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A Thermometer for Geothermal Thermometry in Geothermal Wells

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ABSTRACT

Geothermal thermometry in geothermal wells is carried out to detect the channels through which geothermal fluids enter a borehole and to determine the temperature distribution in geothermal fluids. The location of the cement tops behind the casings of a well is also determined by temperature measurements in wells. In order to treat the temperature variations due to drilling operations or other nonstationary processes analytically, it is necessary to obtain reliable temperature logs.

An accurate and inexpensive thermometer using a platinum wire resistor as a sensing probe has been developed to meet the increasing requirements for reliable temperature logs, and was named a geothermometer. The geothermometer was designed to meet such specifications as having a measuring range up to 300°C and being waterproof up to 150 bar. The laboratory tests of the thermometer confirmed that it worked satisfactorily up to a temperature of 213°C and an external pressure of water less than 90 bar. In the field tests in the Denken borehole at the Otake geothermal area, Ohita, Japan, the performance of the thermometer was checked with a maximum depth of 340 m and a maximum temperature of 176°C.

The present paper explains in detail structure of the thermometer, temperature calibration, hydraulic tests, method of determination of time constant, and field tests.

INTRODUCTION

Thermometry in geothermal wells is carried out to detect the channels through which geothermal fluids enter a borehole and to determine the temperature of geothermal fluids. Other important applications of temperature logs are to determine the location of the cement tops behind the casing of a well and to obtain data by which the transient flow of fluids through permeable media can be estimated. Quantitative interpretation of electric logs also requires knowledge of the temperature of the formation.

During the drilling of a production well, there are usually short breaks in the drilling. The sensing probe for temperature measurements can be lowered into holes on such occasions. Temperature measurements in production wells should be made as quickly as possible to ensure safety and efficiency of drilling. In the course of drilling, the temperature field of the surrounding formation is disturbed by the circulation of the drilling fluid. When drilling is stopped, the temperature of the fluid in the borehole and the adjacent strata attains thermal equilibrium gradually as time elapses. In order to estimate the temperature change with time after drilling operations or other nonstationary processes, it is necessary to develop sensible and reliable temperature logs.

The depth of production wells at geothermal areas in Japan quite often exceeds 1000 m, and the temperature range to be measured must cover higher values, between 150 and 300°C. For these reasons, all logging equipment must have high performance and be heat resistant, and waterproof.

Up-to-date mercury maximum thermometers, geothermographs developed in New Zealand; Amerada-type thermometers made by the Kuster Co., USA; thermistors; and so forth have been used as sensing probes in geothermal wells. The first three are not suitable for recording the transient temperature distribution in wells. The last, the thermistor, has the disadvantage of relatively poor long-term stability of temperature-resistivity characteristics; and therefore there is some question about the reproducibility of its temperature measurements. We investigated the principles of temperature measurement for geothermal use from a viewpoint of accuracy, stability, dynamic performance, remote sensing, and automatic recording. As a result, the thermometer type using platinum resistance was determined to be most adequate, and the design of the probe and electrical circuit were made. The first thermometer assembly equipped with a platinum-wire resistance-measuring probe was made in August 1967; and the temperature distribution was successfully recorded to a depth of 460 m in the Hatchobaru No. 2 production well, Ohita, Japan, with this equipment. With confidence from this experience, the equipment was improved, mainly in size, in January 1968 to become the geothermometer. In July and October 1968, several attempts to log temperatures in the Denken borehole at the Otake geothermal area were made. Analysis of data obtained justified the use of this type of thermometer in the geothermal branch. We have not yet had the opportunity to test the equipment in deeper holes.

This paper describes the geothermometer, temperature calibration, hydraulic tests, method of determination of time constant, and field tests.

