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13. *Development of a New Multiple Sensor Type Borehole Thermometer for the "Buried Thermistor Probe Method."*

By Satoru HONDA, Hideyuki FUJISAWA,
Earthquake Research Institute, University of Tokyo,

Taro UYEDA*,
Department of Electronic Engineering, University of Tokyo,

Yukio MATSUBARA** and Seiya UYEDA,
Earthquake Research Institute, University of Tokyo.

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Abstract

We have developed a new multiple sensor type borehole thermometer for the "Buried Thermistor Probe Method, (UYEDA *et al.*, 1974, 1976)". Utilizing digital CMOS circuits, we can operate multiple sensor thermometer system by only one six-conductor cable. This system, installed in a borehole, enables one to measure the detailed temperature distribution against depth and to monitor its time variation. By this system, we can obtain accurate data sets to determine true terrestrial heat flow values from deep wells and boreholes more easily and more definitively than by conventional methods, because we can get information on the stability of the underground temperature field and on the effects of the thermal disturbance caused by drilling. Some results obtained by this thermometer are briefly described.

1. Introduction

Making heat flow measurements on the land area is a difficult task. Ordinarily we need deep wells or boreholes to avoid natural temperature disturbances, such as those due to the daily and annual variations of surface temperature and water flow. However, when we use a borehole to measure the temperature, we need to wait till the artificial temperature disturbances, such as those caused by drilling and water circulation, decay. Boreholes are, however, usually collapsed or buried soon after the completion of drilling. In such a case, if we want to be assured of obtaining

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* Now at Department of Botany, Faculty of Science, University of Tokyo.

** Yukio MATSUBARA died of cancer on the 11th February, 1980 at the age of 25.

the temperature by a conventional method, we must measure the downhole temperature in the casing pipe before the rig is removed. Then, the obtained temperature is usually still much disturbed.

To avoid these difficulties, UYEDA *et al.* (1974) proposed the "Buried Thermistor Probe Method" in which thermistor probes are lowered right after the completion of drilling and left in the hole for the later measurements. By this method, we can expect to obtain the undisturbed temperature distribution. In addition, we may even be able to estimate the effects of the various disturbances mentioned above by making long term observations. The method proposed by UYEDA *et al.* (1974, 1976) is very simple. However, it has some shortcomings. Because a pair of conductor cables are needed for each sensor (e.g. thermistor), there must be as many pairs of conductor cables as the number of the temperature sensors.

In this paper, we describe a new type thermometer system for the "Buried Thermistor Probe Method" and report several observations conducted with it. Our method is very flexible and we need only one six-conductor cable, which removes the shortcomings of the earlier method. The number of sensors can theoretically be infinite. The interval of each sensor can be easily varied and sensors other than thermistors can also be used. Cox *et al.* (1965) developed a system with a purpose similar to the present one, i.e. to have a number of sensors with a small number of conductors. Their method made use of the time constants of circuits which vary with the resistance of thermistors. Our system is probably more general than theirs.

2. Development of the System

2.1 Overall Description of the System

The sketch of our thermometer is illustrated in Fig. 1. The thermometer consists of a six-conductor cable and sensor units (30 mm in diameter and 160 mm in length) which are waterproof. In each sensor unit there is an electrical circuit and a thermistor probe (Fig. 2). They are attached to a circuit board and molded in an acrylite pipe (Mitsubishi Rayon Co. Ltd., standard polymethylmethacrylate pipe: see Fig. 5a) of about 20 mm in diameter by Araldite (Chiba-geigy Co. Ltd.), an epoxy resin. The surface of the acrylite pipe is enclosed by a rubber cover of about 2.5 mm in thickness for waterproofing. Finally, to prevent any leakage of water, we envelope the system with "F-COTAPE No. 1" (Furukawa Electric Co. Ltd.), a self bonding insulating tape, and vinyl tape.

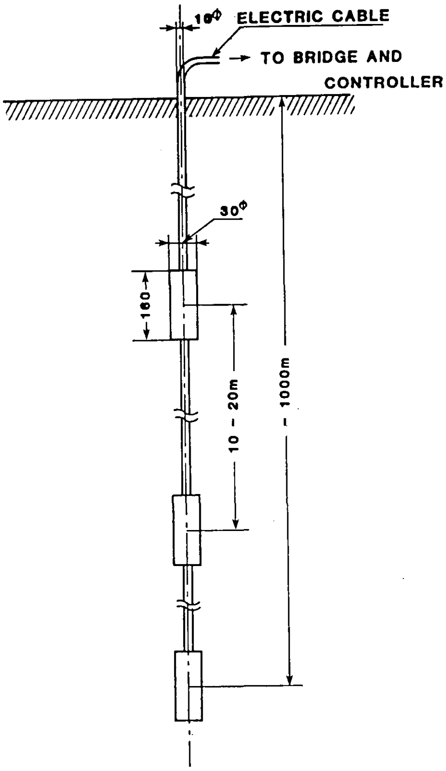


Fig. 1. An outline of our new type thermometer. The boxes in the figure show the sensor units where the thermistor and the electrical circuits are molded with resin.

