Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

DEVELOPMENT OF DIRECT MEASUREMENT METHOD FOR THERMOPHYSICAL PROPERTIES OF RESERVOIR ROCKS IN SITU BY WELL LOGGING

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Key Words: reservoir evaluation, development, well log, thermophysical properties, laboratory experiment

ABSTRACT

Thermophysical properties of deep reservoir rocks should be directly obtained by a measurement technique in situ, because their values by laboratory measurements using samples might be influenced due to the intracrystalline microcracks originating from a stress released from the core during the drilling. The authors have developed a new method and system for simultaneous measurements of the thermal conductivity, the thermal diffusivity, and the specific heat of rocks in situ at temperatures from 273 to 473K, by applying the transient, hot-wire comparative method. In this paper, a hot wire with diameter, d=80, 50 or 30 μ m and length=50mm was inlaid in the center of the surface of the substrate(elastic silicon gum plate of 40mm × 90mm × 10mm) used as a reference material. Three K-thermocouples, T_0, T_1 and T_2 of diameter d[μ m] were inlaid at x_0, x_1 and x_2[mm] from center of the hot-wire, respectively, in the surface. Temperature rise $\triangle\theta_0$ at x_0, and the temperature difference $\triangle\theta_{12}$=(θ_1- θ_2) between θ_1 at x_1 and θ_2 at x_2 against logarithmic time ln(t) and 1/(t), respectively, were used in calculation of the thermal conductivity, λ_s, and the thermal diffusivity, α_S ,respectively. Originally this method is applied for flat boundary surface of half infinite body of the sample whose thermal conductivity is λ_{FS}(= λ_s). In this paper, the effect of a ratio of the curvature radius of a borehole, R[mm]=D/2 (D:diameter) to the radius of the hot wire, r=d/2, and the ratio to the reference thermal conductivity of the substrate, λ_R, to the sample thermal conductivity of the rocks in situ, λ_s, on measurement values for curved boundary surface of the borehole, λ_{CS}, was studied to evaluate the values of λ_s. Model boreholes from 66 to 120mm in diameter were drilled in each several blocks of rocks having different values of λ_s. Six types of sensors inlaying the hot-wire and the thermocouples having different diameters, d[μ m] of 80, 50 and 30 were used. The inlaid positions of x_0, x_1 and x_2 were fixed at 0.5, 2.0 and 4.0mm, respectively. As the results, suitable design parameters were obtained in order to evaluate the thermal conductivity, λ_{FS}. If the measured λ -values on the curved boundary surface in the borehole drilled into the subsurface material having λ_{FS} were λ_{CS}, the ratio of (λ_{CS}/ λ_{FS}) were less than +10% for the ratios larger than D/d=2400, and less than +5% for the ratios larger than D/d= 3000, respectively, without dependency of the ratio of (λ_s/ λ_R).

1.INTRODUCTION

It is difficult to precisely measure the thermal conductivities of rocks and its measurement is very time-consuming. To make laboratory measurements on all rock types of possible interest and under all environmental conditions of temperature, pressure and fluid saturation would be forbidding in terms of time and expense. Consequently, a great deal of efforts has been made into the development of models relating thermal properties and behavior to other physical properties of rock/fluid systems able to be easy to measure. The difficulties of obtaining reliable data to characterize the thermal properties and thermal behavior of subsurface rock/fluid systems have led to efforts to obtain such data from borehole logging measurements. Two different approaches have been applied so far.

The first approach is to use well log data directly and attempt to correlate these data with measured laboratory values of thermal conductivity or to use interpreted well log data and apply these data to previously established correlation. The second approach is to derive thermal properties data from temperature gradient surveys in the boreholes. However, the values of the thermal conductivity obtained from laboratory measurement samples may be influenced by intra-crystalline microcracks originating from the stress released during the drilling process of the core from deep underground. From these points of view, the thermal conductivity of stratum at great depths should be evaluated taking account of the micro-cracks' effect, or should be directly measured by a technique in situ.

Needs of the measurement in situ for thermophysical properties of subsurface materials have been recognized, so far. Bloomer and Ward(1979), Goodrich(1985) and Murphy and Lawton(1977) measured the thermal conductivity of subsurface materials, using transient needles having diameters of 1.7mm, 3.0mm and geothermal well size, respectively. Vost(1976) measured the thermal diffusivity of rock masses by obtaining temperature variations in the rock masses which were caused by seasonal change of ventilation temperatures. Sherratt and Hensley(1961) measured the thermal diffusivity of rock masses by obtaining temerature variations in the rock masses which were caused by forcedly heating specified surface of the rock masses from underground space. Danko and Mousset-Jones(1989) measured the thermal conductivity and the thermal diffusivity of the rock masses by obtaining temperature variations at shallower part and deeper part from a borehole heater in the rock masses which were caused by forcedly heating specified depth inner part in a relatively small diameter borehole by the borehole heater.