GENERAL CONSIDERATIONS

Methods of signal transmission, principle of sensing, and advantages and disadvantages in geothermal use are listed in Table 1. Thermometers can be classified into two groups, that is, the self-recording expansion type and the electric-transmission type, depending upon whether or not the temperature signal from the transducer is transmitted to the display device some distance apart. A self-recording expansion thermometer is convenient and simple and has the advantage of not requiring an expensive heat-resistant cable. However, it requires frequent manual operation to lower and raise the thermometer many times in the well to observe temperature changes over a definite time interval, and it cannot record any long-term variation of temperature. In general, sensitivity is not very high. Transmission of the signal and remote sensing in this type of thermometer is very difficult.

Electric-transmission thermometers may be subdivided into thermocouples and resistance thermometers, such as a platinum resistance thermometer or a thermistor. These thermometers have the advantage of transmitting the transduced signal from the position of the probe to the display located on the ground surface. Signal transmission is mostly done by electric cable, but radio methods may also be used. Temperatures can be recorded continuously, for example, from the top to the bottom of the hole by lowering the probe gradually. The electric signal transmitted can be recorded by analog or digital display and is ready for data processing. The accuracy of the electrical thermometers depends mostly upon the calibration and the stability of their electrical circuits with time.

The simplest electrical thermometer is a thermocouple. However, thermocouples only measure the difference between two temperatures; they always require expensive compensating leads; and the terrestrial potential field which occurs in boreholes would upset the thermoelectric electromotive force as a spurious signal. Resistivity thermometers need no reference temperature or compensating leads and are therefore ideal for field application in this respect. The choice of the temperature transducer elements should be made between resistance thermometer elements such as platinum, nickel, and semiconductors of ceramic material (thermistors). Thermistors have questionable long-term stability and reproducibility of measurement as mentioned above. For these reasons, a platinum resistance thermometer was selected as a convenient solution for reliable temperature logs under field conditions. The platinum resistance thermometer is a thermometer with the best stability, reproducibility, and traceability; and it is specified as the interpolation device for the range between 13.81 and 903.89 K in the International Practical Temperature Scale, 1968. After this decision, we began a design process to meet the specifications listed in Table 2.

DESIGN FEATURES

A complete set-up is shown in Figure 1. The sensing probe with the geothermometer (G) is equipped with a platinum resistor as the transducer, by which the temperature is converted into electric resistance. The electric circuit (E) and recorder (R) by which the resistance of the platinum wire in the probe can be determined, the cable (C) connecting the probe and electric circuit, the motorized winch (M), and the depth counter (D) are also shown.

Table 1. Classification of thermometers for geothermal thermometry.

Signal transmission and principle of transducer	Thermometer	Example	Features
Self-recording-expansion	Liquid in tube	Mercury-maximum	1. Cheap, convenient, and simple, but fragile. 2. Long time constant. 3. Automatic recording and remote sensing are not applicable.
	Bimetal	Geothermograph	1. An expensive cable is not necessary. 2. Heat-resistance and waterproofing are very good. 3. Movement of recording sheet (smoked glass plate) is uncertain. 4. Continuous measurement is impossible.
	Bourdon tube	Amerada type	1. Driving of recording chart is done by clock. 2. Has the same disadvantages as those of the geothermograph.
Transmission electric	Thermoelectric	Thermocouples	1. Expensive long compensating lead is necessary. 2. Terrestrial potential field may superpose on emf of thermocouples.
	Electrical resistance	Thermistor	1. Expensive electric cable is necessary. 2. Reproducibility is poor due to the time deterioration of the semiconductor.
		Platinum resistor	3. Remote sensing and automatic recording are easy. 4. High accuracy is attainable. 5. Time constant is comparatively small.

Figure 2 shows the simplified section of the geothermometer. It is equipped with a guard casing pipe (*12*) with many circular holes to ensure that the resistance element (*11*) has good thermal contact with the ambient fluid in the wells. A dead weight made of brass (*13*) is attached to the end of the guard casing pipe to give a total weight of 2 kg. The overall length of the assembled probe is 50 cm, and its maximum external diameter is 5 cm. This type of probe must be heat resistant and waterproof. The present design requires waterproofing at two positions. One is between the cable and the protecting pipe made of brass (*8*), which contains the holding plug and socket (*9*); and the other is at the compression fitting (*10*). Waterproofing at the former position is achieved with the combined use of an O-ring made of teflon or nitrile rubber (*6*) and a tempered copper back-up ring (*5*), the latter position with taper screws known as the compression fitting. The total weight of the probe is supported by the tapered screw (*3*) with clump (*2*) at the outer covering of the cable.