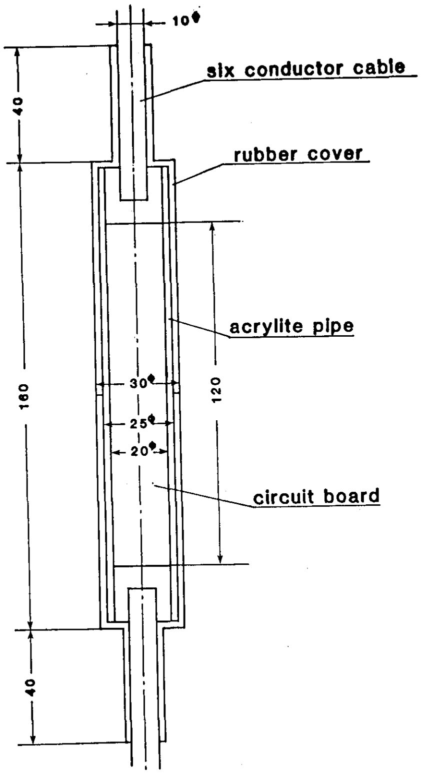
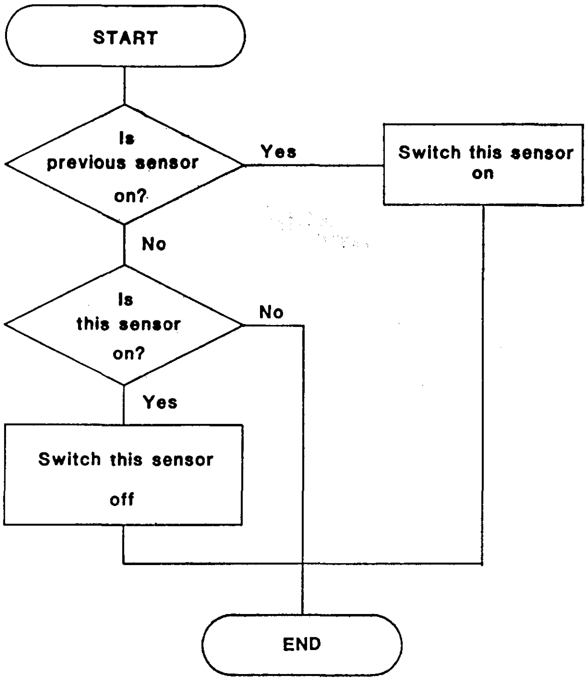


Fig. 2. The cross section of sensor housing. The size is shown in mm.

2.2 Sensor Unit

The action of each sensor unit is driven by a controller set on the ground. When a first pulse is transmitted into the system from the controller, the sensor situated nearest the controller, i.e. the uppermost sensor, switches "ON". When a sensor goes "ON", the thermistor attached to it gets connected in series with the measuring system. Then, we can measure the resistance of that thermistor by a Wheatstone's bridge (5 or 4 place). The second signal from the controller will turn the "ON" sensor "OFF" and the next sensor "ON". This action is repeated for the rest of the sensors through this system. This way we can obtain the information of the temperature versus depth throughout the hole.

The flow chart of the action of a sensor is shown in Fig. 3 and Fig. 4. shows the simplified diagram of the circuit that realizes the above stated function. A pair of conductors is used to measure the resistance



Flow chart.

Fig. 3. The flow chart of the logic of a sensor unit. When the sensor accepts the pulse from the controller, it checks the state of the previous sensor, i. e. the sensor which is directly above. When the state of the previous sensor is "ON", then it turns itself "ON". If not, it checks its own state. If its state is "ON", it turns "OFF".