One of the present authors previously developed a needle probe method to measure seven points' local thermal conductivity in a small diameter borehole(D=26mm) made in relatively soft subsurface materials(Kiyohashi et al.,1988). Then, as for the hard subsurface materials, Kiyohashi et al. (1985, 1988) developed a transient hot ringed wires comparison method to measure the seven points' local thermal conductivity in a large diameter borehole(D=115~130mm) having relatively shallow depth (L=1500mm) drilled in the rock masses. However, the former could not be applied to the measurement in the hard rock and at great depth. While the latter had also some week points such that it had two experimental coefficients in the measurement principle, and its cost performance was very low. So, to solve these problems, one of the authors tried to apply the rigid transient hot-wire comparison method (Takegoshi,1981) to measurements of the thermal conductivity of solid materials by the use of circular surfaces(e.g. curved surfaces of a borehole and a core) of the materials. A soft reference material, KARUPU(impervious thermal insulator manufactured by Lion Co.Ltd., heat resistivity is 350K), was used as a sensor substrate (Kiyohashi et al., 1994). This experimental results showed that $\lambda_{CS}/\lambda_{FS}$ decreased with increase of D/d, and the values of $\lambda_{CS}/\lambda_{FS}$ were 1.03 to 1.15 for various values of λ_S/λ_R. Then Kiyohashi et al.(1996) challenged to the simultaneous measurement of the thermal conductivity and the thermal diffusivity, applying a extended hot wire comparative method to flat surfaces of solids and the KARUPU substrate. The results showed that the method under consideration was applicable.

The main purpose of this study is first to establish a measurement technique to simultaneously measure the thermal conductivity and the thermal diffusivity of reservoir rocks in situ by well logging. The second aim is to seek some parameters to design a prototype geo-thermophysical property sensor by laboratory experiments. For the former, the effect of the ratio, D/d, on the value of $\lambda_{CS}/\lambda_{FS}$ is studied in the ranges of D/d from 800 to 4000 by using the imitation boreholes from 66 to 120mm in diameter, drilled into several blocks of rocks which have different thermal conductivities, and by using several types of silicon gum substrate thermophysical property sensors.

2. MEASUREMENT TECHNIQUE

2.1 Hot-Wire Comparative Method

If the temperatures θ_1 and θ_2 of a hot wire on the boundary surface of a reference medium and a medium of unknown thermal conductivity λ_S, are measured by a thermocouple at times, t_1 and t_2, respectively, the λ_S-value of the unknown medium can be calculated from the following equation (Takegoshi, 1981).

$$\lambda_S=(q/2\pi)\cdot[\ln(t_2/t_1)/\triangle\theta]-\lambda_R \tag{1}$$

where q is constant heat rate per unit length and unit time, t_1 and t_2 are times after starting the hot wire heating, $\triangle\theta=\theta_2-\theta_1$, and λ_R is the λ of the reference meadium. Here, $\triangle\theta$ - ln(t) diagram must have a linear relation between t_1 and t_2 at least. The measuring time necessary for calculation of λ_S is determined by the use of the second derivative of the hot-wire temperature with respect to ln(t) (Deguchi et al.,1991).

2.2 Principle of Thermal Diffusivity Measurement

The temperature rise $\triangle\theta$ at time t and at an arbitrary position(x, y=0, z=0) on the boundary between the sub-strate material and the sample, due to the instantaneous heating quantity, q, is given (Takegoshi et al.,1981) by

$$\triangle\theta=-[qk\sigma/(4\pi\lambda_R)]\int_0^1\{Ei[-k^2x^2/(4\alpha_R t(k^2u+1-u))]\}du/[(k^2u+1-u)^{1/2}(1-u+\sigma^2u)^{3/2}] \tag{2}$$

where Ei is the exponential integral function, σ is $(\lambda_S/\lambda_R)(\alpha_R/\alpha_S)^{0.5}$ and k is $(\alpha_R/\alpha_S)^{0.5}$. If $k=\sigma=1$, that is, λ_S is λ_R, and α_S is α_R, Eq.(2) results in Eq.of the hot wire method. From Eq. (2) we can estimate the measurement time limitation, taking account of the value of x, values of λ_S, λ_R, α_S, α_R, and finite size, i.e., thickness s[cm] and length *l*[cm], of the sample(Takegoshi et al., 1981). The measurable time-interval, t_M, to calculate λ_S is given within errors of 3% (Nemoto, 1998) by

$$\{x^2/4\alpha_S,\ x^2/4\alpha_R,\ [(x/\alpha_S)+(\lambda_R/\alpha_R)]x^2/[4(\lambda_S+\lambda_R)]\}_{MAX}\leqq t_M \leqq\{41.87s^2/\lambda_S,\ (16.84/\lambda_S^{0.6})(l/2)^{(2.2-2ro)}\}_{MIN} \tag{3}$$