Table 2. Design of geothermometer compared with that of the geothermograph.

Item	Unit	Geothermograph	Geothermometer
Maximum temperature	°C	300	300
Accuracy	K	±2	±2
Maximum depth	m	–	1500
Size			
diameter	mm	56	50
length	mm	1000	500
Maximum hydrostatic pressure	bar	140	150
Continuous recording time	min	–	500
Time constant	sec	5(water) 30(vapor)	60
Total weight	kg	6.8	20

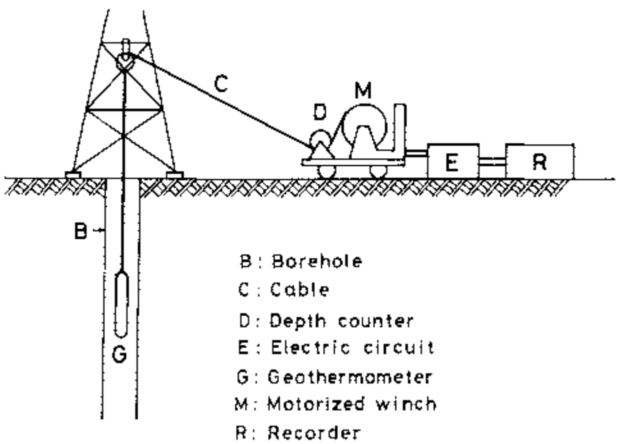

Figure 1. Assembled apparatus for geothermal thermometry in wells.

The sheathed platinum resistance wire element (*11*) fabricated by Okazaki Trade Co. Ltd. and named Resiopak is made by packing a platinum wire in a stainless steel sheath 4.8 mm in diameter and 30 cm long. The measuring range of this thermometer is from −200°C to +500°C; its resistance is 100 ohm at 0°C; and its time constant is 8 sec in a stagnant oil bath. The cable had to satisfy the following conditions: high mechanical strength, small loop resistance, and large shunt resistance. The cable meeting these specifications was supplied by Furukawa Electric Co. Ltd. with a motorized winch. It has four tinned copper wires insulated with teflon and glass fiber and two armor wrappings of galvanized steel wire. Its weight, loop resistance, and maximum breaking load are 200 kg/km, 50.8 ohm/km, and 450 kg respectively.

Because the resistance of the platinum resistance wire element (100 ohm at 0°C) is of the same order as that of the connecting cable (50.8 ohm at 20°C), it is necessary to use three of the four wiring leads to fully compensate for changes in cable resistance due to temperature changes in the ambient fluid in the well. The measuring circuit employed is the potentiometric circuit shown in Figure 3. Resistance of the platinum resistance wire element R_x is