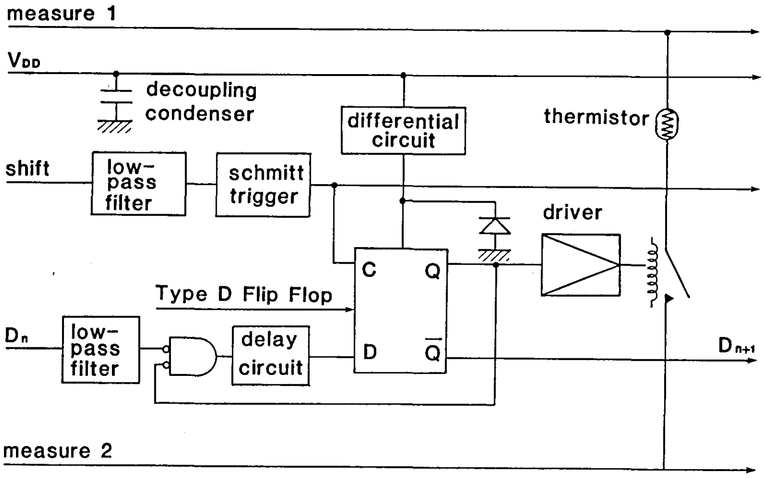


Fig. 4. The block diagram of a sensor circuit.

of the thermistor. The third conductor is used for the power supply, the fourth for the ground, the fifth for the transmission of pulse signals from the controller and the last one for the transmission of signals from the previous sensor. The square box in the middle of Fig. 4 shows a "flip-flop circuit". The flip-flop becomes "ON" (i.e. Q is high and $\bar{Q}$ is low) when it receives the pulse (i.e. C gets the pulse) from the controller with high D. If D is not high, it does not go "ON" (i.e. Q is low and $\bar{Q}$ is high). D that controls the "ON" and "OFF" of the flip-flop becomes high only when $\bar{Q}$ is low (i.e. the previous sensor is "ON"). When Q becomes high, the thermistor enters into the measuring system with the aid of a relay, and the state of sensor becomes "ON". The system is usually operated by a D.C. 12V dry battery.

2.3 Accuracy of the Measurements

The accuracy of this system is mainly controlled by that of the calibration of thermistors. It is about 0.1 degrees in the absolute temperature and about 0.01 degrees in the variation of temperature. The correction for the resistance of the conductor is made by a dummy sensor which has no thermistor. When the dummy sensor goes "ON", the measuring system is short-circuited. So, we can measure the resistance of the conductor at the site where the dummy sensor is installed. The conductor resistance at a desired site is obtained by linear interpolation and/or extrapolation of the data obtained by the dummy sensor. We inferred that the error caused by these interpolation and/or extrapolation is about 0.02–0.15 Ω for usual cases. The characteristic resistance of the thermistor used in this study is about 1–30 kΩ so that the error is negligible.

The long term stability of thermistors is not suifficiently well known. MUNAKATA and ATSUTA (1977) reported that the variation of the thermistor resistance at a constant temperature is about 0.2–0.3% (corresponding to about 0.1–0.2 degrees) in a year. Such a drifting of the resistnace may be found from careful and long observations.

2.4 Durability

We are not certain as to how long this system can stand up under severe conditions. We have perfomed some experiments to check the water tightness of our sensor in a high pressure vessel. No leakage was found after several hours run at the pressure of 200 bars. Field experiments so far have shown that the system has been active after eight months of burial at the depth of 750 m, which corresponds to about 75 bars in pressure and about 55°C in temperature. The integrated circuit we used is guaranteed up to about 80°C. The pictures of a

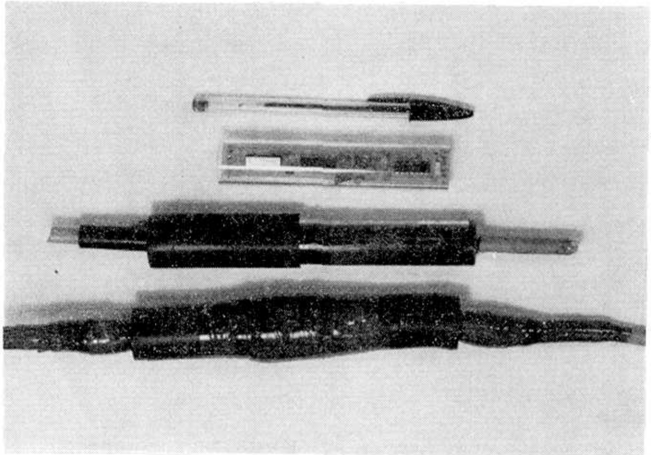


Fig. 5a. Pictures of a sensor unit. The lower picture is the completed unit. The middle picture shows the sensor unit molded with resin and the upper shows the electrical board in the acrylite pipe.