Finally, the measurement principle of α_S is derived as follows. Consider points x_I and x_J apart from the center of heating wire(line heat source) on the interface between two materials as shown in Fig.1 ($x_I=X_1$ and $x_J=X_2$ in this case). Temperature differences, $\triangle\theta_{IJ}$, between θ_I and θ_J at x_I and x_J, respectively, are given from the primitive function of Eq.(2) (Nemoto, 1998) by

$$\triangle\theta_{IJ}=\{q/[2\pi(\lambda+\lambda_S)]\}\{2\ln(x_I/x_J)-[(\lambda/\alpha)+(\lambda_S/\alpha_S)](x_J^2-x_I^2)/[(\lambda+\lambda_S)4t]\} \tag{4}$$

Equation (4) shows that $\triangle\theta_{IJ}$ is a linear inverse function of t and also a function of α_S, and the gradient, S_D, of the linear part of the $\triangle\theta_{IJ}$ vs. (1/t) diagram is minus. Hence the term S_D is defined as

$$S_D=q[(\lambda_S/\alpha_S)+(\lambda_R/\alpha_R)](x_J^2-x_I^2)/[8\pi(\lambda_S+\lambda_R)^2] \tag{5}$$

Accordingly, α formula can be derived as

$$\alpha_S=\lambda_S/\{[8S_D\pi(\lambda_S+\lambda_R)^2]/[q(x_J^2-x_I^2)]-\lambda_R/\alpha_R\} \tag{6}$$

If λ_S is equal to λ_R, the above equation results in

$$\alpha_R=q(x_J^2-x_I^2)/(16\pi\lambda_R S_D) \tag{7}$$

Equation (6) will give a reasonable values of α_S, provided that the time interval, t_M, on the $\triangle\theta_{IJ}$-(1/t) diagram may satisfy Eq.(3).

3. MEASURING SYSTEM AND PROCEDURE

3.1 Rock Sample Blocks and Model Boreholes

Five kinds of rocks were selected as samples of the present experiment, taking account of thermal conductivities given in Table 1. Four blocks of one side length of 160mm cubic were quarried out from these rocks. Then models of borehole having 66, 76, 90 and 120mm in diameter were drilled into each rock block.

3.2 T.P.-Sensor for the Measurement of λ and α

We designed the T.P.-sensor(Thermophysical Properties' Plate Sensor) for measuring λ and α, as follows: The sizes of the sensor was 30mm×90mm×10mm as shown in Fig.2.

As for the material of the T.P.-sensor substrate, silicon gum was chosen as there were several published data on its thermophysical properties. A heating wire of 80, 50 and 30 μm in diameter and 50mm in length of a constant resistivity material was used considering t_M obtained from Eq.(3). As for temperature sensors, K-thermocouples of 80, 50 and 30 μm in diameter were used. The heating wire and the three thermocouples were buried in very shallow grooves carved on the center line, at x=0.5, 2.0 and 4.0mm on the surface of 30mm× 90mm of the silicon gum substrate, respectively. Specifications and naming(No.) of the T.P.-sensor are shown in Table 2.

3.3 Measuring System

The measuring system is divided into two parts as shown in Fig.3.: the measuring part and the part of a test section containing the model of borehole. The former is mainly composed of a T.P.-sensor in the borehole in the test section, a constant power supply, an automatic switch of dummy load to each hot wire in the sensor, a multi-channel digital data recorder, a microcomputer, an electric cold junction. The latter is composed of an insulation box, two rock blocks which a model borehole is drilled respectively into, two sensor fixing devices, a stop valve, a pressure gage, an oil pressure pump, a bridge box and a strain meter, as shown in the figure. Figure 4 shows details of the T.P.-sensor fixing device.

3.4 Measuring Procedure

Five series of tests have been conducted in these experiments under room temperature condition. Test I is the experiment to obtain thermophysical properties of the sensor substrate, which is, silicon gum. Test II is the experiment to decide a suitable pressure pressing the T.P. sensor against the curved wall in a borehole sufficiently. In this case, the hot-wire must be set in parallel to the borehole axis. Test III is the experiment to evaluate performance of the T.P.-sensor and the measurement system. For the Test III, reference samples and their published data(JSTP, 1990) shown in Table 3 were used. Test IV is the experiment to measure the thermophysical properties on the flat surface of the rock blocks. Finaly, Test V is the experiment to measure the thermophysical properties on the curved surface in the model borehole drilled into the rock blocks.