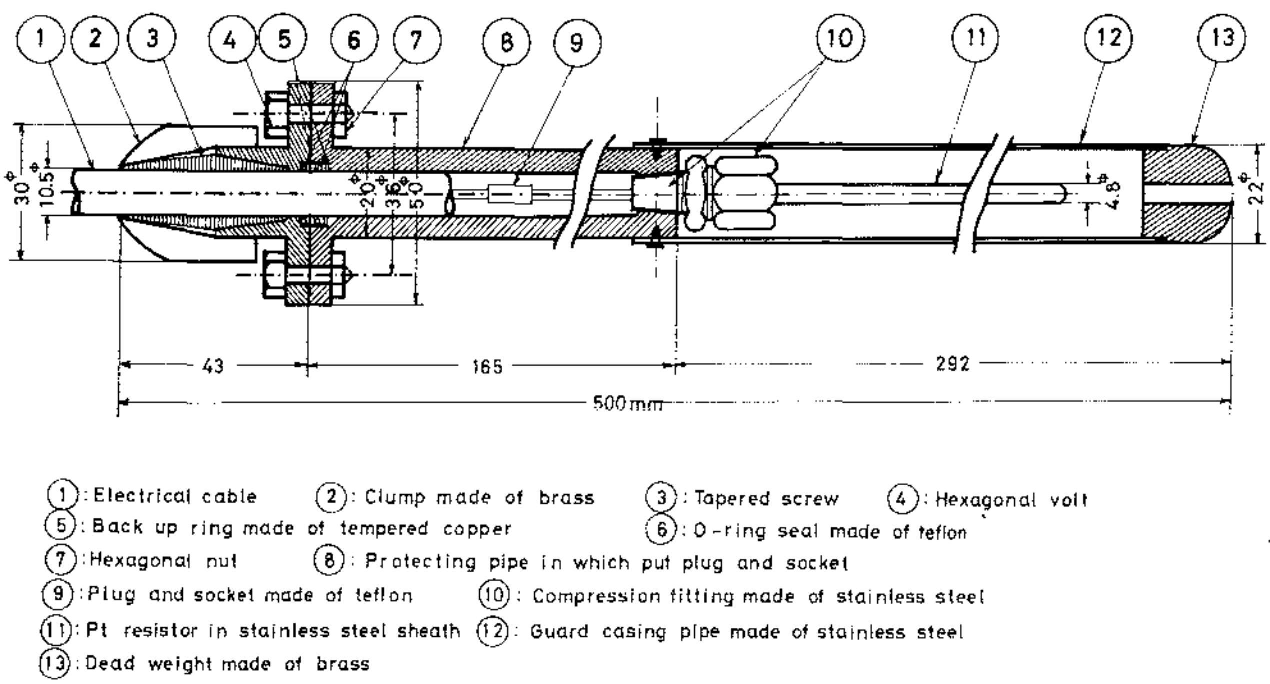

Figure 2. Simplified section of the geothermometer.

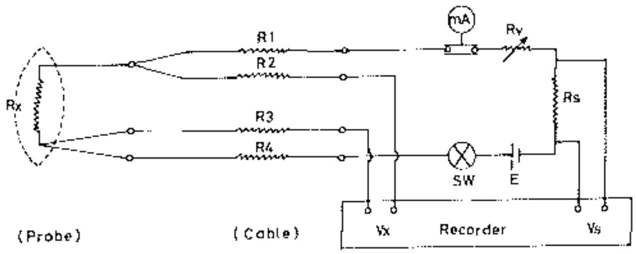

Figure 3. Potentiometric circuit. (R_x) resistance of the probe, 100 ohm at 0°C; (R_s) standard resistance, 100 ohm at 20°C; (R_v) variable resistance, maximum of 100 ohm; (mA) milliammeter; (R_1, R_2, R_3, R_4) loop resistance of the cable, 50.8 ohm/km; (SW) switch; (E) dry cell, 1.5 to 3 V.

determined by measuring the potential drop across $R_x + R_2 + R_3$, V_x, and that across the standard resistance R_s, V_s:

$$R_x = R_s(V_x/V_s)$$

The effect of lead resistance is completely eliminated if the resistances of the leads R_1, R_2, R_3, and R_4 are much greater than the input impedance of the voltmeter used. In the field measurements V_x and V_s are recorded automatically by an electronic pen-recorder. The temperature is determined by means of the calibration chart or table. The geothermometer was calibrated against a standard thermometer in a bath. No significant change occurred in the calibration of the geothermometer after several field tests.

CALIBRATION AND HYDRAULIC TEST

The geothermometer was calibrated against calibrated copper-constantan thermocouples in the arrangement shown in Figure 4. The calibration was made by the following procedures:

