough strength with a low specific gravity should be developed to enable proper cementing. This will prevent problems with production and reduce additional work for repairs.

Main specifications for the development of cement slurries are as follows:

- Formation temperature : 350 deg.C.
- Depth of well : 3000 - 4000 m
- Cement slurry density : 1.35 g/cm3
- Thickening time (curing condition: at 230deg.C, for bottom hole circulating temperature with mud) : over 3Hr
- Compressive strength : 35 kg/cm2
  strength of the hardened cement slurry (curing time;24Hr, temp; 350deg.C, press;210 kg/cm2)
- Compressive strength of the aging cement slurry : 70 kg/cm2
- Filtration of cement slurry : < 500 ml / 30 min.
- Permeability : 0.25 md

Main objectives of the development are as follows:

- Reduction of cement slurry density
- Cement with enough compressive strength to function for a long time at high temperatures
- Slurry that can reduce dehydration at high temperature
- Cementing system

In the previous fiscal year, cement slurry for stable use at 350 deg.C. was manufactured in a laboratory for trial. It has excellent filtration characteristics and compressive strength under high temperature.
The test results are shown in Table 2.

TABLE 2. TEST RESULT OF CEMENT SLURRY (Density :1.5, 300deg.C.)

Cement Slurry	Filtration (ml / 30min)	Thickening Time (200deg.C.)	Compressive Strength (kg/cm2) Aging Dates at 300deg.C.			Permeability (md) x 1000 Aging Dates at 300deg.C.		
			1 day	7 days	28 days	1 day	7 days	28 days
Sample 1	320	3:55	141.0	105.0	102.0	3.5	11.7	16.4
	215	4:01	132.0	105.0	98.0	6.1	11.0	31.9
Sample 2	370	4:23	110.0	78.0	79.0	8.1	18.4	21.8
	344	4:03	101.0	89.0	81.0	7.5	15.7	29.9
Sample 3	335	4:12	123.0	98.0	92.0	6.6	13.5	19.3
	320	4:23	118.0	79.0	87.0	8.0	13.9	23.0
Spec.	*< 500*	*> 3:00*	-	-	*> 70*	-	-	*< 250*

(4) High-Precision, High-Inclination Directional Drilling Technology (Downhole Motors: DHM)

In the drilling of deep geothermal resources, as in the development of shallow reservoirs, areas available for drilling are limited and protection of the environment must be considered. It is therefore essential to improve the basis for directional drilling of production and reinjection wells toward the target reservoirs from smaller land areas by controlling the well's trajectory. Usually, a downhole motor is used to control well trajectory. Since there is no current downhole motor for high temperatures, the targeted area cannot be reached because changing the direction of the well's trajectory becomes impossible. So, re-drilling of the well must be conducted, or the well's trajectory has to be controlled from a shallow depth. Consequently, drilling costs increase due to controlling well trajectory. A downhole motor for high temperatures should therefore be developed to make the well's trajectory control more efficient and reduce drilling costs by reaching the targeted area without failure.

Main specifications for the development of DHM are as follows:

- DHM type : Positive Displacement Motor
- Bit size : 8-1/2 inch
- Outer dia : 6-3/4 inch
- Length : 20-26 ft
- Mud flow rates : 210-530 gal/min.
- Rotation speed : 50 - 150 rpm
- Max. torque : 3,600 ft-lb
- Max. power : 80 HP
- Weight on bit : 20 ton (approximately)
- Acceptable max. temperature (operating) : 250 deg.C (100 Hr)
- Acceptable max. temperature (survival) : 350 deg.C (10Hr)

There are two types of downhole motors. One is the all metal turbine type. Rubber products, which lack heat-resistance, are not needed for this type. However, this type is not suitable for rock bits because the motors rotate at high speed. The other type is PDM (Positive Displacement Motor) of the Moineau type. This is a low rpm high-torque type. However, the elastomers currently used as stator manufacturing material do not have enough heat-resistance.