4. Results

4.1 Thermophysical Properties of the Sensor Substrate

Figures 5 and 6 show examples of temperature data to calculate the thermal conductivity and the thermal diffusivity, respectively, of the silicon gum which is the same material as the sensor substrate. These data was obtained in flat surfaces of the sample. Table 4 shows the thermophysical properties of the silicon gum obtained by this experiment and its reference values from literatures (JSME, 1986; JSTP, 1990). The λ-value of 0.256W/(m･K) with sensor #080 was obtained as an average value of the experimental values which were almost constant with variation of sensor pressing force, P[N/cm^2] in the cases of larger P than P=2.5. Each experimental point with the sensors of #080A, #080B and #080C means each average value of three experimental values measured per each sensor. Also, the λ-value of 0.250W/(m･K) with sensor #030 was obtained as an average value of the experimental values with the sensors of #030A and #030B. These results show that the λ-value of the silicon gum has almost no difference between the sensors of #080 and #030. These values of λ agree with the reference values of A and B (JSME, 1986; JSTP, 1990) within reasonable ranges, if we take account of disagreement of density among their samples. Consequently, these experimental values shown in Table 4 were used as thermophysical properties of the silicon gum sensor substrate in the present study. For thermophysical properties of the silicon gum sensor substrate of #050, a mean value of measured values with the sensors, #080 and #030, was used.

4.2 Decision of Suitable Sensor Pressing Force

Relations between measured values of the thermal conductivity in the flat surface, λ_{FS}, of the sample of "Amerika-shoume" and sensor pressing force, P, were obtained with sensors, #080, #050 and #030. The values of λ_{FS} increased with increase of P, and then became a constant at larger P than P=2.5N/cm^2. From these experimental results, the suitable sensor pressing force was decided as P=2.5N/cm^2.

4.3 Evaluation of Performance of the Measurement System

Evaluation of performance of the present measurement system was conducted using experimental data for four reference samples shown in Table 3 and their published data. The relations between measured values of λ_{FS} and their published data, between measured values of thermal diffusivity, α_{FS}, and their published data, and between measured values of specific heat, c_{FS}, and their published data, respectively were obtained to make comparisons between the measured values and their published data. Reasonable accordance between the measured values and the published data for the good conductivity samples has not been obtained. This disagreement between the measured values and the published data for the samples which have larger thermal conductivity than 6.21W/(m･K) of Quartz may mean that we should have give more larger sensor pressing force for the good conductivity samples. Because thermal contact resistance between the sample surface and the sensor substrate surface have an effect on figures of the temperature increase diagrams versus logarithmic time shown in Fig.5.

4.4 Effect of Curvature on Measurement Values of λ

Figure 7 shows that relations between measured values of the thermal conductivity in the curved surfaces of the model boreholes, λ_{CS}, of the sample of "Hachikou-ishi" and diameter of the borehole, D, obtained with sensors, #080, #050 and #030. This figure indicates that the values of λ_{CS} decrease with increase of D, and the values have much smaller ones for the smaller diameter, d, of the hot wire. The relations between $\lambda_{CS}/\lambda_{FS}$ and D/d for the all experimental data obtained in the present experiments are shown in Fig.8. The values of ratio, $\lambda_{CS}/\lambda_{FS}$, are larger than unity, and scatter at lower D/d, but they converge to plus one at larger D/d than D/d=2400, independent of the values of the ratio, λ_S/λ_R, as shown in the figure.

From the above experimental results, we can obtain following design parameters of a proto-type of thermophysical properties measurement sensor in situ in a borehole. If the thermal conductivity of the rock mass are smaller than, or equal to the thermal conductivity of granite(about 3.0W/(m·K)), we can measure the thermal conductivity of the rock mass by the new method proposed by the authors within errors of +10%, using the sensor having the parameter of D/d=2400, and within errors of +5.0% using the sensor having the parameter of D/d= 3000.

5. CONCLUSIONS

A new method and system for simultaneous measurements of the thermal conductivity, the thermal diffusivity, and the specific heat of reservoir rocks in situ by borehole logging has been developed by applying the transient hot-wire comparative method and silicon gum substrate sensors. If the thermal conductivity of the rock mass are smaller than, or equal to one of granite (about 3.0 W/(m·K)), and the ratio of borehole diameter to hot-wire diameter is D/d, we can measure the thermal conductivity of the rock mass by the new method proposed by the authors within errors of +10%, using the sensor having the parameter of D/d=2400, and within errors of +5.0% using the sensor having the parameter of D/d=3000.

ACKNOWLEDGEMENTS

The authors wish to express their deep thanks to Dr. H. Masuda, Professor Emeritus of Tohoku University, for many helpful discussions.

REFERENCES

Bloomer,J.R. and Ward,J.(1979). A Semi-automatic Field Apparatus for the Measurement of Thermal Conductivities of Sedimentary Rocks. J. Phys. E:Sci. Instrum.,Vol.12, pp.1033-1035.