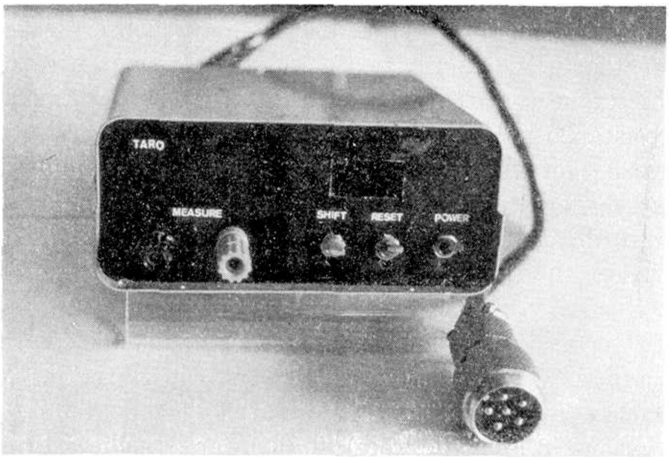


Fig. 5b. Picture of the controller. The two terminals shown on the left are used for measuring the resistance of the thermistors.

sensor and the controller of this system are shown in Figs. 5a and 5b respectively.

3. Observations

We briefly show some of the results of the observations obtained by the present system. More detailed discussions and the geophysical interpretation of this data will be described elsewhere. Fig. 6 shows the

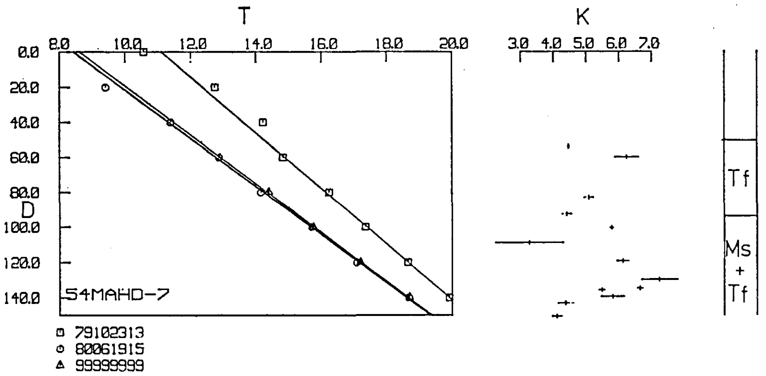


Fig. 6. The relation between the temperature, the conductivity of rocks and the depth, and the geologic column at the borehole 54 MAHD-7 near Lake Towada. The left figure is the relation between the temperature T (°C) and depth D (m), the middle is that between the conductivity K($\times 10^{-3}$ cal/cm sec) and the depth and the right figure is the geologic column (Tf: Tuff, Ms: Mudstone). The details are described in the text.

temperature variation plotted against the depth for different dates. The thermometer was installed in the borehole " 54 MAHD-7 " drilled by the Metal Mining Agency of Japan to search for the Kuroko deposits near Lake Towada, Tohoku district, northern Japan. The first measurements were made at the end of the drilling as shown in Fig. 6 by the symbol " 79102313 ". In this first trial, we used only seven thermistors, although we could use an " infinite " number of them as already stated. The inferred values "99999999" in this figure are estimated from the equation

$$\Delta T = A \ln (1 + s/t) \tag{1}$$

where ΔT is the disturbance temperature at each depth caused by the drilling, A is a constant related to the strength of the line heat source that represents the drilling effect, s is the time during which the drilling continued and t is the time after the end of the drilling (BULLARD, 1947; LACHENBRUCH and BREWER, 1959). t and s can be obtained from the record of the drilling. Note that although t is the same for all depths, s is not the same because of the difference of the circulation time at each depth. This equation is frequently used (e.g. LACHENBRUCH and BREWER, 1959; HONDA *et al.*, 1979), but rigorous experimental confirmation has been made only in a few cases. Fig. 7 shows the experimental results. The inferred equilibrium temperatures in Fig. 7 are plotted in Fig. 6 by the symbol " 99999999 ". Data taken about eight months after the end of drilling is also shown in Fig. 6 by the symbol " 80061915 ". Fairly

