

DISTRIBUTED OPTIC-FIBRE TEMPERATURE SENSING (DTS):  
A NEW TOOL FOR DETERMINING SUBSURFACE TEMPERATURE CHANGES  
AND RESERVOIR CHARACTERISTICS

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ABSTRACT

The DTS technique is a temperature-sensing method based on the Raman effect of the backscattering of light along an optic fibre that allows the measurement of temperature instantaneously over the entire length of a logging cable by real-time surface data readout. Because the DTS cable can be left in place, long-term monitoring of temperature conditions can be readily conducted. Here, we report the results from borehole logging focused on investigating the accuracy of the method and utilizing the technique in a fluid experiment under temperature conditions up to 120°F (about 50°C).

INTRODUCTION

Currently, two types of advanced technology temperature logging systems are widely used to obtain continuous logs in boreholes with sufficient accuracy and precision for both temperature and depth. Thus, it is now possible to obtain continuous temperature logs to the nearest of 0.001°C (Blackwell and Spafford, 1987). Electric-line tools have an electrical connection to the surface and digital recording, whereas temperature sensing "slick-line" or "memory tool" computer systems are connected by a solid cable, with no real-time data readout (Wisian and others, 1997). As reported by these authors, each of the systems has advantages and disadvantages.

With the new temperature logging principle based on optic fibres, a method is developed which differs from conventional temperature

logging techniques. The DTS method offers a broad range of potential applications that cannot be realized easily with conventional methods. For example, the technique has a great potential for monitoring dynamic systems because the temperatures are obtained instantaneously, repeatedly, and simultaneously for the entire depth profile without physically disturbing the borehole medium by moving in the logging tool. Also effects on the quality of logging data caused by the logging rate are not relevant.

In Europe, the first application of the Distributed optic-fibre Temperature Sensing (DTS) for geoscience purposes was in 1992 (Hurtig and others, 1993) under steady-state borehole conditions. Later on, the technique was utilized in the Grimsel Rock Laboratory of NAGRA (Switzerland) where the impact of injected warm and cold fluids on the temperature profiles was measured (Hurtig and others, 1994). Several other applications are given in a paper by GroOwig and others (1996). At about the same time in Japan, the first applications of optic-fibre temperature sensing were made in field tests by Sato and others (1994), Sakaguchi and Matsushima (1995), and Osato and Takasugi (1996).

TECHNICAL BACKGROUND

The method of Distributed optic-fibre Temperature Sensing (DTS), which was developed at the beginning of the 1980s at Southampton University in England is based on the Optical Time-Domain Reflectometry (OTDR). An extensive list of literature providing the details

of the basic physics behind the concept is given in Forster and others (1997). In principle, if a laser pulse is coupled to an optic fibre the light will propagate through the fibre and be backscattered during propagation. The intensity of the Raman back-scattered light component is temperature dependent. Thus, the basic principle of fibre-optic temperature sensing consists of filtering the Raman back-scattered components (the Stokes and Anti-Stokes spectral lines) out of the backscattering light. Because the velocity of light propagation in the optic fibre is well known, the distance can be determined from the attenuation of the intensity of the backscattered light. This is similar to the Radar principle. Another difference in regard to conventional temperature logging is that temperature data are integrated over distance intervals, e.g. 1 m, and not obtained at single points of measurement.

### THE LOGGING EQUIPMENT

The DTS system used at the GeoForschungs-Zentrum (GFZ) Potsdam consists of a gradient-index fibre and the DTS device as the transmitting and recording unit for measuring the intensity of backscattered light. A PC acting as a data acquisition and controlling unit is attached to the DTS device (Fig. 1).

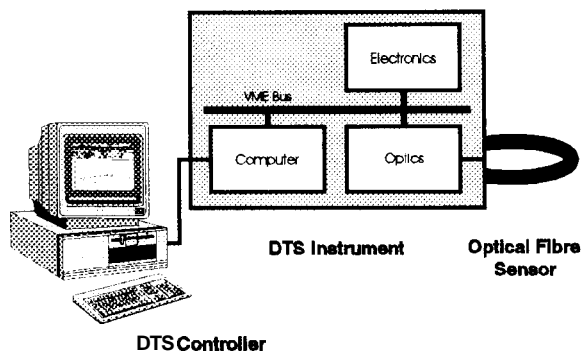


Fig. 1. The concept of the DTS system with the main units: the DTS device of about 40x30x30cm<sup>3</sup>, the optic-fibre cable, and a portable computer.

The laser pulse through the optic fibre has a wavelength of 1064 nm. The pulse duration of the

laser is 10 ns. An optic-fibre cable (the distributed sensor) of 1000 m length is connected to the DTS device using two pigtailed. Although the DTS technique in its present form is suitable for borehole logging to 10 km depths (depending on the hardware configuration), the system used by us is configured for fibre lengths up to 4 km.

Our equipment presently has a 1000-m sensor cable consisting of a high-grade steel tubule (2 mm diameter), in which the optic fibres coated by an acrylic material are embedded. The entire fibre system itself is embedded in a plastic material (Fig. 2).