Danko,G. and Mousset-Jones,P.(1989). An In Situ Technique for Rock Thermophysical Property Measurement and Site Characterization. Proc. of Workshop on Earth Crust Stress Measurement, Section Committee of Underground Measurement in MMIJ, pp.28-48.

Deguchi,M.,Kiyohashi,H. and Suzuki,S.(1991). Accurate Measurement of Thermal Conductivity of Rocks by the Transient Hot Wire Comparison Method. J. MMIJ, Vol.107, No.1, pp.17-22.

Goodrich,L.E.(1986). Field Measurement of Soil Thermal Conductivity. Can. Geotech. J., Vol.23, pp.51-59.
JSME,(1986). Data Book for Heat Transfer Engineering. JSME, Tokyo, p.321.

JSTP,(1990). Thermophysical Properties Handbook. Youkendo, Tokyo, pp.27, 261, 433, 437.

Kiyohashi,H.,Deguchi,M.,Harashima,H.,and Kyo,M.(1987a). Development of a System for Measuring Local Effective Thermal Conductivities of Rock Mass In Situ by Transient Hot-Wire Comparison Method. The Ninth Japan Symposium on Thermophysical Properties 1988, pp.69-72.

Kiyohashi,H.,Harashima,H.,Deguchi,M.,and Kyo,M.(1987b). Developmental Studies of Measurement System of In Situ Local Thermal Conductivity of Pavement. Report for Toyota Institute, No.40, pp.89-97.

Kiyohashi,H.,Deguchi,M.,Kyo,M.,and Tanaka,S. (1988). Development of a System for Measuring Local Thermal Conductivities of Surface Soil In Situ. J. Geothermal Research Soc. Japan. Vol.10,No.3, pp.251-273.

Kiyohashi,H.,Ogawa,T.,and Iiboshi.S.(1994). Measurement of Thermal Conductivity of Solids by Applying Hot-Wire Comparison Method to Circular Curved Surfaces of the Solid. The Fifteenth Japan Symposium on Thermophysical Properties 1994, pp.117-120.

Murphy,H.D. and Lawton,R.G.(1977). Downhole Measurements of Thermal Conductivity in Geothermal Reservoirs. J. of Pressure Vessel Technology, Trans. of the ASME, Nov., pp.607-611.

Sherratt,A.F.C. and Hensley,F.B.(1961). A Heating Experiment to Determine the Thermal Constants of Rocks In Situ. The Mining Engineer, June 1961, pp.700-714.

Takegoshi,E.,Imura,S.,Hirasawa,Y.,and Takenaka,T.(1981). Measurement Method of Thermal Coductivity of Solids by Transient Hot-Wire Comparison Method. Trans. JSME(B), Vol.47, No.419, pp.1307-1316.

Vost,K.R.(1976). In Situ Measurements of the Thermal Diffusivity of Rock Around Underground Airways. Transactions Inst. Min. Metall.,U.K.,Vol.85, pp.A57-A62.

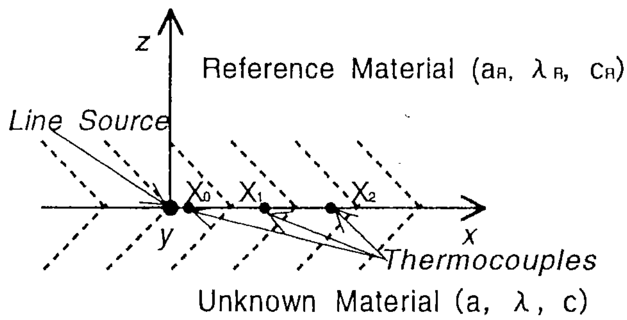

Fig.1. Simultaneous measurement principle of λ and α.

Table 1. Physical data of the rock blocks

Commercial name	Rock kind	Home	Thermal conduc.*	Dry Densi.**
Hachikou-ishi	granite	Japan	2.86	2556
Bianko-Carrara	marble	Italy	2.31	2719
F.G.	gabbro	S. Africa	2.14	2898
Amerika-shoume	granite	U.S.A.	1.93	2602
Akiyu-ishi	tuff	Japan	0.62	1529

*Measurement values by Sensor #080. [W/(m·K)]
**Density[kg/m³]

Table 2. Specifications of the T.P.-sensor

Sensor No.	Dia. of hot-wire	Dia. of K-T.C.	Characteristic common to all
#030A	30[μm]	30[μm]	Length of hot-wire:50mm
#030B	30	30	Material of hot-wire:
#030C	30	30	Advance wire
#050A	50	50	Positions of T.C.:
#050B	50	50	X_0=0.5mm
#050C	50	50	X_1=2.0mm
#080A	80	80	X_2=4.0mm
#080B	80	80	Material of substrate:
#030C	80	80	Silicon gum

Table 3. Published data of reference samples*

Reference sample	ρ [kg/m³]	λ [W/(m·K)]	α [m²/s]	c [kJ/(kg·K)]
SUS304	7,900	16.0	4.07×10^{-6}	0.499
Quartz⊥C	2,600	6.21	3.21	0.745
Quartz Glass	2,200	1.38	0.906	0.692
PTFE	2,200	0.38	0.165	1.05

*JSTP,(1990).Thermophysical Properties Handbook, Youkendo, Tokyo, pp.27, 261, 433, 437.