NEDO has developed the PDM type DHM by researching the materials used for motor rotors.

Main objectives of the development are as follows:

- Stator material for high temperatures
- Highly heat-resistant bearings and seals for high temperatures

DEVELOPMENT OF PRODUCTION TECHNOLOGY

(1) PTSD Logging Technology

By measuring the pressure(P), temperature(T), flow velocity(S:spinner) and fluid density(D) of a geothermal well both in static and dynamic conditions, data for efficient control of production can be acquired. The logging cable widely used for PTS logging is a Teflon-coated type and is heat-resistant up to 315 deg. C. Its performance is not adequate for the logging of deep geothermal wells where temperatures are predicted to be 300-400 deg.C. Logging cables made with a non-organic insulator are highly heat-resistant. However, manufacturing a long cable of this type is difficult and costly, and the tensile strength is not adequate for use in deep wells. The heat-resistance of the conventional equipment, including the chamber which contains the logging sensors, is also not adequate. For these reasons, the PTSD logging system adopted a measuring method in which the logging data is recorded a memory module into the logging tools.

Main specifications for the development of PTSD logging tools are as follows:

- Acceptable max. temperature : 400 deg.C
- Acceptable max. pressure : 490 kg/cm^2
- Acceptable max. logging time : 6hours
- Measurement method : sensors to record data in a memory module
- Power supply : battery module
- Measurement interval : min. 0.1 sec
- Dimension (outer-dia x length) mm : PT-probe (56 x 2,700), S-probe (70 x 3,700)

Main objectives of the development are as follows:

- Heat-resistant chamber
- Heat-resistant, pressure-resistant sealing mechanism
- Smaller electronic devices which consume less power

In the memory-type PTSD logging system. control information such as the start time, measuring interval and logging time are preset into the memory module on the surface before logging. While logging, each probe can measure downhole conditions and record the time-transient logging data to the memory module. After the logging, recorded data in the memory module is transferred to the data processor, where it then can be converted to depth-data by using the logging depth-time data measured by a cable encoder.

The construction outlines of a PT-probe and an S-probe are shown in Fig.3 and 5.

(a) PT-probe

The PT-probe, which contains a memory module, battery module, pressure sensor and temperature sensor, is included in the dewar. A pressure quartz gauge and a platinum resistance thermometer are applied to pressure and temperature sensors, respectively.

Elemental technology development of the PT-probe includes:

- Comparison of the battery type and battery life
- Evaluation of memory module, pressure gauge, thermometer
- Heat-resistant chamber
- Heat-resistant, Pressure-resistant sealing mechanism

Based on the results of this elemental technology development, a preliminary PT-probe was manufactured for field test. In last March, a PT-probe developed for stable use at 400 deg.C was tested in a deep geothermal well to check its performance and determine whether other problems remained. Results of this trial under static conditions are shown in Fig.4.

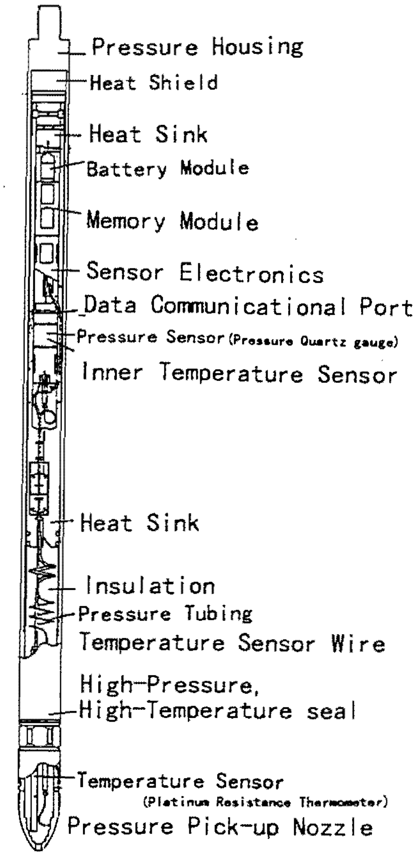

Fig. 3. Main components of advance PT-probe logging tools.