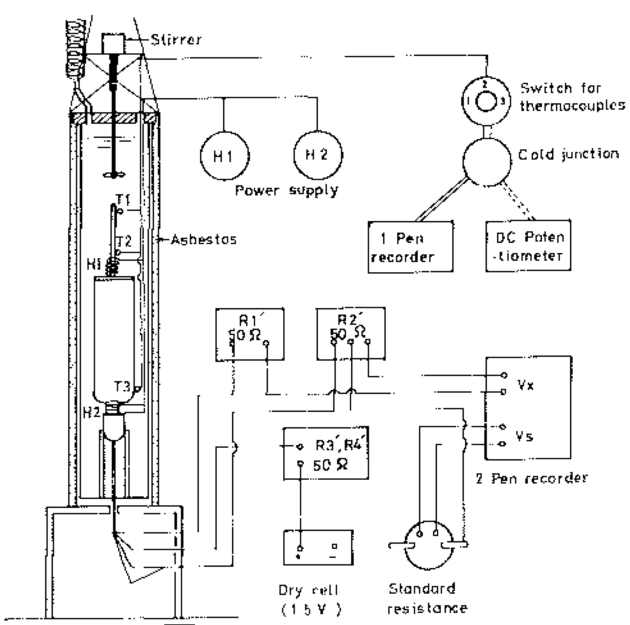

Figure 4. Apparatus for temperature calibration. (T_1, T_2, T_3) standard thermocouples; (H_1, H_2) heater, 1 kW; (R_1, R_2, R_3) resistance inserted instead of loop resistance of cable.

1. The geothermometer is completely immersed in a cylindrical bath filled with polychloro-biphenyl (PCB).
2. The fluid in the bath is gradually heated by the 1-kW heaters fixed at the upper and lower parts of the bath.
3. The electromotive force of the thermocouples and the resistance of the platinum are simultaneously measured after checking the uniformity and steady state of the heated liquid in the bath.
4. Measurements are repeated at suitable temperature intervals, 10°C for example, by raising the temperature of the liquid in the bath gradually.

The boiling point of the liquid used in the bath is 320°C. However, the surface of the covering of the cable was found to degrade at temperatures higher than 200°C. The calibration was therefore done at temperatures less than 220°C.

Instead of the loop resistance of the cable, resistances of about 50 ohm are connected simulating the R_1, R_2, R_3, and R_4 resistances in Figure 3. During the course of temperature calibration, these resistances were changed in the range between 1 and 500 ohms, but no significant changes in the measured value of the resistivity could be observed. In other words, the electrical circuit could compensate completely for changes in the cable resistance due to temperature changes in wells. The calibration chart was constructed as shown in Figure 5. The linear relationship between temperature and resistance is seen within the measured range, is fitted by a regression analysis and yields the relationship:

$$T = 2.60\,R - 261$$

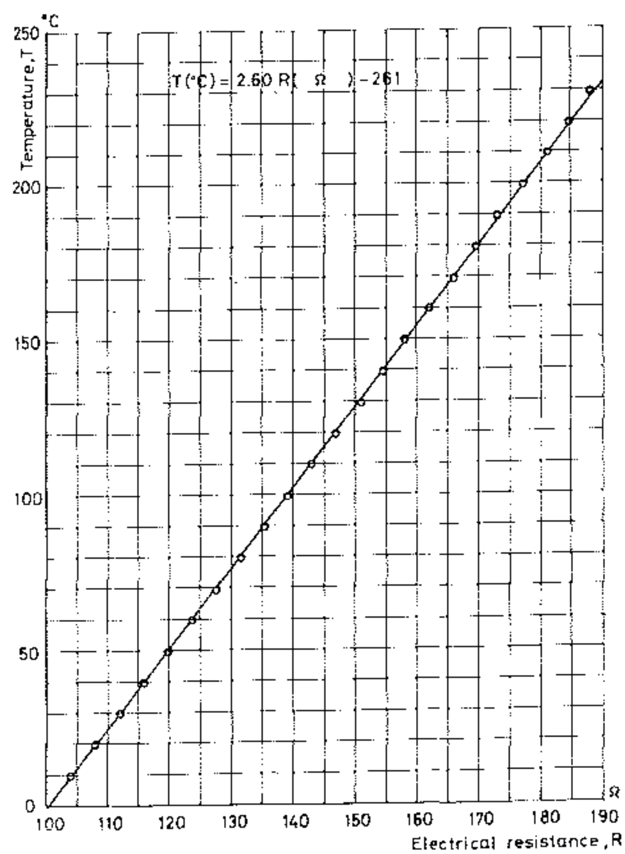

Figure 5. Calibration chart for the geothermometer.