Table 4. Thermophysical properties of the silicon gum

Sensor used	λ [W/(m·K)]	α [10^{-6}m²/s]	c [kJ/(kg·K)]	ρ [kg/m³]
#080	0.256	0.212	1.07	1150
#030	0.250	0.194	1.16	1150
Ref.A*	0.20	0.14	1.6	970
Ref.B**	0.23	–	–	1100~1600

*JSTP(1990, p.437), **JSME(1986, p.321)

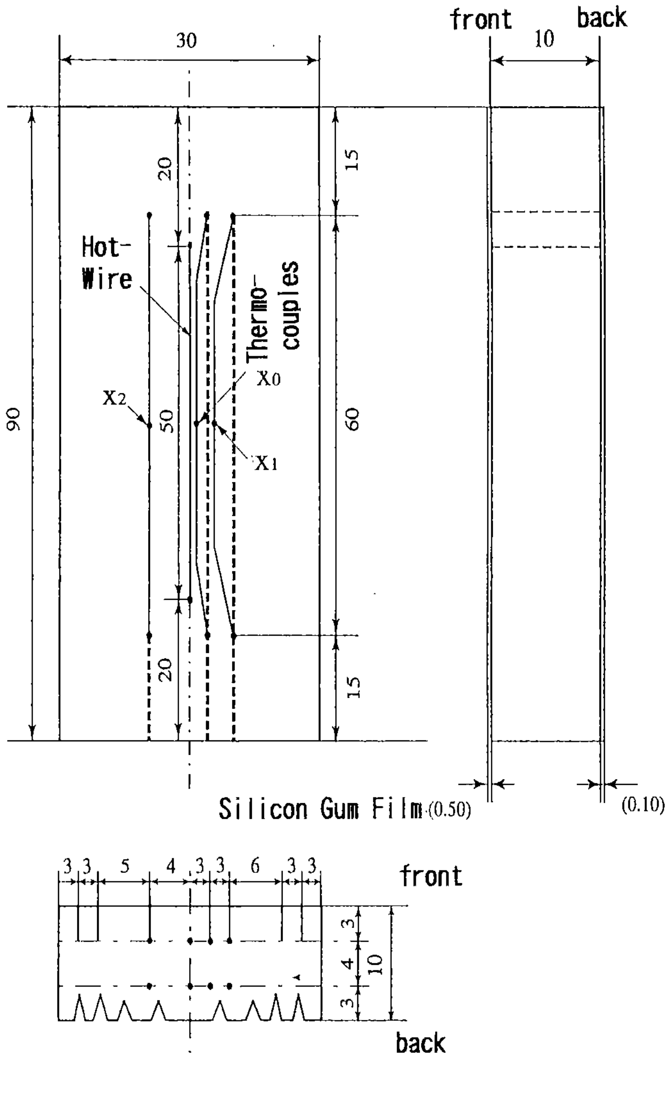

Fig.2. Design and size of T.P.-sensor.