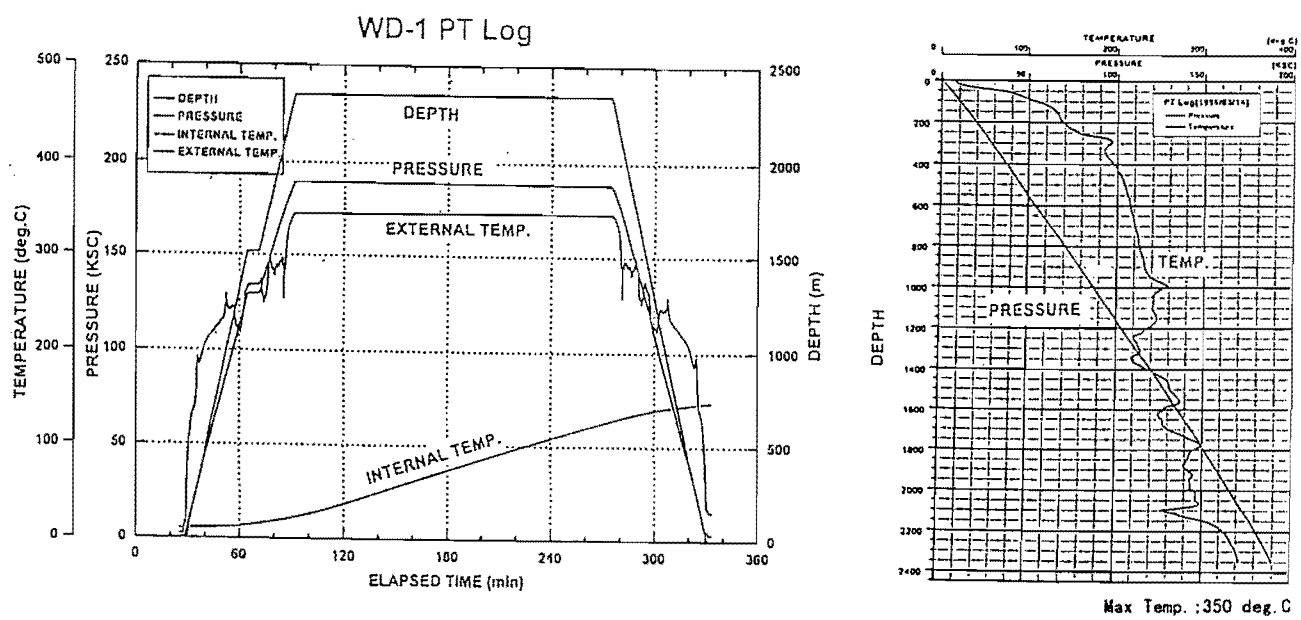

Fig. 4. Response of the advance PT logging tool.

(b) S-probe

The S(spinner)-probe, which measures the flow velocity of geothermal fluids in a well under dynamic conditions, determines feed points, injection points and the boiling point.

As shown in Fig.5, this probe comprises a spinner sensor unit and an electronics cartridge which is covered with a dewar and pressure vessel. The electronics cartridge includes a memory module, battery module and sensor electronics. And spinner sensor unit contains an impeller that rotates according to flow velocity, a target that converts the rotations into the electric signals, and an eddy current type flow sensor that transfers the electric signals into the memory module.

Elemental technology development for the S-probe includes:

- Development and confirmation of the conversion efficiency the eddy current type flow sensor
  (pressure range:0-500kgf/cm2,max.temperature: 400 deg.C).
- Development and performance evaluation of the electronics cartridge.
- Heat-resistant chamber
- Heat-resistant, Pressure-resistant sealing mechanism

(c) D-probe

The D(fluid density)-probe, which comprises a radioactive source(Sc-137), a detector and other electronics, is contained the collimator. A radioactive source emits gamma rays into the geothermal fluids in the borehole, where the rays are then received by the detector. The rays lose some of their energy because of Compton scattering.