Figure 6 shows the apparatus for the hydraulic test for the geothermometer. In order to make a seal between the cable and the pressure vessel, the same method of sealing used for the geothermometer was applied. Liquid in the pressure vessel was pressurized by a hydraulic pump. The pressure test was carried out by the following procedures: (1) the geothermometer was immersed in a water bath and set in the pressure vessel; (2) the pressure in the vessel was gradually increased by a hydraulic pump and kept at its maximum value (90 bar in the laboratory experiment) for about one hour; and (3) the geothermometer was then taken out of the pressure vessel and disassembled with great care. No leakage of water into the geothermometer was detected.

DETERMINATION OF TIME CONSTANT

We have to know the response time of a thermometer in an environment similar to that in application. When a thermometer at a temperature θ_0 is put into some fluid at a temperature θ_e at the instant $t = 0$, the temperature of the thermometer varies with time according to

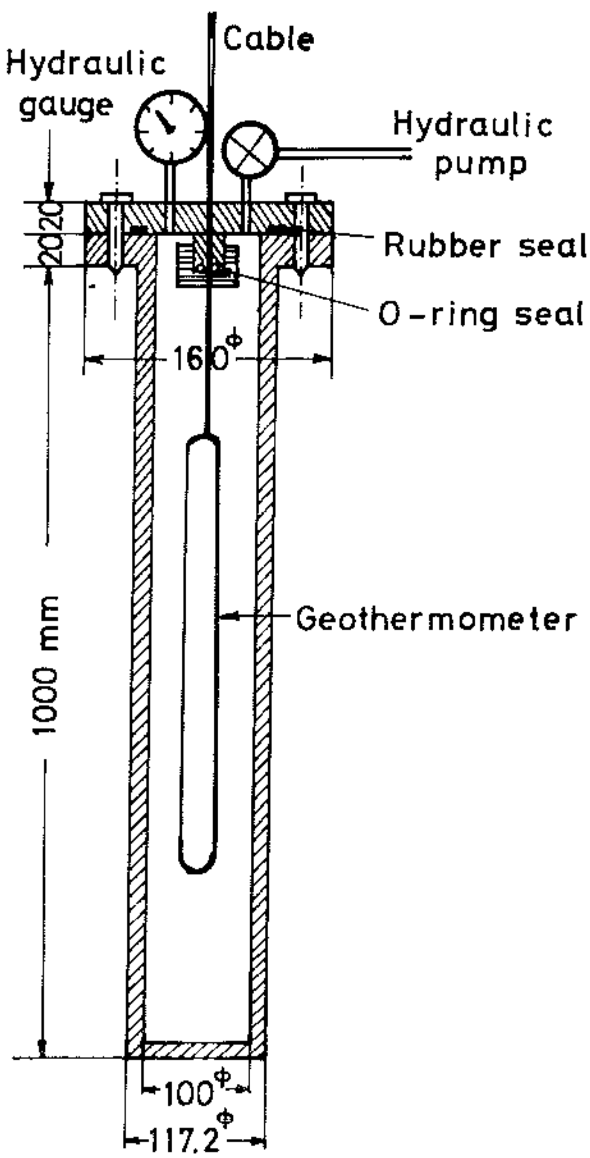

Figure 6. Apparatus for hydraulic test.