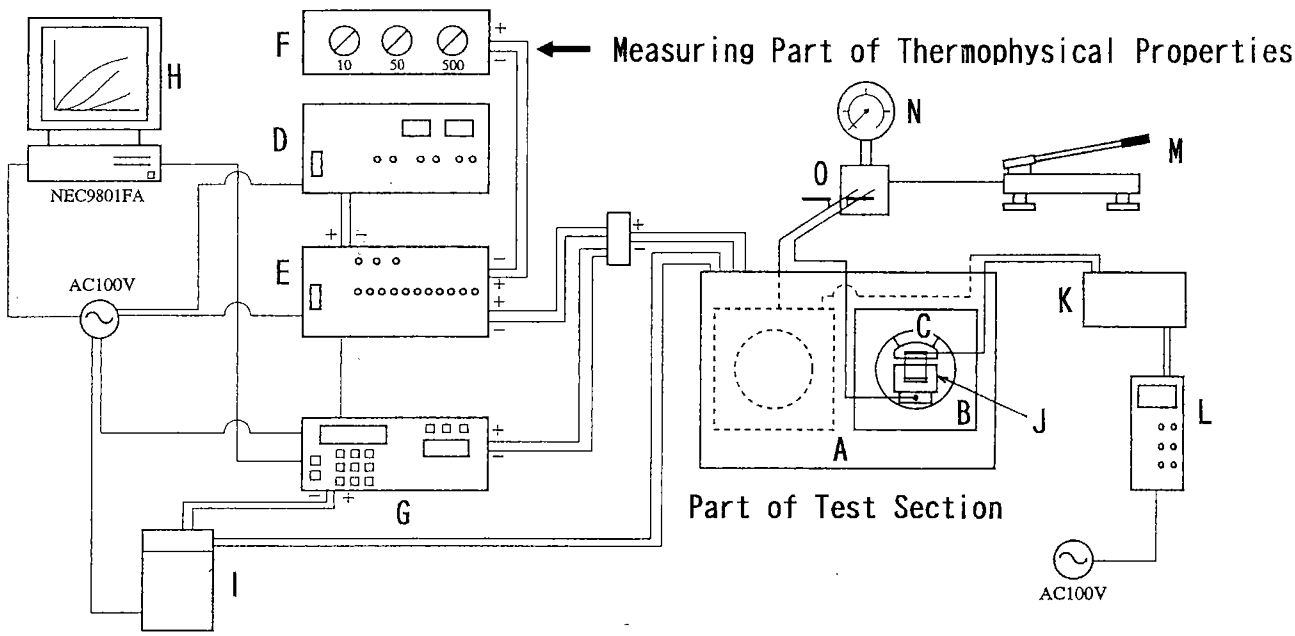

Fig.3. A schematic diagram of the measuring system for thermophysical properties of rock masses using imitation boreholes.

A:Insulation Box	E:Auto. Channel Switch	H:Microcomputer	L:Strain-meter
B:Rock Specimen	F:Dummy Load	I:Electric Cold Junction	M:Oil Pump
C:T.P.-Sensor	G:Multi-channel Digital Data Recorder	J:Hydraulic Jack	N:Pressure Gage
D:Constant Power Supply		K:Bridge Box	O:Stop Valve

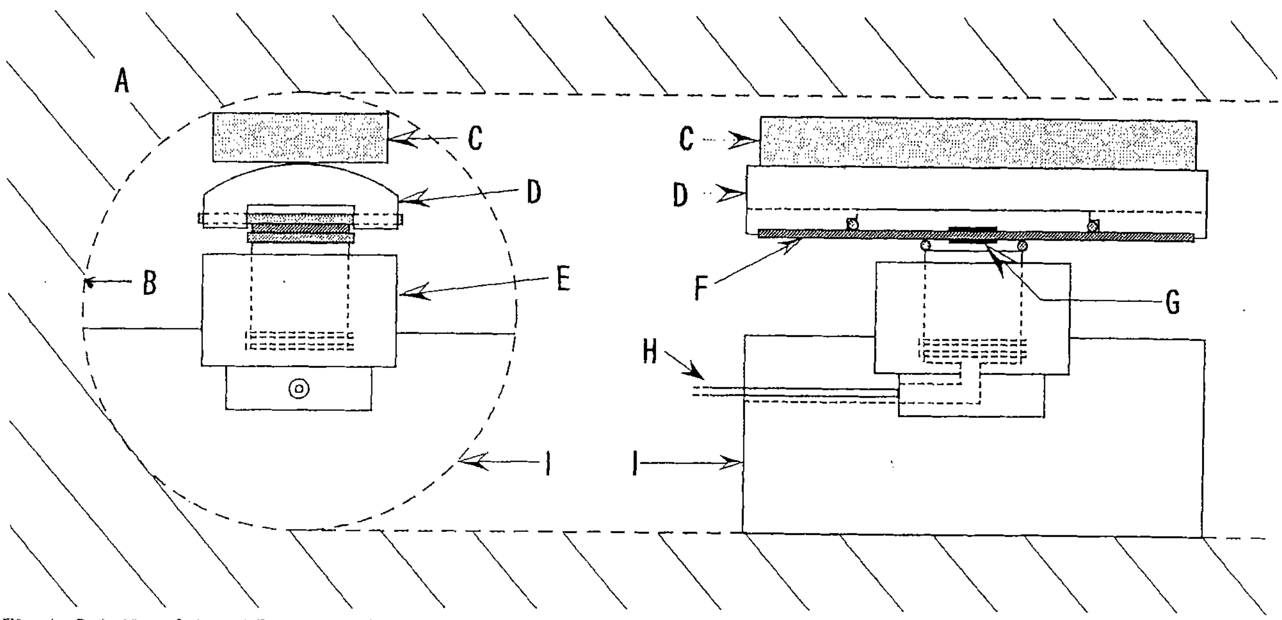

Fig.4. Details of the T.P.-sensor fixing device.
A:Rock Specimen C:T.P.-Sensor E:Hydraulic Jack G:Strain Gauge I:Supporting Base
B:Imitation Borehole D:Sensor Pressing Board F:Pressure Detecting Element H:Hydraulic Pipe