Fig. 2. Optic-fibre cable as used presently at the GFZ Potsdam.

To achieve a closed fibre loop two fibres embedded in the cable are connected in a specially designed waterproof tool at the end of the cable. The cable is on a reel weighting about 20 kg and has to be installed in the borehole prior to logging. The temperature limit of the logging system in its present form is 80°C caused by the material from which the cable is made. The DTS laser unit however, allows temperature

measurements to several hundred degrees Celsius. The gradient-index fibres embedded in the cable have a temperature limit of about 120°C. However, laboratory experiments have shown that an optic fibre surrounded by a steel tube could work for short time at temperatures up to 550°C (H. Hohberg, pers. comm., 1993) or even at higher temperatures up to 750°C depending on configuration of the DTS system as stated by fibre manufacturers.

#### LOGGING RESULTS UNDER STEADY-STATE CONDITIONS

A comparison of temperature profiles obtained with the DTS tool to those obtained with a conventional temperature logging tool (electric-line system) was made to determine to what degree DTS results can resolve the thermal structure in a thin-bedded sedimentary environment (Forster and others, 1997). Although it is known that the DTS tool has a resolution of about 0.1°C and data precision of about 0.3°C, which is lower compared to conventional tools (0.001°C and 0.1-0.01°C, respectively), the comparison was made to quantify the DTS logging results in terms of differences in interval and formation temperature gradients. This evaluation is necessary to properly interpret the DTS results when using them in the framework of heat-flow studies and in situations where no high-resolution logging tool can be applied readily, for example in air- or gas-filled wells.

The major result obtained by Forster and others (1997) in the Smokyhill borehole (Kansas/Midcontinent) is the close resemblance in form and value between the temperature logs from the two types of instruments and a good response of DTS temperature gradients to the alternating lithologic units of different thermal conductivity. The logging interval for both tools was 1m. Differences in 1-m interval temperature gradients from the two tools result from the lower resolution of the DTS technique. The gradient differences however are smaller the greater the gradient interval that is selected or the larger the smoothing function applied to the DTS values. For example, the difference in interval gradients between the two tools can be minimized to about

10°C/km when using 10-m gradient intervals for the DTS data or applying a smoothing function with a spacing of 5 m.

#### LOGGING RESULTS UNDER DYNAMIC CONDITIONS

To show the advantage of the technique in monitoring transient temperature changes in boreholes an experiment was made in the Big Springs borehole (Kansas) (Forster and others, 1996). This is a 7" (18 cm) borehole drilled to a depth of 880 m into the Ordovician Arbuckle Dolomite. The borehole is lined with a steel casing and open at the bottom of the hole allowing fluids to co-mingle with the Arbuckle aquifer. Prior to the fluid experiment a temperature profile was obtained under steady-state conditions, which serves as a reference curve for the logs obtained during temperature perturbation. After the DTS cable was installed in the borehole, 520 gallons (about 2000 liters) of warm fluid heated to a temperature of 120°F (about 50°C) was put into the well to disturb the equilibrium temperature conditions. The amount of water disposed of is equivalent to a water column of 250 ft (about 76 m) and took 15 minutes. Simultaneous temperatures logs were obtained after cessation of water disposal, (each with 1-minute recording interval over the time span of 4 hours) to monitor the change of temperature conditions in the entire water column.

Figure 3 and Figure 4 show a selection of temperature profiles measured at different time intervals after water disposal compared to the temperature log ( $t_0$ ) obtained prior to the perturbations. At 3 minutes after disposal, the watertable is at a depth of 87 m, which is 34 m higher than under static conditions (Fig. 3). Also, parts of the cool water that was originally in the uppermost part of the borehole (between 76 and 155 m) was displaced already by warm fluid. The adjustment of the elevated watertable to static conditions is related to the downward fluid flow caused by the inflow of water into the bottom-hole aquifer. As a consequence of fluid flow, temperatures in the depth interval below the warm water decrease by about 1-3°C.