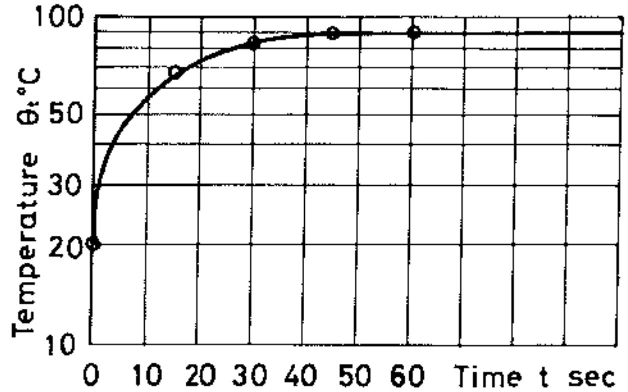

Figure 7. Step response of the geothermometer.

$$(\theta_e - \theta_t)/(\theta_e - \theta_0) = \exp(-hA/Wc)t \qquad (1)$$

where θ_t is the temperature at time t, h is the coefficient of heat transfer at the surface of the probe, and A, W, and c are respectively outer area, weight, and specific heat of the probe. For a system which has this kind of behavior, we may note that when $t = T$

$$T = Wc/hA \qquad (2)$$

The ratio $(\theta_e - \theta_t)/(\theta_e - \theta_0)$ drops to 36.8% of its initial value. T is the time constant of the system. Thus the time constant is usually taken as a measure of the time needed for the system to settle into a steady state. Substituting Equation (2) into Equation (1), and taking the logarithm, we get the equation:

$$\log_{10}[(\theta_e - \theta_t)/(\theta_e - \theta_0)] = -(\log_{10} e/T)t \qquad (3)$$

Taking the left hand term in Equation (3) as the ordinate, and time t as abscissa and plotting in a semi-log paper, we get a linear relation. The time constant T can be determined from the slope of the line.

In the laboratory test, the geothermometer in thermal equilibrium with room temperature was suddenly put into boiling water. The output of the thermometer varied exponentially with time (Fig. 7), closing to the final temperature as shown in Figure 8, and the time constant of the geothermometer was determined to be 14.3 sec.

FIELD TEST

The whole assembly was tested in the Denken borehole at the Otake geothermal area, Ohita, Japan. The hole is cased from the head of the well to a depth of 120 m with a casing pipe of 4 in. diameter and is cased with a slotted liner between the depths of 20 and 350 m. Two kinds of tests were carried out in the field. In one type, the thermometer was vertically traversed up and down through the fluid in the borehole at a constant speed by a motorized winch. In the other, the thermometer was at rest, and the temperature variation was continuously recorded at each depth until steady states were obtained. The temperature in the well was measured in the second test at 10-m intervals, and the results are summarized in Table 3. Figure 9 shows the temperature of the fluid in the well plotted against the depth covered. The dashed line is the temperature log in the well,

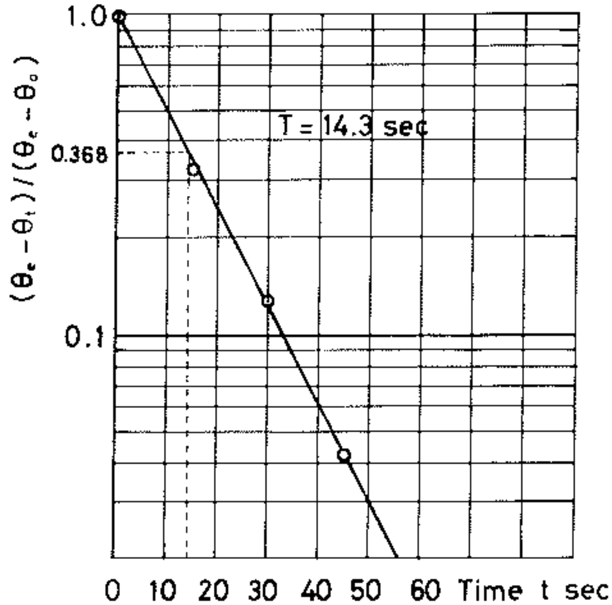

Figure 8. Determination of the time constant.

Table 3. Temperature measured at the Denken borehole at the Otake geothermal area.