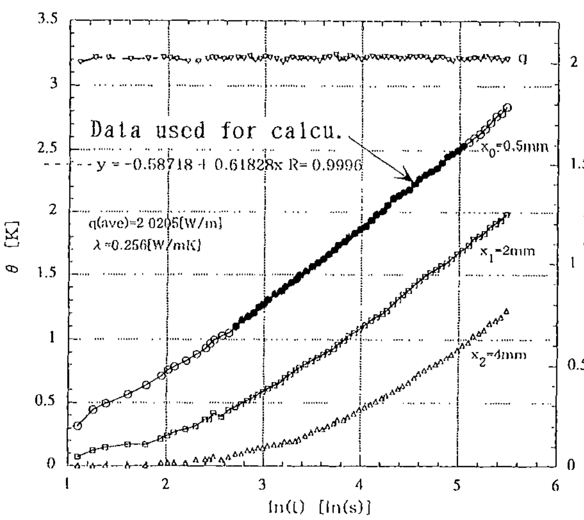

Fig.5. Experimental data on the λ-value of silicon gum.

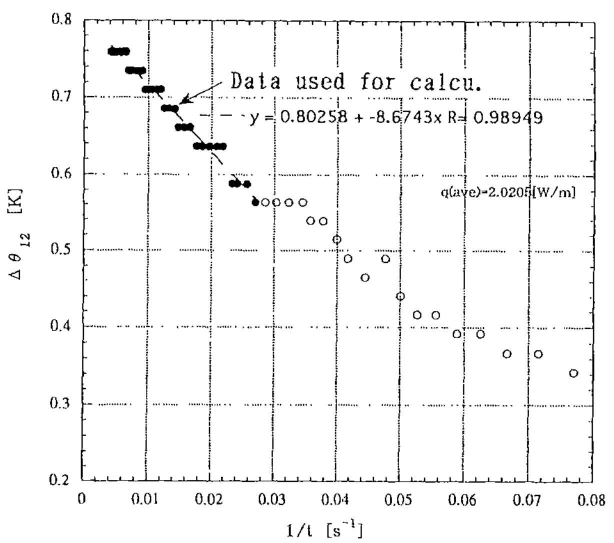

Fig.6. Experimental data on the α-value of silicon gum.

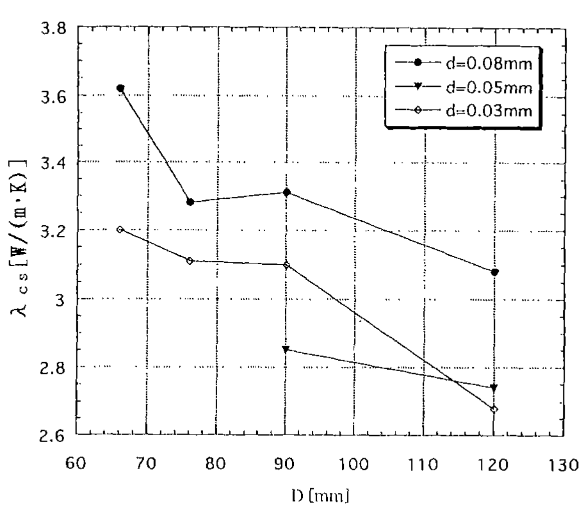

Fig.7. λ_{cs} vs. borehole diameter, D, for all the sensors in the case of Hachikou-ishi.

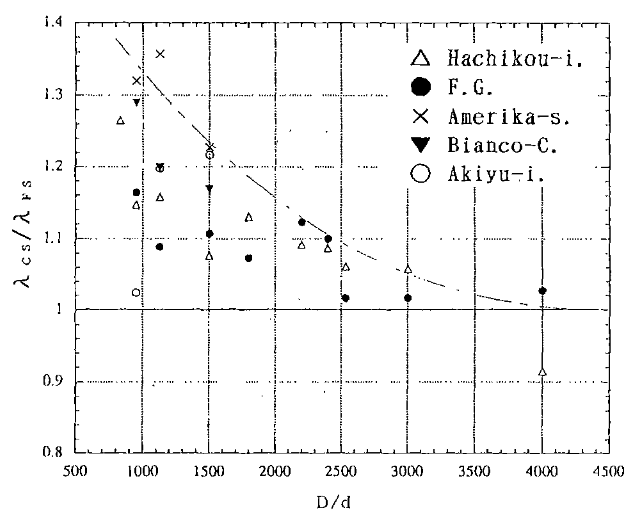

Fig.8. $\lambda_{cs}/\lambda_{FS}$ vs. D/d for all the imitation boreholes and all the rock blocks.