The scattered gamma rays reaching the detector, at a fixed distance from the source, help reveal the geothermal fluid conditions. The number of Compton-scattering collisions is related directly to the number of electrons in the geothermal fluid, relevant to the fluid density.

Elemental technology development for D-probe includes:

- Optimization of the detector's response as related to the energy level of the radioactive source and the distance between the source and the detector.
- Comparison of the material for collimator.

Fig.6 shows the conceptual design of the D-probe.

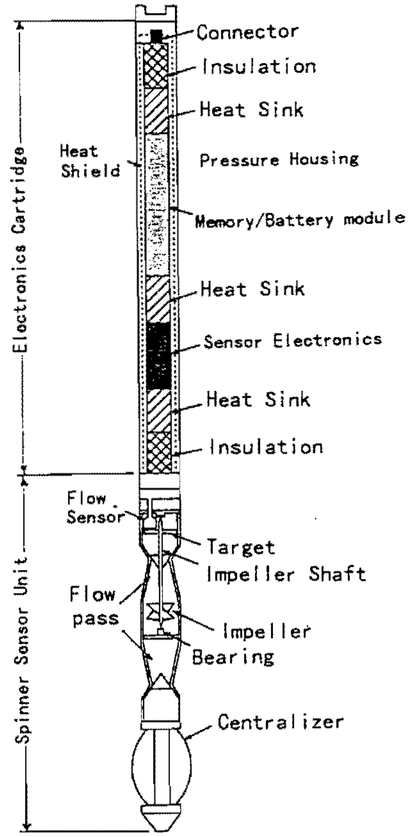

Fig. 5. Main components of advance S-probe logging tools.

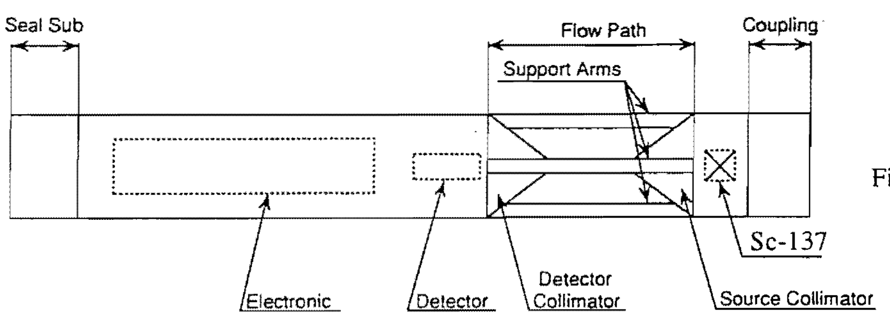

Fig. 6. Concept of D probe

(2) PTC Monitoring Technology

By monitoring the temperature and pressure of a geothermal reservoir, its productivity can be predicted. The temperature and pressure of the reservoir, as well as the chemical characteristics of the geothermal fluids, are also extremely important in controlling production. PT monitoring is currently being conducted using metal capillary tubing and optical fiber methods. However, these methods are not suitable for use in deep geothermal wells because the capillary tubing has low tensile strength and the optical fiber is heat-resistant only up to about 300 deg.C. The reliability of the collection mechanism is low.

Main specifications for the development of PTC monitoring technology are as follows:

- Acceptable max. temperature : 400 deg.C
- Acceptable max. pressure : 490 kg/cm2
- Max. depth of well : 4,000 m
- pH condition : pH3 (assumed)
- Sampling volume : 2,000 cc
- Outside dia : 60 mm

(a) PT-monitoring

The Pressure(P)-monitoring system consists of a pressure chamber, capillary tube and pressure gauge. The bottomhole pressure is transmitted directly to a surface pressure gauge through the inside of a pressurized capillary tube that has been set in the geothermal well.