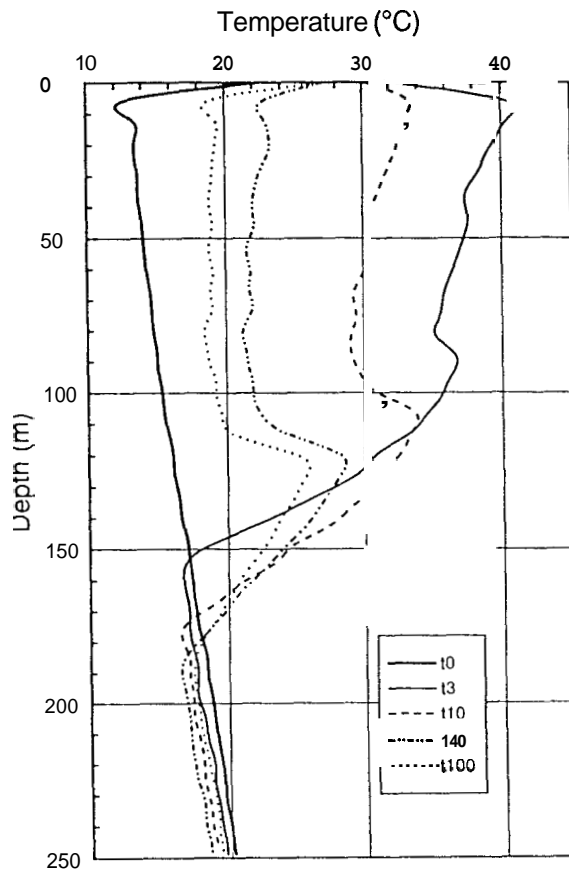


Fig. 3. Selection of temperature-depth profiles obtained with the DTS technique in the borehole Big Springs. The upper part of the logs to a depth of 250 m is shown.  $t_0$  is the reference temperature curve obtained under steady-state conditions. The static watertable at 121 m depth cannot be identified on the  $t_0$  curve, which indicates the suitability of the DTS technique for measuring temperature in air-filled boreholes.  $t_3$ - $t_{100}$  are curves measured in the time span of 3 to 100 minutes after cessation of warm water disposal. Note the recovery of the elevated watertable (at 87 m) to static conditions within 40 minutes and the remaining cooling of the warm fluid in the uppermost part of the water column.

After approximately 40 minutes the watertable in the well recovered to static conditions and downward flow ceased, while the heated uppermost part of the water column continued to adjust to the original subsurface temperature. The

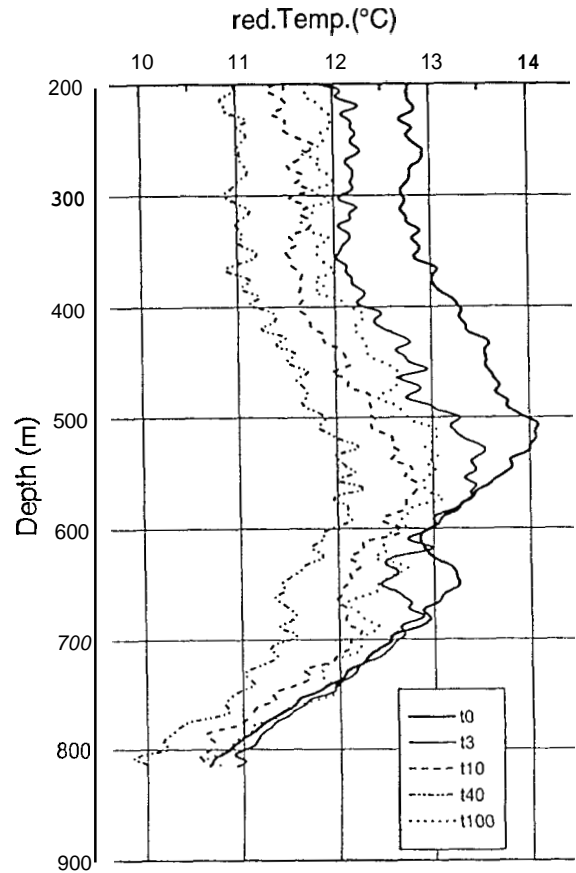


Fig. 4. Transient temperature changes after stimulated fluid flow from the lower part of the borehole Big Springs. Temperature curves are identical with those in Figure 3. Temperatures  $T_{red}$  plotted on a reduced scale are calculated according:  $T_{red}(z) = T(z) - z(dT/dz)$ , with  $dT/dz = 30^\circ\text{C}/\text{km}$ . Temperatures along the profiles  $t_3$ - $t_{40}$  decrease as a result of down-hole flow. The temperatures of profile  $t_{100}$  are partly adjusted to the steady state conditions of profile  $t_0$ .

part of the temperature profiles above the watertable represents mostly the adjustment of the cable after having experienced heating during the water disposal. After cessation of downward flow, temperatures rise again in the depth interval below the warm water column until being adjusted to the steady-state conditions as indicated by the temperature profile  $t_0$  (Fig. 4). The character of the  $t_0$  curve shown in Figure 4 reflects the different thermal conductivity of subsurface

lithologic units, as for example in the interval of the Mississippian carbonates at 520-600 m depth. It is noticeable that the character of the curves remains visible during perturbation, but is shifted downward.

## CONCLUSIONS

Our experience with the DTS technique has shown that the method is suitable for use in heat-flow studies although its resolution is lower than conventional temperature logging techniques. However, the most appropriate application for the DTS logging system may be the installation in a borehole for extended periods of time to monitor dynamic temperature conditions, for example in connection with natural or artificially stimulated fluid flow.

An application of the GFZ DTS logging system in a high-temperature borehole environment is possible in principle, but requires another logging cable in conjunction with an integrated high-temperature fibre. The main problem then is linked with the temperature limits of fibre coatings available, e.g. polyamide or aluminium. On the other hand, cable constructions are needed to protect the fibres mechanically.

For the near future, we are thinking about field tests of the DTS system under temperature conditions of about 250°C using the equipment with a portable logging cable. Although several applications of optic fibres in geothermal wells are known from Japan, there is need for further research until the technique will be used widely in reservoir monitoring and management.

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