Depth (m)	V_x (mV)	V_s (mV)	R_x (ohm)	T (°C)
10	675	487	138.6	99.3
20	675	487	138.6	99.3
30	674	487	138.4	98.7
40	674	487	138.4	98.7
50	673	486	138.5	99.0
60	672	486	138.3	98.4
70	673	486	138.5	99.0
80	673	486	138.5	99.0
90	672	486	138.3	98.4
100	671	485	138.4	98.6
110	674	484	139.3	101.0
120	671	484	138.6	99.4
130	669	484	138.2	98.3
140	686	475	144.4	114.4
150	691	472	146.4	119.5
160	696	468	148.7	125.6
170	709	461	153.8	138.8
180	713	458	155.7	143.7
190	706	461	153.1	137.1
200	717	455	157.6	148.6
210	719	453	158.7	151.6
220	721	449	160.6	156.4
230	720	449	160.3	156.4
240	722	447	161.5	158.9
250	727	445	163.4	163.7
260	727	444	163.7	164.6
270	728	440	165.5	169.1
280	728	439	165.8	170.1
290	732	436	167.9	175.4
300	732	435	168.3	176.4
310	714	442	161.5	158.9
320	696	450	154.7	141.0
330	694	450	154.2	139.9

and the solid line is the saturation temperature curve for pure water corresponding to hydrostatic pressure. The water level in the well might be near 130 m. At a depth of 200 m, marked periodic changes of temperature with an amplitude of 40°C and a period of 480 sec were found. Only the maximum and minimum temperatures were plotted at

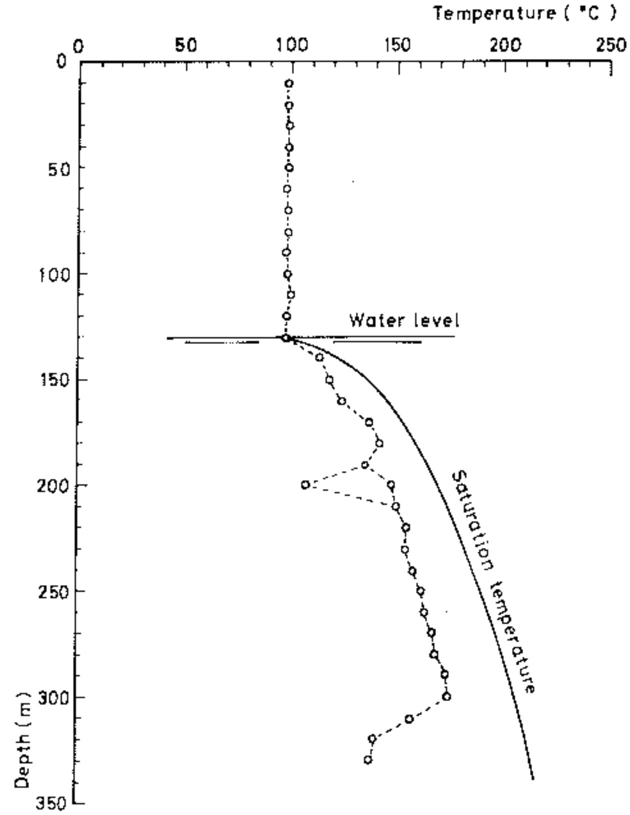

Figure 9. Temperature measured at the Denken borehole at the Otake geothermal area.

this depth as shown in Figure 9. At depths greater than 300 m, some cooling of the fluid in the well was observed. The maximum reading was 178°C, and the maximum expected hydrostatic pressure was 20 bar. We concluded that the state of the fluid in the well was compressed water because the temperature of the fluid in the well was lower than the value of the saturation temperature for all the depths observed.

CONCLUSION

The geothermometer was designed to be heat resistant up to 300°C and waterproof up to 150 bar. Laboratory experiments established that it was heat resistant up to 213°C and waterproof up to 90 bar. The geothermometer worked quite well in the field test up to a maximum temperature of 178°C and up to a maximum hydrostatic pressure of 20 bar. Finally, we concluded that the geothermometer, including the electrical circuit, depth counter, and auxiliary equipment, was satisfactory for making field observations.

Unfortunately, we did not have the opportunity to make measurements in deeper holes. If there are any problems in deeper holes, the first would be the seal between the cable and the protecting pipe with O-ring and back-up ring. In order to make faster temperature measurements in the fields, some sophisticated electronic devices should be used.

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