The main components of the temperature(T)-monitoring system include an optical fiber for the temperature sensor, a laser diode drive circuit and a personal computer.

After inputting a laser pulse light into the optical fiber on the surface, the laser pulse light scatters while traveling through the optical fiber. A part of the scattered light returns to the input end on the surface. The depth of a point where light changes direction and returns to the surface is determined from the light's velocity and the delay time from the pulsed light input to its return. The Raman scattered light's frequency of the light that returns to the surface is directly divided into the Stokes light and the Anti-Stokes light. The intensity of the Anti-Stokes light is related to temperature. The temperature of the scattered light point is analyzed basically by the intensity ratio of the Stokes light and the Anti-Stokes light.

Conventional optical fibers can be protected from the effect of high temperatures by metal coating.

Elemental technology development for the PT-monitoring system includes:

- In the optical fiber sensor, optimization of the metal coating method so as to increase the temperature limit (below 400 deg.C) and minimize the optical loss caused by the deference in thermal strain between the optical fiber and coating metals.
- Development of an armored capillary tube with sufficient heat-resistance and tensile strength.
- Development of a method to manufacture the long capillary tube which is placed inside the optical fiber (approximately 4,000m).

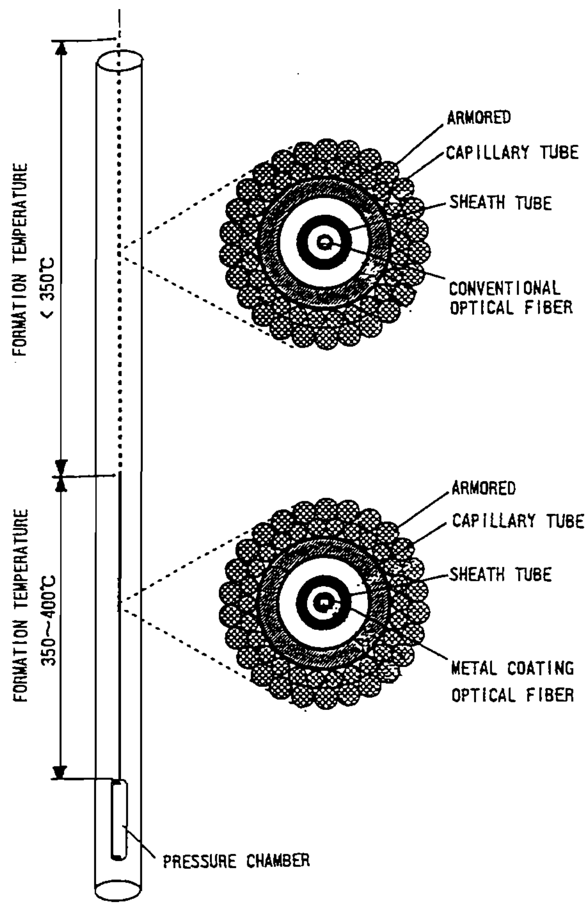

Fig. 7. Outline of PT monitoring System.

Fig.7 shows the outline of a PT-monitoring system with two types of optical fiber sensors (conventional type and heat-resistance metal coating type sensors).

(b) C-monitoring

It is very important to investigate the chemical characteristics of geothermal fluids for proper production control. The C(chemical)-monitoring system consists of a downhole fluid sampler which samples geothermal fluids directly in the production well, and a sample extraction system on the surface. The downhole fluid sampler, which comprises electronics, an actuator and a sample chamber, is covered with a dewar and pressure vessel to protect it from high temperature, high-pressure and shock. In order to maintain a quality of sampling fluids and a high sampling recovery rate, the controlled displacement type sampler was adopted as the downhole fluid sampler.