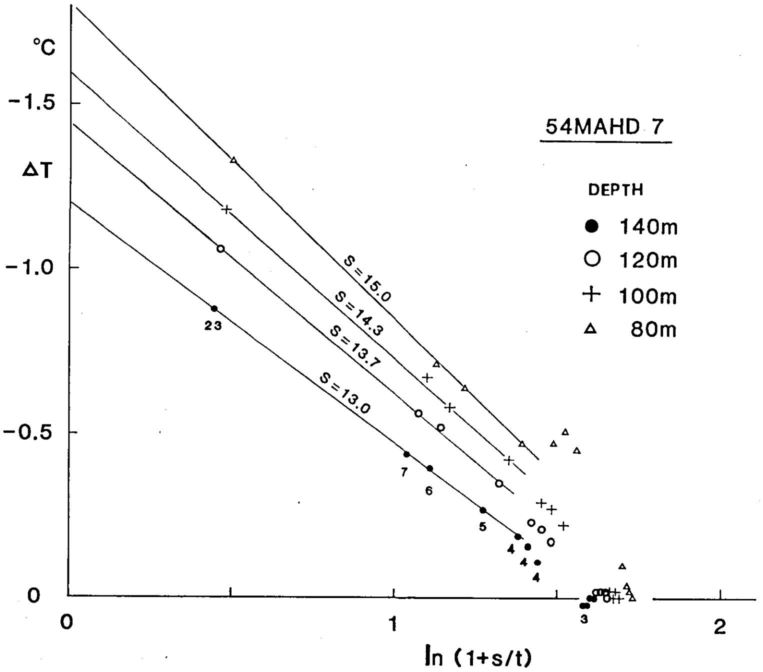


Fig. 7. The variation of the temperature with time at the borehole 54 MAHD-7. The ordinate is the temperature variation measured from an arbitary reference point, and the abscissa is ln $(1+s/t)$. Numerals shown in this figure are the number of days after the cessation of drilling. On each line, values of s which is the duration time (unit: day) of drilling at each depth are shown.

good coincidence can be observed between the 'inferred' values and data of "80061915". This implies that the equation (1) holds well in this case.

4. Future Work

Our newly developed borehole thermometer may become more useful if an automatic recording system can be attached. Often, boreholes are opened at localities where natural conditions are severe. For example, at several places where we have installed our thermometers, it begins to snow in early November and the snows do not melt until June. In such cases, repeated temperature measurements that will probably be useful to correct the annual variations of surface temperature and the effects of drilling are difficult to perform. To supplement this inconvenience we are now developing an automatic recording system. Probably the coupling of our thermometer and the automatic recorder will be useful in other contexts also. For example, a continuous and systematic measurements of temperature in a hydrothermal area may help our understanding of the movements of fluids.

It is thought that the principle of the present system can be widely applied to any system where a large number of sensor circuits are to be operated by a cable with a small number of conductors.

5. Acknowledgement

The Metal Mining Agency of Japan provided the authors an opportunity to measure the temperature in the borehole drilled as a part of its Regional Geological Survey Program. Especially, Dr. T. Sato of the Agency is greatly thanked. Dr. H. Ito of the Geological Survey of Japan kindly assisted in our tests on waterproofing. The authors are also grateful to the staff of the Okutama Industrial Construction Co. Ltd., the Nikko Exploring Co. Ltd., the Dowa Engineering Co. Ltd., and the Nissaku Co. Ltd., for their assistance in setting the instruments into boreholes.

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13. 新型多点埋め込み方式温度計の開発

地震研究所 本多　了
地震研究所 藤沢英幸
東京大学工学部 上田太郎*
地震研究所 松原幸夫**
地震研究所 上田誠也

より多くの孔井内で精度のよい温度測定を行なうために，埋め込み方式による新型の温度計を開発した．埋め込み方式は，既に提案されているが，温度センサー（サーミスター）をボーリング終了直後に孔井内にそう入し，そのまま放置しておく方法である．この方法は簡便であるが，いくつかの短所をもつ．たとえば，サーミスター一つに対して一対の測定線を必要とするため，多くのサーミスターを使用する際には，取り扱いが複雑となり，不適当である．我々の方法では，簡単な電子回路を用いることにより，一本の六芯のキャブタイヤケーブルを用いるのみで，任意の数の温度センサーを任意の間隔で取り付けられるようになっている．また，原理的には，センサーはサーミスターに限らず他の型のセンサーも使用できる．このシステムは本研究の目的以外にも多点素子を用いるシステムにおいては広い応用性をもつものと考えられる．最後にこの温度計を用いて測定した結果を簡単に示した．

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* 現在，東京大学理学部植物学教室

** 1980年，2月11日，胃がんのため死去