In this type of downhole fluid sampler, a needle powered by an actuator system perforates the rapture-disc shield, creating an entrance to the sample chamber at the sampling point. Highly pressurized fluid in the geothermal well enters the sample chamber through the hole in the rapture-disc, pushing a piston to the bottom of the sample chamber. Working fluid on the other side of the piston is pushed into a low pressure chamber. When the sample chamber is filled with the well fluid, the entrance of sample chamber is closed by a non-return valve.

After logging, the sampling fluid is removed from the downhole fluid sampler by the sample extraction system for chemical analysis.

Elemental technology development for the C-monitoring system includes:

- Development of the actuator system which applies force to the needle so as to perforate the rapture-disc.
- Comparison of the tool materials with a high resistance to heat, shock and corrosion.
- Comparison of the seal materials and development of dynamic seal mechanism for chamber piston and various valves.

(3) Tracer Monitoring Technology

To predict and evaluate the life of a geothermal reservoir, the permeability between the reservoir and production and/or reinjection wells should be understood. Tracer monitoring should be conducted for this purpose. Conventional tracer materials are used at maximum temperatures of 200 to 300 degrees C. Technologies to analyze flow in deep areas and areas between deep and shallow zones have not yet been established. Tracer materials for high temperatures and tracer flow analyzing technology therefore should be developed. Vapor phase tracers and two-phase tracers considered to be practical as tracers for high temperatures have not yet been developed.

Main specifications for the development of tracer monitoring are as follows:

- Assumed formation temperature : 350 deg.C.

Main objectives of the development are as follows:

- Selection of two-phase tracer materials for high temperatures
- Tracer flow analyzing technology

(4) Scale Monitoring Technology

Dissolved materials and the depositing conditions of deep-seated geothermal resources and their relationship with respect to shallow reservoirs are not yet known. Conditions regarding the formation of scales and adhesion which occur during production, use and reinjection of geothermal fluids need to be understood in order to conduct appropriate control of the formation of scales.

Main objectives of the development are as follows:

- Non-destructive scale detection method
- Elucidation of scale forming mechanism

(5) Anti-Scale Technology

Scale formation accompanying production, use and recycling of geothermal resources substantially affects the drilling costs. Technologies to prevent the formation of scales, as well as technologies to remove them, should be developed to reduce the costs of additional well drilling and maintaining surface production facilities. Measures against scales which can be applied to deep geothermal resources and shallow reservoirs should also be developed.

Main objectives of the development are as follows:

- Technology to prevent scale formation
- Technology to remove scales

OUTLINE OF THIS PROJECT

Fig.8 illustrates the target technologies and schedule for this development project. This project began in FY1992, and drilling technology has a priority over other technologies.

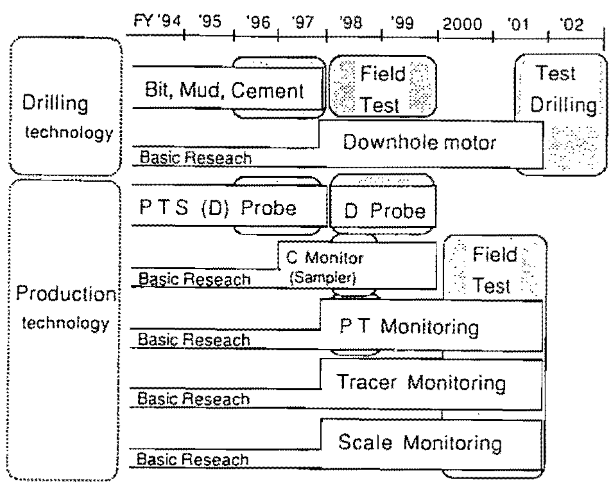

Fig. 8. Outline of this development project.

CONCLUSION & SUMMARY

This development project is progressing steadily and it is expected that the acceptable maximum temperature of conventional drilling methods will be increased to 350 deg.C. and drilling cost will be reduced. This development project should lead to more economic geothermal power generation from both deep reservoirs and shallow reservoirs.

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